U.S. DEPARTMENT OF COMMERCE/ National Oceanic and Atmospheric Administration

OFCM

OFFICE OF THE FEDERAL COORDINATOR FOR
METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

PROCEEDINGS OF THE 2nd International Conference on Volcanic Ash and Aviation Safety

June 21-24, 2004
Hilton Alexandria Mark Center Hotel
Alexandria, Virginia (USA)

THE FEDERAL COMMITTEE FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH (FCMSSR)

VADM CONRAD C. LAUTENBACHER, JR., USN (RET.)
Chairman, Department of Commerce

DR. KATHIE OLSEN
Office of Science and Technology Policy

DR. RAYMOND MOTHA
Department of Agriculture

BRIG GEN DAVID L. JOHNSON, USAF (RET.)
Department of Commerce

MR. ALAN SHAFFER
Department of Defense

DR. ARISTIDES PATRINOS
Department of Energy

DR. PENROSE C. (PARNEY) ALBRIGHT
Science and Technology Directorate
Department of Homeland Security

DR. ROBERT M. HIRSCH
Department of the Interior

MR. RALPH BRAIBANTI
Department of State

MR. RANDOLPH LYON
Office of Management and Budget

MR. NORMAN FUJISAKI (Acting)
Department of Transportation

MR. DAVID MAURSTAD (Acting)
Federal Emergency Management Agency
Department of Homeland Security

DR. GHASSEM R. ASRAR
National Aeronautics and Space Administration

DR. MARGARET S. LEINEN
National Science Foundation

MR. PAUL MISENCIK
National Transportation Safety Board

MR. JOHN W. CRAIG
U.S. Nuclear Regulatory Commission

DR. GARY FOLEY
Environmental Protection Agency

MR. SAMUEL P. WILLIAMSON
Federal Coordinator

MR. JAMES B. HARRISON, Executive Secretary
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

THE INTERDEPARTMENTAL COMMITTEE FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH (ICMSSR)

MR. SAMUEL P. WILLIAMSON, Chairman
Federal Coordinator

MR. THOMAS PUTERBAUGH
Department of Agriculture

MR. JOHN E. JONES, JR.
Department of Commerce

RADM STEVEN J. TOMASZESKI, USN
United States Navy
Department of Defense

BRIG GEN THOMAS E. STICKFORD, USAF
United States Air Force
Department of Defense

MR. RICKEY PETTY
Department of Energy

MS. NANCY SUSKI
Science and Technology Directorate
Department of Homeland Security

MR. LEWIS T. MOORE
Department of the Interior

MS. REGINA MCELROY
Federal Highway Administration
Department of Transportation

MS. LISA BEE
Federal Aviation Administration
Department of Transportation

DR. JONATHAN M. BERKSON
United States Coast Guard
Department of Homeland Security

MR. JEFFREY MACLURE
Department of State

DR. S. T. RAO
Environmental Protection Agency

MR. JOHN GAMBEL
Federal Emergency Management Agency
Department of Homeland Security

DR. RAMESH KAKAR
National Aeronautics and Space Administration

DR. JARVIS MOYERS
National Science Foundation

MR. DONALD E. EICK
National Transportation Safety Board

MS. LETA A. BROWN
U.S. Nuclear Regulatory Commission

MS. ERIN WUCHTE
Office of Management and Budget

MR. JAMES B. HARRISON, Executive Secretary
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

OFFICE OF THE FEDERAL COORDINATOR

FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

8455 Colesville Road, Suite 1500
Silver Spring, Maryland 20910
301-427-2002
www.ofcm.gov

PROCEEDINGS

OF THE

2nd International Conference on Volcanic Ash and Aviation Safety

June 21-24, 2004
Hilton Alexandria Mark Center Hotel
Alexandria, Virginia (USA)

Washington, DC
November 2004

FOREWORD

In February 1997, the White House Commission on Aviation Safety and Security recommended a national goal for government and industry of reducing the fatal aviation accident rate by 80 percent in 10 years. The National Aviation Weather Program Council adopted the 80 percent reduction goal and in February 1999 the *National Aviation Weather Initiatives* document was published as the next major step in coordinating the many federal and nonfederal programs relevant to improving aviation safety. Because of the serious threat posed by volcanic ash and other airborne hazardous materials, these were identified as one of the principal service areas for the aviation weather program.

Although there have been no fatal accidents caused by encounters with volcanic ash, there have been close calls with aircraft experiencing in-flight engine failures. Fortunately, these aircraft were able to land safely, but in some instances the cost to repair the aircraft was in the millions of dollars. The fact that there have not been recent incidents or accidents speaks to the work of the Volcanic Ash Advisory Centers around the world but there is more we can do to ensure that encounters are reduced to zero and that there is never a fatal accident resulting from a volcanic ash encounter.

This document summarizes the proceedings of the 2nd International Conference on Volcanic Ash and Aviation Safety and provides a roadmap for building on our successes in aviation safety over the next decade. I wish to thank the U.S. Geological Survey, the National Oceanic and Atmospheric Administration, the Federal Aviation Administration, the National Aeronautics and Space Administration, the Smithsonian, the Air Line Pilots Association, the Meteorological Service of Canada, the International Association of Volcanology and Chemistry of the Earth's Interior, and the Tenix Corporation for their sponsorship of this conference. In addition, I want to thank the Director of the National Museum of Natural History, Smithsonian Institution, for his warm welcome at our reception and private viewing of the museum. Special thanks goes to the Working Group for Volcanic Ash, the conference planning committee, and to the colleagues from the 21 countries, 15 airlines, 12 universities, 6 private corporations and other participants who were instrumental in making this conference a huge success.

Sincerely,

Samuel P. Williamson
Federal Coordinator for Meteorological
Services and Supporting Research

TABLE OF CONTENTS

OPENING SESSION

Conference Goals and Objectives

Goals of the Second International Conference on Volcanic Ash and Aviation Safety

- ***Consolidate and communicate*** the substantial progress made in the technical, operational, and scientific aspects of ash hazard mitigation since the first international meeting in 1991.
- ***Identify requirements and opportunities for further improvements*** in each component of the coordinated, international mitigation system.
- ***Leverage the ongoing investment*** of effort and resources by the international programs, technology R&D partners, and the aviation industry to ensure the greatest return in reducing risks to safety and socioeconomic consequences.

The Risk to Aviation from Airborne Volcanic Ash

More than 100 commercial aircraft have had ash-encounter incidents. Damage to a single aircraft has been as high as $80 million.

Airborne volcanic ash poses a serious threat to aviation, but this threat can be mitigated through the combined efforts of scientific specialists, the aviation industry, and air traffic control centers. More than 100 commercial and military aircraft have unexpectedly encountered volcanic ash clouds in flight. The consequences of an aircraft flying into an ash cloud can include degraded engine performance (including flameout), loss of visibility, and failure of critical navigational and operational instruments. Several encounters have resulted in multiple engine failures, and disastrous crashes have been only narrowly averted. In addition to major repair costs from encountering a dense plume (up to $80 million in damages have occurred to a single aircraft), aircraft encountering less dense volcanic ash clouds have required increased maintenance of engines and external surfaces.

In 15 hours, the Mt. St. Helens plume traveled 600 miles down-wind. After 2 weeks, ash had circled the Earth.

The safest mitigation strategy is for aircraft to avoid flying into an ash plume. Avoidance requires knowing where an ash plume exists before entering it. Dispatchers, pilots, and air traffic controllers must be quickly informed of pre-eruptive volcanic activity, explosive eruptions, and the location and direction of ash plumes anywhere these may occur around the globe. On average, about 15 major explosive eruptions—those powerful enough to inject ash above 25,000 feet into the stratosphere—occur per year. The ash plume from a major eruption, such as Mt. Pinatubo in 1991, can affect aircraft thousands of miles downwind. When Mt. St. Helens erupted in 1980, the plume reached an altitude of 90,000 ft. in 30 minutes and was 50 miles wide.

An International Problem that Requires an International Solution

Volcanic ash is a worldwide aviation problem that demands an international solution. A volcanic "ring of fire" circles the Pacific basin from South and Central America through the Pacific Northwest and Alaska, and around to Kamchatka, Japan, Indonesia, the Philippines, and Micronesia. This region is often cited as having the greatest volcanic ash risk because of the number of active volcanoes and their proximity to major aviation routes. About 100 potentially dangerous volcanoes lie under air routes in the North Pacific region alone. Other regions of volcanic activity are in the Caribbean and Mediterranean basins and south Asia, as well as Iceland and the Azores in the Atlantic basin. Ash carried downwind from an eruption in any of these regions can endanger aircraft flying in its path.

The International Civil Aviation Organization (ICAO) began adopting provisions in 1987 for volcanic ash warnings to be included in aviation SIGMETs. In 1998, ICAO established the International Airways Volcano Watch, which consists of nine Volcanic Ash Advisory Centers (VAACs) to provide an interface between volcano observatories, meteorological agencies, and air traffic control centers. Each VAAC uses reports from volcano observatories and satellite imagery to track volcanic activity and ash clouds in its designated region.

Improving the International System for Volcanic Ash Risk Mitigation

The 1991 symposium on volcanic ash and aviation safety brought international stakeholders, as well as U.S. Federal agencies and many R&D partners, together for the first time. Since then, the nine VAACs have been established, along with channels for rapid communication of volcano eruption and plume movement information to the aviation community. Methods for observing and analyzing the indicators of an impending eruption have been improved. New satellite-based remote sensing techniques are being used or developed for both volcano monitoring and ash-cloud identification and tracking.

Accurate, timely reporting of an eruption, including premonitory information about the build-up phase and real-time detection of the eruption, is an important component of mitigating the risk to aviation. Various physical and chemical signals, called “volcanic unrest,” are related to the rise of magma toward the Earth’s surface. Tracking these signals over periods of weeks to years before an eruption, combined with knowledge of a volcano’s eruptive history, allows volcanic unrest to be monitored and interpreted. Volcano observatories use this approach to forewarn, to the extent possible, of impending eruptions.

Once an explosive eruption occurs, polar-orbiting and geosynchronous satellites can use radiometry, multispectral analysis, and other techniques to detect and track ash clouds. These satellite images provide snapshots in time of the location of airborne ash. Atmospheric dispersion models provide forecasts of where an ash cloud is headed, to give pilots, dispatchers, and controllers warning in advance. Airborne detection systems for volcanic gas and ash detection are being developed and tested.

Just as important to risk mitigation as these technological advances is the operational experience of the aviation community—commercial carriers, pilots, air traffic controllers, flight service specialists, etc.—with the still-evolving international system for detecting and communicating volcanic ash hazards. The time is right to bring all these stakeholders together again, to assess how the current system is operating and to focus attention on the critical areas for improvement.

The Second International Conference on Volcanic Ash and Aviation Safety is designed to meet these objectives. Its plenary and breakout sessions cover the major components of volcanic ash hazard mitigation, progress in technology and operations, the needs of the aviation community, and future directions for coordinated efforts. Agenda topics for the 4-day conference include:

- Physical damage to aircraft from encounters with volcanic ash clouds and the socioeconomic consequences of the volcanic ash hazard.
- The volcanic source: operations and improvements in eruption monitoring and reporting.
- Ash-cloud observations and forecasting: improving ash-cloud detection and modeling capabilities.
- Operations and capabilities at the regional VAACs: improving VAAC communications and operational capabilities to meet world aviation safety needs.
- Aviation industry perspectives: transferring technology from research into operations to meet aviation needs.
- Education and outreach to pilots, air traffic controllers, dispatchers, the aviation industry, and the meteorological and communications support services to aviation.

Airborne volcanic ash will persist as a serious aviation hazard. Mitigation strategies are working now but can and should be strengthened. The Second International Conference on Volcanic Ash and Aviation

Safety brings the scientific, technology development, and aviation communities together to consolidate and communicate the progress that has been made, identify requirements and opportunities for further improvements, and leverage the ongoing investment of effort and resources to ensure the greatest return in reducing the risks.

Conference Objectives

- Identify new operational needs/requirements and the research and development needed to satisfy those requirements.

- Match operational and research and development needs/requirements to ongoing programs/projects to maximize partnership efforts.

- Develop a roadmap for improved volcanic ash-related education, training, outreach, and decision tools.

- Develop a framework for improved partnerships within the international volcanic ash community to leverage resources and capabilities across the spectrum of operations and research and development.

Keynote Address and Invited Presentations

Keynote Address:

The Keynote Address was to be given by the **Honorable Ted Stevens**, Senator, Alaska; however, Senator Stevens was unable to attend due to legislative obligations. A letter from Senator Stevens was read to the conference attendees (see p. 1-7). **Dr. James R. Mahoney**, Assistant Secretary of Commerce for Oceans and Atmosphere and National Oceanic and Atmospheric Administration (NOAA) Deputy Administrator, delivered the keynote address since Senator Stevens was not available. He discussed the role NOAA has played in the detection and monitoring of volcanic ash since the early 1980's. This role was made more formal in 1988 for aviation safety with the near real-time ash monitoring, tracking, and composition of global volcanic activities. NOAA's role also includes the operation of Meteorological Watch Offices, the development of numerical models for the forecasting of ash cloud motion, and the R&D of enhanced volcanic ash detection techniques for use in real-time operations.

Invited Presentations:

Dr. Charles G. Groat, Director of the U.S. Geological Survey (USGS) described the leading role of USGS in the global mitigation efforts to reduce the threat to aviation from volcanic ash, through an integrated program of volcanic monitoring and research, eruption reporting, and hazard education. Dr. Groat described the development of a color-coded notification alert scheme for volcanic ash warnings to the air carrier industry, which is now being recommended for worldwide use by the International Civil Aviation Organization (ICAO). With the establishment of the Alaska Volcano Observatory, the USGS has organized interagency communications procedures for volcanic eruption and airborne volcanic ash hazards in the North Pacific.

Rear Admiral James P. Schear, U.S. Naval Reserve (Ret.), Federal Aviation Administration (FAA) Air Traffic Organization's Vice President for Safety related that during the last two decades more than 80 jets suffered damage because of encounters with volcanic ash. These encounters resulted in hundreds of millions of dollars in damage to aircraft and unknown costs due to operational delays. The FAA has been a stakeholder in improving aviation weather services which has resulted in a safer and more efficient international airspace. RADM Schear stated that one of the principal goals is to "Increase the safety and capacity of the global civil aerospace system in an environmentally sound manner." The FAA works closely with ICAO to adopt common international safety standards, air traffic procedures, and technologies. In addition, the FAA supports the operations of the Volcanic Ash Advisory Centers (VAACs) and the ICAO International Airways Volcano Watch Operations Group. RADM Schear also stated that more advanced countries need to help countries with limited resources that have active volcanoes where early detection is critical for flight safety.

Mr. Ronald J. Birk, Director of the Earth Science Applications Division, Office of Earth Science, National Aeronautics and Space Administration (NASA), spoke on NASA's new vision of integrating Earth observations into decision-support tools for aviation and other applications of both national and international priority. NASA is working with the interagency Joint Planning and Development Office to produce a plan for a precise, continuous, and dynamic aviation weather digital database to support the aviation information infrastructure. Mr. Birk showed a movie, "A Vision of the Future," and invited the global community to share in this vision. One dimension for accomplishing this vision is to extend the benefits of the sensors on NASA and NOAA Earth observation satellites to provide critical information on the early detection and transport of volcanic ash and gas. NASA and its partners benchmark practical uses of observations and predictions from Earth science models for decision-support tools that serve operational and policy decision makers. Mr. Birk discussed the Advanced Satellite Aviation-weather Products project which is a partnership between NASA and FAA intended to integrate satellite observations into a wide range of graphical products, including volcanic ash.

Mr. Gianni Semenzato, Senior Flight Inspector with the Ente Nazional per L'Aviazione Civile (Italian Civil Aviation Authority) described the Catania Fontanarossa Airport's procedures for flight operations in the presence of volcanic ash. Based on information provided by ICAO, an organizational structure was identified of different civilian and military bodies involved in ensuring the operational condition for the airport during periods of strong volcanic activity. Mr. Semanzato spoke of the authorities involved, the monitoring and alarm capabilities, and the tasks and responsibilities of each group during an event. He concluded with the guidelines for evaluating the procedures.

United States Senate
COMMITTEE ON APPROPRIATIONS
WASHINGTON, DC 20510–6025
www.senate.gov/~appropriations

June 18, 2004

Mr. Sam Williamson
Federal Coordinator for Meteorology
Office of the Federal Coordinator for Meteorology
8455 Colesville Road Suite 1500
Silver Spring, Maryland 20910

Dear Sam:

I am honored to have been invited to be the keynote speaker at the 2nd Conference on Volcanic Ash and Aviation Safety. I regret that I am unable to attend due to obligations in Washington, D.C.

The threat to aviation posed by airborne volcanic ash is a serious matter. Volcanic ash poses a risk to aviation in Alaska due to the large number of active volcanoes in our state. As you know, Anchorage is one of the world's busiest cargo airorts and is a common technical stop for transpacific passenger flights. Additionally, seventy percent of Alaska's communities are not on the road system and depend on aviation for most goods and services. For this reason I have long supported a robust volcano monitoring system throughout Alaska and the North Pacific.

Thanks to all of you for the extraordinary job you have done making our skies safer.

With best wishes,

Cordially,

TED STEVENS

PANEL DISCUSSIONS

Panel 1: Airborne Volcanic Ash: Perspectives, Challenges, and Opportunities

Moderator: Dr. Elbert (Joe) Friday, *WeatherNews Professor of Meteorology and Founding Director of the Sasaki Applied Meteorology Research Institute, University of Oklahoma*

Rapporteur: Mr. Floyd Hauth, *Science and Technology Corporation*

Panelists:
Dr. Thomas P. Miller, *Scientist Emeritus, USGS Alaska Volcano Observatory*
Dr. Louis Uccellini, *Director, NOAA's NWS National Centers for Environmental Prediction*
Ms. Gloria Kulesa, *Manager, Aviation Weather Research Program, FAA*
Mr. Alan Shaffer, *Director, Plans and Programs, Office of the Secretary of Defense*
Mr. Peter Chen, *Environment Canada, Atmospheric and Climate Science Directorate*

Synopsis: This panel focused on the progress of key actions/recommendations from the first conference; the current state of volcanic ash operational support and the status of supporting research; resource coordination and leveraging across the spectrum of operations and research; the transition of research into applications; and opportunities for the future, including efficient leveraging of the national and international technologies and research. Highlights included noting the good progress on volcanic ash initiatives since the first symposium and that partnerships and collaboration in the area of detection and warning are healthy. It was also noted that gaps continue in our understanding of the ash hazard and that some deficiencies continue with observations (analyses), modeling, and warning delivery. It was also noted that volcanic ash can reach commercial flight levels in as little as 5 minutes which poses a real challenge for the volcanic ash warning system.

Dr. Thomas Miller: Dr. Miller summarized the composition of volcanic ash, the stringent requirement for timeliness of warnings, and information on the threat of encounters. He indicated that much progress had been made since the first symposium, but there is a need to continue efforts to improve the warnings.

Dr. Louis Uccellini: Dr. Uccellini noted that the 5-minute requirement was hard to achieve but provided a good challenge to improve observations, modeling (forecasts), and delivery processes. Progress continues in model improvements, but the analysis process still requires too much time and delays warnings.

Ms. Gloria Kulesa: Ms. Kulesa described FAA program investments in science and technology for aviation support. There are many partnerships in place, and collaborations continue to be healthy.

Mr. Peter Chen: Mr. Chen stated that volcanic ash warning requirements demand quick response and action for aviation safety. The providers of products and services need to continue to invest in modeling and supporting computation capability. There is also a need to determine the gaps in capabilities to deal with volcanic ash. He is also concerned about the possibility of higher false alarm rates when efforts push for achieving the 5-minute warning goal.

Mr. Alan Schaefer: Mr. Schaefer described DOD activities and capabilities that support aviation operations threatened by volcanic ash. He also reported on progress supporting research projects. He indicated that satellites have the best potential to meet observation/detection needs. Navy centers currently issue tailored ash forecasts.

Panel 2: Education, Training, and Outreach

Moderator: Dr. Gregory S. Forbes, *Severe Weather Expert, The Weather Channel*

Rapporteur: Mr. Donald Carver, *FAA*

Panelists: Ms. Cyndie Abelman, *Meteorologist-In-Charge, NOAA's NWS, Oklahoma City, OK*
Captain Albert Beerley, *US Airways Airbus, US Airways/ALPA Training Committee*
Mr. John O'Brien, *Director, Engineering and Air Safety Department, Air Line Pilots Association*
Mr. Saburo Onodera, *Manager, Flight Crew Training Department, Japan Airlines*
Professor Eric Doten, *Director of Center for Aerospace Safety/Security Education, Embry-Riddle Aeronautical University*

Synopsis: The diverse panel discussed the education, training, and outreach activities within the university structure, the FAA, the airlines, as well as the international community. While many training/education programs exist, the panel highlighted the need for more training on the coordination of military and civil airspace during volcanic ash hazards; for continued development of bibliographies for training materials and case studies; and the need for outreach to agencies on understanding the risk and the reasons to provide resources for volcanic ash mitigation.

Ms. Cyndie Abelman: Ms. Abelman stated that the FAA academy has intense weather training for flight service specialists. In the near future the training will include a volcanic ash hazards module. En route center controllers are assisted/advised by NWS personnel in Center Weather Service Units.

Captain Albert Beerley: Captain Beerley noted that U.S. Airways trains on specific risk areas relative to their routes and terminals of operation. Training includes approach/departure procedures and sources of advisory/warning services.

Mr. John O'Brien: Mr. O'Brien noted that the Air Line Pilots Association promotes operational awareness and procedures to enhance safety among its global membership. Members support programs plus outreach to agencies, controlling resources for research and development for better services.

Mr. Saburo Onodera: Mr. Onodera stated that Japan Airlines has established a syllabus for training for each level of crew competencies, including volcanic ash avoidance and limits to operations. They emphasize route selection alternatives and simulations/drills.

Professer Eric Doten: Dr. Doten stated that Embry-Riddle Aeronautical University has 130 centers where they confer degrees in applied science for meteorology, including research opportunities.

PLENARY SESSIONS

These sessions covered five areas: volcanic ash encounters; volcanic ash source; ash cloud observation, modeling, and forecasting; Volcanic Ash Advisory Center (VAAC) operations and capabilities; and aviation industry perspectives. The sessions consisted of both oral and poster presentations from the international community and set the stage for related breakout sessions. Papers for some presentations can be found in Appendix C.

Session 1: Encounters, Damage, and Socioeconomic Consequences

Session Chairs: Mr. Edward Miller, *Air Line Pilots Association*
Mr. Leonard Salinas, *United Airlines*

Rapporteur: Mr. Donald Carver, *Federal Aviation Administration (FAA)*

This session featured six oral and two poster presentations focused on aircraft encounters with volcanic ash and the impacts of volcanic ash on airline operations. Aircraft encounters with Montserrat, Mt. Hekla, Rabaul, and Miyakejima were described, as well as how the volcanic ash hazard impacts the operations of airlines such as United Airlines and Air Niugini. The fact that ash can reach commercial flight levels within minutes and that even apparent diffuse ash can cause significant engine damage highlighted the need for early detection and warning.

Session 2: The Volcanic Ash Source - Eruption Monitoring and Reporting

Session Chairs: Ms. Marianne Guffanti, *United States Geological Survey (USGS)*
Dr. Steven McNutt, *Geophysical Institute, University of Alaska and the International Association of Volcanology and Chemistry of the Earth's Interior*

Rapporteur: Ms. Terry Keith, *USGS*

This session featured eight oral and 13 poster presentations focused on eruption monitoring and reporting. The first oral presentation provided a global perspective on volcanoes and their eruptions and noted that many of the world's active volcanoes are in developing countries and that monitoring these volcanoes is difficult. Several of the presentations noted the difficulty in monitoring volcanoes and in determining the timing and strength of potential eruptions. There were also presentations on current capabilities for monitoring volcanic eruptions in the North Pacific and in the Western Pacific. Other initiatives such as a prototype infrasound system; an alert-level notification scheme for aviation, using volcanic tremors in estimating eruption parameters; and ground-based detection of ash and sulphur dioxide were presented as well. Points emerging from this session included the need for instrumenting more volcanoes that pose a threat to aviation, the need for more research on volcanic processes and ash cloud characterization, and the need for a standardized warning system.

Session 3: Ash Cloud Observations, Modeling, and Forecasting

Session Chairs: Dr. William Rose, *Michigan Technological University (MTU)*
Ms. Barbara Stunder, *NOAA Air Resources Laboratory*
Mr. Andrew Tupper, *Bureau of Meteorology, Volcanic Ash Advisory Centre, Darwin, Australia*

Rapporteur: Ms. Alexandria Matiella, *MTU*

This session featured eight oral and 22 poster presentations focusing on ash cloud observations and forecasting ash cloud movements, using volcanic ash transport and dispersion models. Several different transport and dispersion models including VAFTAD, CANERM, HYSPLIT, and PUFF were presented. Various techniques for detecting volcanic ash clouds, using satellite and radar, were also presented. It was also noted that use of various satellite techniques provide valuable information on the wet and dry processes that remove ash particles. Speakers agreed that difficulties in knowing the ash plume parameters and the meteorology often cause uncertainties in the models.

Session 4: Volcanic Ash Advisory Center (VAAC) Operations and Capabilities

Session Chairs: Ms. Grace Swanson, *NOAA National Environmental Satellite, Data, and Information Service, Volcanic Ash Advisory Center, Washington, D.C.*
Mr. Rene Servranckx, *Environment Canada, Canadian Meteorological Center, Volcanic Ash Advisory Centre, Montreal, Canada*

Rapporteur: Mr. Donald Carver, *FAA*

This session featured ten oral and seven poster presentations focusing on various aspects of VAAC operations. Two papers highlighted the roles of the ICAO and the World Meteorological Organization (WMO) in dealing with the volcanic ash threat. Several papers provided operational capabilities at several VAACs, including the Washington VAAC, the Tokyo VAAC, the Montreal VAAC, the London VAAC, and the Darwin VAAC. The importance of shared situational awareness and collaboration were stressed in several papers, and the capabilities of a new pilot program called the Volcanic Ash Collaboration Tool were highlighted as a possible way to enhance collaboration among international agencies.

Session 5: Aviation Industry Perspectives

Session Chairs: Mr. Steven Albersheim, *FAA*
Mr. John Murray, *National Aeronautics and Space Administration/Langley Research Center*

Rapporteur: Mr. Floyd Hauth, *Science and Technology Corporation*

This session featured seven oral and one poster presentations focusing on the volcanic ash threat from the perspective of the aviation industry. Highlighted areas dealt with the transfer of R&D to operations, how volcanic ash impacts airport operations, and the impact of volcanic ash on air traffic control. The importance of the timely dissemination of volcanic ash information was stressed and a conceptual framework for streamlining the flow of information was provided.

Plenary Sessions Summary

Two themes that emerged from the plenary sessions were better communications and more education/training. Specific actions included:

- Improve communications to move data and information between all entities.
- Increase post-encounter investigations for development of better procedures and services.
- Provide airline pilots with more training with emphasis on hazard awareness.
- Increase the number of potentially hazardous volcanoes that are monitored by ground geophysical instruments.
- Perform more research on ash cloud characteristics to better define the hazard for dispersion models.
- Perform more research on fundamental volcanic processes that lead to "eruptions" versus "failed eruptions." This will help provide improved forecasts on the type, size, and duration of the eruption column as well as the end of the eruption.
- Obtain adequate funding to ensure that all potentially active volcanoes in the U.S. are instrumented and monitored.
- Standardize formats in alert messages.
- Optimize current satellite sensors for ash detection (atmospheric corrections, e.g., SO_2).
- Provide users more information in the pilot report (PIREP), in addition to a broader transmission of all reports in real time.

BREAKOUT SESSIONS

The associated breakout sessions provided an opportunity for continued discussion of issues raised by presenters in the five plenary sessions.

Breakout Session 1: Improving Volcanic Ash Cloud Detection

Session Moderators: Dr. David Schneider, *U.S. Geological Survey (USGS), Alaska Volcano Observatory*
Dr. Steven Ackerman, *Cooperative Institute for Meteorological and Satellite Services, University of Wisconsin - Madison*

Rapporteur: Ms. Emily McCarthy, *Michigan Technological University (MTU)*

This breakout session was associated with Plenary Session 3 (Ash Cloud Observations, Modeling, and Forecasting). Some of the issues discussed dealt with enhanced satellite imagery for ash detection, satellite-based assessments of ash density and height, and ash detection using remote sensing by radar and reconnaissance flights.

Breakout Session 2: Improving Modeling Capabilities

Session Moderators: Mr. Rene Servranckx, *Environment Canada, Canadian Meteorological Center, Volcanic Ash Advisory Center, Montreal*
Ms. Barbara Stunder, *National Oceanic and Atmospheric Administration/Office of Oceanic and Atmospheric Research/Air Resources Laboratory (NOAA/OAR/ARL)*

Rapporteur: Ms. Alexandra Matiella, *MTU*

This breakout session was associated with Plenary Session 3 (Ash Cloud Observations, Modeling, and Forecasting). Some of the issues discussed dealt with defining the ash cloud edge, identifying source-term improvements, assimilating ash cloud observations into dispersion models, and educating the user of model output for better interpretation and decision making. It was recommended that a database be established for use by researchers, modelers, volcanologists, etc. The database would include information on eruptions, ash clouds, satellite imagery, and model output and would serve as a central location of information.

Breakout Session 3: Understanding the Socioeconomic Consequences

Session Moderators: Mr. Floyd Hauth, *Science and Technology Corporation (STC)*
Mr. Peter Lechner, *Civil Aviation Authority of New Zealand*

Rapporteur: Mr. Floyd Hauth, *STC*

This breakout session was associated with Plenary Session 1 (Encounters, Damage, and Socioeconomic Consequences). Some of the issues discussed dealt with the costs to en route operations associated with the ash hazard; identifying the impact on aerodrome operations; identifying the cost benefits associated with improved detection, reporting, and forecasting; and identifying criteria for prioritizing research. Recommendations included identifying costs associated with ash encounters and the benefits from mitigation efforts; establishing a process for closing an airport because of volcanic ash; and establishing a policy on the required spatial separation for ash avoidance. It was also recommended that all volcanic ash incidents, level 3 and above, be reported.

Breakout Session 4: Improving Volcanic Eruption Reporting

Session Moderators: Ms. Christina Neal, *U.S. Department of the Interior/USGS/Alaska Volcano Observatory*
Ms. Cynthia Gardner, *U.S. Department of the Interior/USGS/Cascades Volcano Observatory*

Rapporteur: Ms. Gari Mayberry, *USGS*

This breakout session was associated with Plenary Session 2 (The Volcanic Source-Eruption Monitoring and Reporting). Some of the issues discussed dealt with identifying new methods of volcano monitoring in support of aviation users, characterizing the type of volcano activity report that is optimal for aviation users, and identifying where volcano reporting can be improved. The group agreed that the characteristics of a good volcanic activity report included being timely, consistent, and simple. Other considerations for aviation users included plume height, use of feet, miles, and decimal degrees as the preferred units, and the notification of increasing volcano activity.

Breakout Session 5: Technology Transfer from Research into Operations

Session Moderators: Mr. Mark Andrews, *Department of Commerce/NOAA/National Weather Service/Aviation Weather Services*
Ms. Debi Bacon, *U.S. Department of Transportation/Federal Aviation Administration*

Rapporteur: Mr. Thomas Fraim, *Office of the Federal Coordinator for Meteorological Services and Supporting Research*

This breakout session was associated with Plenary Session 5 (Aviation Industry Perspectives). Some of the issues discussed dealt with current technology transfer procedures and possible improvements to these procedures, the private-sector perspective implementing new technologies, and understanding how technology is introduced in support of international air navigation. The discussion focused on the FAA's Aviation Weather Technology Transfer (AWTT) process which covers end-user products. Systems such as the Integrated Terminal Weather System (ITWS) do not come under the AWTT process. It was noted that one product (Volcanic Ash Graphic) is currently in the AWTT pipeline. It was recommended that the AWTT process be expanded to include agencies involved in more basic research in order to better link basic research with operational applications.

Breakout Session 6: Improving VAAC Operational Capabilities

Session Moderators: Mr. Raul Romero, *International Civil Aviation Organization, Montreal, Canada*
Ms. Grace Swanson, *U.S. Department of Commerce/NOAA/National Environmental Satellite, Data, and Information Service (NESDIS)/Volcanic Ash Advisory Center, Washington, D.C., USA*

Rapporteur: Ms. Donna McNamara, NOAA/NESDIS

This breakout session was associated with Plenary Session 4 (VAAC Operations and Capabilities). Some of the issues discussed dealt with reducing inconsistencies among VAACs and Meteorological Watch Offices (MWOs) in interpreting the significance of ash events, achieving necessary staffing levels and training, reducing communications problems, and leveraging opportunities for improved cooperation and sharing of information. Two issues from this session concerned the dissemination of Volcanic Ash Advisories and training. Graphical products are preferred, but format standardization and communications present challenges. Training is a continuing issue. It was noted that ICAO only sets training requirements; the actual training is the responsibility of individual states. The biggest operational challenges are eruption notification, determining plume height, model inaccuracies, and communications.

Breakout Session 7: Meeting Aviation Needs

Session Moderators: Mr. William Phaneuf, *Air Line Pilots Association*
Mr. Richard Heuwinkel, *FAA*

Rapporteur: Mr. Donald Carver, *FAA*

This breakout session was associated with Plenary Session 5 (Aviation Industry Perspectives). Some of the issues discussed dealt with requirements for the dissemination and display of volcanic ash information, evaluating current and proposed products, the ash threshold for closing airspace and the criteria for resuming operations, and the timeliness of reports and ash information. Emerging themes from this session included the standardization of products from VAAC to VAAC, the need for graphical products, communication links to get the information to the cockpit, and training.

Breakout Sessions Summary

The breakout sessions continued to have similar issues and action items which were first mentioned in the plenary sessions. These are:

○ Clearly define the 5-minute warning issue as a requirement or a goal.
○ Define a detection threshold concentration for volcanic ash cloud.
○ Establish a database on volcanic eruption for use by all interested parties. This database would include, for example, information on ash clouds, satellite data, and model output.
○ Establish a web page for volcanologic community to contain at a minimum 1) sample interagency plans and notification strategies; 2) recommended standard reporting format for volcanic warnings from volcanologists; 3) tutorial for volcanologists on the aviation and aviation-meteorology terms and procedures (e.g., SIGMETs); and 4) information on how to obtain ICAO Annex 3 and the ICAO Manual on Volcanic Clouds.
○ Explore the issue of uncertainty in modeling results. Would a measure of uncertainty be useful to the user community?
○ Provide education/training on models and on the interpretation of model results. As a first step, model guidance could be posted on VAAC web sites for education and decision making.
○ Establish a process to identify and collect cost/benefit data.
○ Establish/coordinate a policy on spatial avoidance of known volcanic ash clouds.
○ ICAO should initiate/coordinate a requirement to report all volcanic ash incidents on Level 3 and above (severity scale index).
○ Improve the FAAs technology transfer process to include more participation from users, particularly those agencies involved in basic research (e.g., NASA), to provide a user’s utility feedback loop.
○ Improve the requirements for advanced sensors for ash and eruption detection on future geostationary satellites.

○ Improve and provide more graphical depiction of volcanic ash products and forecasts to pilots/dispatchers for situational awareness and route planning.

○ Standardize products between VAACs.

REGIONAL BREAKOUT SESSIONS

The regional breakout sessions were intended to provide a forum to discuss issues pertinent to particular regions. By bringing together operators, researchers, and scientists who work in a given region, operational improvements can be identified for issues, ranging from eruption reporting to model output to VAAC protocols. Many user needs were brought out, including the need for continuing efforts directed at improving the timely detection and forecasting of ash dispersion and the need to reduce inconsistencies across adjacent areas of responsibility when different dispersion models are used.

Breakout Session 8: North Asia Pacific (e.g., Alaska, Russia, Japan)

Session Moderators: Mr. Christopher Strager, *U.S. Department of Commerce/National Oceanic and Atmospheric Administration*
Ms. Terry Keith, *U.S. Department of the Interior/U.S. Geological Survey/Alaska Volcano Observatory*

Breakout Session 9: The Americas and the Caribbean (excluding Alaska)

Session Moderators: Dr. Patricia Mothes, *Instituto Geofísico de la Escuela Politécnica Nacional, Ecuador*
Mr. J. Armando Saballos, *Instituto Geofísico de la Escuela Politécnica Nacional, Ecuador*
Richard Hernandez, *Federal Aviation Administration*

Breakout Session 10: Europe, Africa, and the Middle East

Session Moderators: Dr. Gerald Ernst, *Department of Geology and Soil Science, University of Ghent, Belgium*
Mr. Jean-Philippe Desbios, *Volcanic Ash Advisory Center, Toulouse, France*

Breakout Session 11: South Asia Pacific (e.g., Indonesia, the Philippines, Australia, and New Zealand)

Session Moderators: Mr. Rodney Potts, *Australian Bureau of Meteorology Research Centre*
Captain David Innes, *Air Niugini*

The regional breakout sessions had one underlying issue they would like to see addressed:

○ Conduct regional workshops to provide training on volcanic ash and to improve the implementation of the International Airways Volcanic Watch. In particular, there is a need to refine communication protocols through table-top exercises, multiagency operational plans, etc.

CLOSING SESSION

ICAO's Commitment to Mitigating the Volcanic Ash Hazard

On Thursday morning, Mr. William Voss, Director, Air Navigation Bureau, ICAO, was represented by Mr. Raul Romero, Technical Officer, Meteorology Section, International Civil Aviation Organization. Mr. Romero addressed the background of the ICAO and WMO involvement in volcanic ash, with respect to airline regulations and the formation of the Volcanic Ash Advisory Centers and the International Airways Volcano Watch. He stressed the importance for the volcanic ash community to continue to work together, especially in the areas of communications, training, and education.

Conference Highlights

The overall goal of providing a forum for exchanging scientific and operational information for the purpose of identifying ways to improve the mitigation of the volcanic ash hazard to aviation was met. With over 20 countries represented, this conference provided an unparalleled opportunity for the attendees to network and strengthen the partnerships in mitigating the volcanic ash hazard. The key stakeholders represented included government and academic scientists, operational meteorologists, product developers, aviation regulators, pilots, dispatchers, and international organizations dealing in aviation and meteorological matters. The operational components of the International Airways Volcano Watch team were represented, including all the VAACs, the volcano observatory community, and many of the Meteorological Watch Offices (MWO). With a goal of reducing volcanic ash encounters to zero, two basic actions emerged from the conference: sustained vigilance and regional workshops. Sustained vigilance in order to avoid complacency, and additional regional workshops in order to improve implementation of the International Airways Volcano Watch.

Building on Our Successes in Aviation Safety for the Next Decade

Identify new operational needs/requirements and the research and development needed to satisfy those requirements. These included:

- Need for additional information in PIREPs for use in defining existence or dissipation of volcanic ash.
- Definition of the airlines' need for 5-minute notification of volcanic eruption.
- Optimizing current satellite sensors for ash detection, including ensuring volcanic ash community is directly involved with satellite detection research projects (e.g., SO_2 detection).
- Need for more access to airlines reporting engine problems from volcanic ash encounters after-the-fact to be able to study the effects of damage.
- Provide satellite requirements for volcanic eruptions and ash plumes to the Group on Earth Observations (GEO) Architecture Subgroup for critical elements for the Global Earth Observing System.

Where possible, match operational and research and development needs/requirements to ongoing programs/projects to maximize partnership effort.

- NASA will continue to leverage resources in their aviation weather research, especially the areas for hazard mitigation research associated with the Advanced Satellite Aviation-Weather Products project.

- FAA's Aviation Weather Research Program provides opportunities for collaboration on mitigation of volcanic ash in the Oceanic Weather Product Development Team.

Develop a roadmap for improved volcanic ash-related education, training, outreach, and decision tools.

- Conduct regional workshops to provide training on the volcanic ash and aviation safety issue and improve implementation of the International Airways Volcano Watch. Especially, refine communications protocols through table-top exercises, multiagency operational plans, etc.

- Recommend ICAO provide a website for an international source of training materials.

- Conduct training for both sources and users (volcanologists/meteorologists & Automated Flight Service Station personnel/airline dispatchers/aircrews).

- Develop a final four-dimensional graphic of the volcanic ash situation and expected changes for both airline pilots and dispatchers.

Develop a framework for improved partnerships within the international volcanic ash community to leverage resources and capabilities across the spectrum of operations and research and development.

- Identify additional sources of funding within WMO, ICAO, and U.S. agencies for improvements to communications (e.g., between MWO and VAACs) and training.

- Form an aviation issues group within IAVCEI for addressing volcanic ash mitigation for airline safety. In addition, work with the IAVCEI Commission on Education to provide training to vulcanologists on the effects on aviation safety.

- Create a new list serve on the internet focused on ash mitigation issues, particularly those covered during the conference.

Next Steps

The OFCM Working Group for Volcanic Ash (WG/VA) will take action on the conference action items and recommendations including: (1) seek help, input, and advice from international partners and the International Civil Aviation Organization, (2) sort action items and recommendations into short- (0-12 month), mid- (1-4 year), and long-term (4-10 year) actions and prioritize them, and (3) develop and gain approval of a Volcanic Ash Implementation Plan, outlining program goals, operational needs/requirements, and R&D needs and priorities, within the next 12 months. OFCM will publish a proceedings volume from the conference by early fall.

APPENDIX A

AGENDA

AGENDA

Sunday 20 June 2004

5:00 PM Early Registration (5:00-8:00)

Monday 21 June 2004

7:00 AM Registration open

Continental Breakfast

Opening Session

8:30 AM Conference Welcome and Introduction of the Mayor of Alexandria, VA

- Mr. Samuel P. Williamson, Federal Coordinator for Meteorological Services and Supporting Research

8:35 AM Welcome

- Mayor William "Bill" Euille, Alexandria, VA

8:45 AM Conference Objectives and Introductions

- Mr. Samuel P. Williamson, Federal Coordinator for Meteorological Services and Supporting Research

9:00 AM Keynote Address/Invited Speakers

- The Honorable Ted Stevens, United States Senate (invited)
- Dr. James R. Mahoney, Assistant Secretary of Commerce for Oceans and Atmosphere and NOAA Deputy Administrator
- Dr. Charles G. Groat, Director, U.S. Geological Survey
- RADM. James P. Schear, Vice President for Safety, Federal Aviation Administration

10:30 AM Morning Coffee Break (10:30 – 11:00)

- Mr. Ronald J. Birk, Director of the Earth Science Applications Division, Office of Earth Science, NASA
- Mr. Gianni Semenzato, Senior Flight Inspector, Ente Nazional per L'Aviazione Civile (Italian Civil Aviation Authority)

12:00 PM Luncheon (Sponsored by Air Line Pilots Association)

- Guest Speaker: Captain Eric Moody, British Airways (Ret.), *Gliding a B747 Out of Volcanic Ash.*

1:30 PM **Panel 1 – Airborne Volcanic Ash: Perspectives, Challenges, and Opportunities**

Panel Moderator: Dr. Elbert W. (Joe) Friday, WeatherNews Professor of Meteorology and Founding Director of the Sasaki Applied Meteorology Research Institute, University of Oklahoma

Panelists:
- Dr. Thomas P. Miller, Scientist Emeritus, USGS Alaska Volcano Observatory
- Dr. Louis W. Uccellini, Director, NOAA's NWS National Centers for Environmental Prediction
- Ms. Gloria Kulesa, Manager, Aviation Weather Research, FAA
- Mr. Alan Shaffer, Director, Plans and Programs, Office of the Secretary of Defense
- Mr. Peter Chen, Director, Operations Branch, Canadian Meteorological Center, Environment Canada

3:00 PM Afternoon coffee break (3:00-3:30)

3:30 PM **Panel 2: Education, Training, and Outreach**

Panel Moderator: Dr. Gregory S. Forbes, Severe Weather Expert, The Weather Channel

Panelists:
- Ms. Cyndie Abelman, Meteorologist-In-Charge, National Oceanic and Atmospheric Administration/National Weather Service, Oklahoma City, OK
- Captain Albert M. Beerley, US Airways Airbus, US Airways/ALPA Training Committee
- Mr. John O'Brien, Director, Engineering and Air Safety Department, Air Line Pilots Association
- Mr. Saburo Onodera, Manager, Flight Crew Training Department, Japan Airlines
- Professor Eric Doten, Director of Center for Aerospace Safety/Security Education, Embry-Riddle Aeronautical University

5:00 PM **Administrative Remarks**
Erin McNamara, Conference Coordinator for Logistics

Exhibits open
Posters displayed

OFCM Staff Meeting

5:30 PM Icebreaker (Sponsored by Tenix Corporation)

Tuesday 22 June 2004

7:00 AM **Continental Breakfast**

7:55 AM **Administrative Remarks**
Erin McNamara, Conference Coordinator for Logistics

Plenary Sessions

8:00 AM **Session 1: Encounters, Damage, and Socioeconomic Consequences**
Session Chairs: Mr. Edward Miller, Air Line Pilots Association (ALPA)
Mr. Leonard Salinas, United Airlines (UAL)

8:00 AM 1.1 *2003 Caribbean Volcanic Ash Encounters*
Captain Albert M. Beerley, US Airways ALPA Training Committee, Philadelphia, PA, USA

8:20 AM 1.2 *Engine Damage to a NASA DC-8-72 Airplane from a High-Altitude Encounter with a Diffuse Volcanic Ash Cloud*
Thomas J. Grindle, NASA, Edwards, CA, USA; and Frank W. Burcham, Jr.

8:40 AM 1.3 *Aircraft Encounters from the 18th August 2000 Eruption at Miyakejima, Japan*
Andrew Tupper, Bureau of Meteorology, Darwin, Australia; and Yasuhiro Kamada, Noriyuki Todo, Ed Miller

9:00 AM 1.4 *Impacts of Volcanic Ash on Airline Operations*
Leonard J. Salinas, United Airlines Flight Dispatch, Chicago, Illinois, USA; and Daniel Watt

9:20 AM 1.5 *Air Niugini and the Volcanic Ash Threat*
Captain David Innes, Flight Safety Office, Air Nuigini, Papua, New Guinea

9:35 AM 1.6 *Reducing Encounters of Aircraft with Volcanic Ash Clouds*
Marianne Guffanti, USGS, Reston, VA, USA; and Thomas J. Casadevall, Gari Mayberry

9:45 AM *Poster Preview by Session Chair*

Exhibits open (8:00-5:00)
Posters displayed

10:00 AM Morning coffee break (10:00-10:30)

Exhibits staffed (10:00-3:30)

10:30 AM **Session 2: The Volcanic Source - Eruption Monitoring and Reporting**
Session Chairs: Ms. Marianne Guffanti, U.S. Department of the Interior/U. S. Geological Survey (DOI/USGS)
Dr. Steven McNutt, Geophysical Institute, University of Alaska and the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI)

10:30 AM	2.1	*A Global Perspective on Volcanoes and Eruptions* Richard Wunderman, Smithsonian Institution, Washington, DC, USA; and Lee Siebert, James Luhr, Tom Simkin, Ed Venzke
10:45 AM	2.2	*Promise and Pitfalls in Eruption Forecasting* Chris Newhall, USGS, Seattle, WA, USA
11:00 AM	2.3	*Status of Volcano Monitoring Worldwide* John W. Ewert, USGS, VDAP, Vancouver, WA, USA; and Christopher G. Newhall
11:10 AM	2.4	*Volcanic Alert Systems: An Overview of their Form and Function* Bradley Scott, Institute of Geological and Nuclear Sciences, Wairakei, New Zealand
11:25 AM	2.5	*Recent Etna's Explosive Eruptions Threaten Seriously Aviation in Central Mediterranean Region* Mauro Coltelli, INGV, Catania, Italy
11:40 AM	2.6	*Recent Eruptive Activity in Ecuadorian Volcanoes and its Threat to Aviation Safety* Hugo Yepes A., Instituto Geofisico, Escuela Politecnica Nacional, Quito-ECUADOR
11:55 AM	2.7	*The Alaska Volcano Observatory – Fifteen Years of Working to Mitigate the Risk to Aviation from Volcanic Ash in the North Pacific* Thomas L. Murray, USGS, AVO, Anchorage, AK, USA
12:05 PM	2.8	*Ground-Based Real Time Monitoring of Eruption Clouds in the Western Pacific* Kisei Kinoshita, Kagoshima University, Kagoshima, Japan; and Satoshi Tsuchida, Chikara Kanagaki, Andrew C. Tupper, Ernesto G. Corpuz, Eduardo P. Laguerta
12:20 PM		*Poster Preview by Session Chair*

12:30 PM Lunch (12:30-1:30; catered)

1:30 PM **Session 3: Ash Cloud Observations, Modeling, and Forecasting**

Session Chairs: Dr. William Rose, Michigan Technological University (MTU)

Ms. Barbara Stunder, U.S. Department of Commerce/National Oceanic and Atmospheric Administration/Office of Oceanic and Atmospheric Research/Air Resources Laboratory (DOC/NOAA/OAR/ARL)

Mr. Andrew Tupper, Bureau of Meteorology, Volcanic Ash Advisory Center (VAAC), Australia

1:30 PM	3.1	*Modeling Volcanic Ash Transport and Dispersion: Expectations and Reality* Rene Servranckx, CMC, MSC, Quebec, Canada; and Peter Chen
1:46 PM	3.2	*Discrepancies Between Satellite Detection and Forecast Model Results of Ash Cloud Transport: Case Study of the 2001 Eruption of Mt. Cleveland Volcano, Alaska* David J. Schneider, USGS, AVO, Anchorage, AK, USA; Rene Servranckx, Jeff Osiensky

2:00 PM	3.3	*Assessing Volcanic Ash Hazard by Using the CALPUFF System* Sara Barsotti, Istituto Nazionale di Geofisica e Volcanologia, Pisa, Italy; and Augusto Neri, Joe Scire
2:12 PM	3.4	*Potential of the ATHAM Model for Use in Air Traffic Safety* Christiane Textor, Lab. Sciences du Climate et de L'Environnement, Paris, France; and Gerald Ernst
2:24 PM	3.5	*Volcanic Ash and Aerosol Detection Versus Dust Detection Using GOES and MODIS Imagery* Bernadette Connell, CIRA/CSU, Fort Collins, CO, USA
2:36 PM	3.6	*Ice in Volcanic Clouds: Where and When?* William I. Rose, Michigan Technological University, Houghton, MI, USA
2:48 PM	3.7	*Detection of Upper Level SO_2 via the GOES Sounder* Fred Prata, CSIRO Atmospheric Research, Aspendale, Australia; and Anthony J. Schreiner, Gary P. Ellrod, Timothy J. Schmit
3:00 PM	3.8	*The G-bIRD Volcanic Ash Cloud Detection System* Bill Young, Tenix, Sydney, Australia; and Matthew Simmons
3:12 PM		*Poster Preview by Session Chair*

3:15 PM Afternoon coffee break (3:15-3:45)

3:45 PM **Session 4: VAAC Operations and Capabilities**

Session Chairs: Ms. Grace Swanson, U.S. Department of Commerce/National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service/Volcanic Ash Advisory Center, Washington, D.C., USA (DOC/NOAA/NESDIS/VAAC)

Mr. Rene Servranckx, Environment Canada, Canadian Meteorological Center, Volcanic Ash Advisory Center, Montreal (EC/CMC/VAAC)

3:45 PM	4.1	*The International Airways Volcano Watch (IAVW)* Raul Romero, ICAO, Montreal, Canada
3:55 PM	4.2	*WMO Activities Related to Volcanic Ash* Saad Benarafa, World Meteorological Organization, Geneva, Switzerland
4:00 PM	4.3	*NOAA's NWS Volcanic Ash Program: Current Status and Plans for the Future* Christopher S. Strager, NWS Alaska Region Headquarters, Anchorage, AK, USA; and Jeffrey M. Osiensky, Gary L. Hufford
4:10 PM	4.4	*Volcanic Ash Impact on International Airport of Mexico City (AICM), Due to Emissions of Popocatepetl Volcano* Humberto Rodriguez, DMTA of SENEAM, Mexico, D.F. Mexico
4:20 PM	4.5	*The Darwin VAAC Volcanic Ash Workstation* Rodney Potts, Bureau of Meteorology Research Centre, Melbourne, Australia; and Mey Manickam, Andrew Tupper, Jason Davey

4:30 PM	4.6	*Shared Situational Awareness and Collaboration Through the Use of the Volcanic Ash Collaboration Tool (VACT)* Jeffrey M. Osiensky, NWS Alaska Aviation Weather Unit, Anchorage, AK, USA; and Greg Pratt, David J. Schneider, Lynn Sherretz
4:40 PM	4.7	*Perspectives on Operational Volcanic Ash Warnings* Hordur Thordarson, Meteorological Service of New Zealand, Wellington, New Zealand
4:50 PM	4.8	*Volcanic Cloud Conceptual Models for Volcanic Ash Advisory Centre Operations* Andrew Tupper, Bureau of Meteorology, Darwin, Australia; and Gerald Ernst, Christiane Textor, Kisei Kinoshita, J. Scott Oswalt, Daniel Rosenfeld
5:00 PM	4.9	*Volcanic Ash Advisory Support for the U.S. Department of Defense* Charles Holliday, U.S. AFWA, Offutt AFB, Nebraska, USA
5:05 PM	4.10	*Web Access to the Digital Archive of VAA Messages and VAFTAD Model Output* Paula Dunbar, NOAA/NESDIS/NGDC, Boulder, CO, USA; and Grace Swanson
5:10 PM		*Poster Preview by Session Chair*

5:30 PM Sessions end for the day

OFCM Staff Meeting

7:00 PM Tour Washington VAAC

Wednesday 23 June 2004

7:00 AM **Continental Breakfast**

7:55 AM **Administrative Remarks**
Erin McNamara, Conference Coordinator for Logistics

8:00 AM **Session 5: Aviation Industry Perspectives**
Session Chairs: Mr. Steven R. Albersheim, U.S. Department of Transportation/Federal Aviation Administration (DOT/FAA)

Mr. John Murray, National Aeronautics and Space Administration/Langley Research Center (NASA/LaRC)

8:00 AM 5.1 *Technology Transfer: Moving R&D to Operations*
Steven R. Albersheim, Federal Aviation Administration, Washington, D.C., USA

8:15 AM 5.2 *The Effect of Volcanic Activity on Airports*
Marianne Guffanti, USGS, Reston, VA, USA; and Gari Mayberry, Rick Wunderman, Thomas J. Casadevall

8:30 AM 5.3 *An Air Traffic Controller Perspective on Volcanic Ash: How to Deal with It!*
Richard Hernandez, FAA San Juan Automated International Flight Service Station, San Juan, Puerto Rico, USA

8:50 AM 5.4 *The New Zealand Volcanic Ash Advisory System*
Peter Lechner, Civil Aviation Authority of New Zealand, Wellington, NZ

9:05 AM 5.5 *Prevention of Volcanic Ash Encounters in the Proximity Area Between Active Volcanoes and Heavy Air Traffic Routes*
Saburo Onodera, Flight Crew Training Department, Japan Airlines, Tokyo, Japan

9:20 AM 5.6 *A Program for Research and Systems Integration to Help Mitigate the Volcanic Ash Hazard to Aviation*
Tenny A. Lindholm, National Center for Atmospheric Research (NCAR), Boulder, CO, USA

9:35 AM 5.7 *Explosive Volcanic Eruptions Across the Heavily Traveled North Pacific Air Routes: Frequency, Duration, and Impact on Aviation*
Thomas P. Miller, USGS, AVO, Anchorage, AK, USA

9:55 AM *Poster Preview by Session Chair*

Exhibits open (8:00-5:00)
Posters displayed

10:00 AM Morning coffee break (10:00-10:30)

Exhibits staffed (10:00-3:30)

10:30 AM **Breakout Sessions** (10:30-12:30)

Breakout Session 1: Improving Volcanic Ash Cloud Detection

Session Moderators: Dr. David J. Schneider, U.S. Geological Survey, Alaska Volcano Observatory (USGS/AVO)

Dr. Steven Ackerman, Cooperative Institute for Meteorological and Satellite Services, University of Wisconsin - Madison

Breakout Session 2: Improving Modeling Capabilities

Session Moderators: Mr. Rene Servranckx, Environment Canada, Canadian Meteorological Center, Volcanic Ash Advisory Center, Montreal (EC/CMC/VAAC)

Ms. Barbara Stunder, U.S. Department of Commerce/National Oceanic and Atmospheric Administration/Office of Oceanic and Atmospheric Research/Air Resources Laboratory (DOC/NOAA/OAR/ARL)

Breakout Session 3: Understanding the Socioeconomic Consequences

Session Moderators: Mr. Floyd Hauth, Science and Technology Corporation

Mr. Peter Lechner, Civil Aviation Authority of New Zealand

12:30 PM Lunch (12:30-1:30; catered)

1:30 PM Poster Session (1:30-3:30)

P1.1 *Three Aircraft Encounters over Micronesia*
Andrew Tupper, Bureau of Meteorology, Darwin, Australia; and Jason Davey, Paul Stewart, Barbara Stunder, Rene Servranckx

P1.2 *Sulfurous Odors: A Signal of Entry into an Ash Plume – But Perhaps Less Reliable for Escape*
Richard Wunderman, Smithsonian Institution, Washington, DC, USA

P2.1 *Evaluation of a Prototype Infrasound System for Enhancing Volcanic Ash Warnings*
Henry Bass, University of Mississippi; and Milton Garces, David McCormack, Peter Chen, Michel Jean

P2.2 *Recurrence of Explosive Eruptions at Etna Volcano that Produce Hazard for Aviation*
Paola Del Carlo, INGV, Catania, Italy

P2.3 *A Proposed Alert-level Notification Scheme for Aviation and Ground-based Hazards at U.S. Volcanoes*
C.A. Gardner, USGS, Cascades Volcano Observatory, Vancouver, WA, USA; and M.C. Guffanti, C.C. Heliker, D.P. Hill, J.B. Lowenstern, T.L. Murray

P2.4 *Monitoring and Reporting of Kamchatkan Volcanic Eruptions*
Evgenii Gordeev, Institute of Volcanology and Seismology, Petropavlovsk-Kamchatsky, Russia; and Sergei Senjukov, Olga Girina

P2.5 *Volcano-Related Information Available on the Internet: From Current Activity to the Past 10,000 Years*
Gari Mayberry, USGS, Washington, DC, USA; and Edward Venzke, James Luhr, Richard Wunderman, Lee Siebert, Marianne Guffanti

P2.6 *Volcanic Tremor and its Use in Estimating Eruption Parameters*
Stephen R. McNutt, AVO, Fairbanks, AK, USA

P2.7 *Surprise/Sudden Onset Eruptions: The Case of Reventador Volcano – Ecuador, 03-November, 2002*
Patricia Mothes, Instituto Geofisico, Quito-Ecuador; and Minard L. Hall, Patricia Ramon, Hugo Yepes

P2.8 *Ashfall Scenarios and Aviation Impacts of Future Eruptions of Cotopaxi Volcano – Ecuador*
Patricia Mothes, Instituto Geofisico, Quito-Ecuador; and Minard L. Hall, Pablo Samaniego, Hugo Yepes

P2.9 *Airborne Ash Hazard Mitigation in the North Pacific: A Multi-Agency, International Collaboration*
Christina Neal, USGS, Anchorage, AG, USA; and AVO Staff, Olga Girina, Gail Ferguson, Jeffrey Osiensky

P2.10 *Ground-Based Detection of Volcanic Ash and Suphur Dioxide*
Fred Prata, CSIRO Atmospheric Research, Aspendale, Australia; and Cirilo Bernardo

P2.11 *The New Zealand Volcano Alert Level System – Its Performance in Recent Eruptive Activity*
Bradley Scott, Institute of Geological and Nuclear Sciences, Wairakei, New Zealand

P2.12 *Monitoring of Active Volcanoes of the Kurile Islands: Present and Future*
A.V. Rybin, Institute of Marine Geology and Geophysics, Yuzhno-Sakhalinsk, Russia; and Y.V. Karagusov, P.E. Izbekov, N.S. Terentyev, V.B. Guryanov

P2.13 *Volcanic Eruptions as Thunderstorm Ice Factories*
Earle R. Williams, Parsons Laboratory, MIT, Cambridge, MA, USA; and Stephen R. McNutt

P3.1 *UW-Madison Advanced Satellite Aviation-weather Products MODIS Satellite Volcanic Ash Detection Methodologies*
Steven Ackerman, Wayne F. Feltz, CIMSS/SSEC University of Wisconsin, Madison, WI, USA; and Tim Schmit, John Murray, David Johnson

P3.2 *Removal Processes of Volcanic Ash Particles from the Atmosphere*
Gregg Bluth, Michigan Technological University, Houghton, MI, USA; and Bill Rose, Matt Watson

P3.3 *Sounding of Volcanic Clouds with Balloon-Borne Instruments: Improving Algorithms for Ash and SO_2 in Remote Sensing Imagery*
John Chadwick, Idaho State University, Pocatello, ID, USA; and Zach Lifton, Ken Dean, Jim Chadwick

P3.4 *FALL3D: A Numerical Model for Volcanic Ash Dispersion in the Atmosphere*
A. Costa, Istituto Nazionale de Geofisica e Vulcanologia, Napoli, Italy; and G. Macedonio

P3.5 *Use of Dispersion Models to Track Eruption Clouds*
Ken G. Dean, Geophysical Institute, University of Alaska, Fairbanks, AK, USA; and Rorik A. Peterson, Ken Papp, Jonathan Dehn

P3.6 *Laboratory Measurements of Heterogeneous Ice Nucleation by Volcanic Ash: Importance for Detecting and Modeling Volcanic Clouds*
Adam J. Durant, Michigan Technological University, Houghton, Michigan, USA; and Raymond A. Shaw, Youshi Mi, and William I. Rose

P3.7 *Volcanic Ash Detection and Cloud Top Height Estimation from the GOES-12 Imager: Coping Without a 12μm Infrared Band*
Gary P. Ellrod, NOAA/NESDIS, Camp Springs, MD, USA; and Anthony J. Schreiner, Alonzo M. Brown

P3.8 *Resuspension of Relic Volcanic Ash and Dust from Katmai: Still an Aviation Hazard*
David Hadley, NWS Alaska Aviation Weather Unit, Anchorage, AK, USA; and Gary L. Hufford, James J. Simpson

P3.9 *Observing Popocatepetl's Volcanic Ash Clouds Using MODIS Infrared Data*
M. Alexandra Matiella, Michigan Technological University, Houghton, MI, USA; and Hugo Delgado-Granados, William I. Rose, I. Matthew Watson

P3.10 *Comparison of Ash Detection Techniques Using TOMS, MODIS, AVHRR, and GMS: A Case Study of the August 18 and 28, 2000 Eruption Clouds of Miyakejima, Japan*
Emily McCarthy, Michigan Technological University, Houghton, MI, USA; and Gregg Bluth, Matthew Watson, Andrew Tupper, Yasuhiro Kamada

P3.11 *Predicting Regions Susceptible to High Concentrations of Airborne Volcanic Ash in the North Pacific Region*
Kenneth Papp, Geophysical Institute, University of Alaska, Fairbanks, AK, USA; and Ken Dean, Jonathan Dehn

P3.12 *Reanalysis of Eruption Clouds from the North Pacific Region and Their Impact on Aircraft and Population Centers*
Rorik A. Peterson, Geophysical Institute, University of Alaska, Fairbanks, AK, USA; and Ken G. Dean, Ken Papp, Joanne Groves, Jonathan Dehn

P3.13 *Quantitative Sulphur Dioxide Retrievals from AIRS, MODIS and HIRS*
Fred Prata, CSIRO Atmospheric Research, Aspendale, Australia; and Cirilo Bernardo

P3.14 Sakura – *An Airborne Infrared Imaging Camera for the Detection Of Volcanic Ash and Sulphur Dioxide Gas*
Fred Prata, CSIRO Atmospheric Research, Aspendale, Australia

P3.15 *Testing Real-Time Remote Sensing for Monitoring Volcanic Activity in Central America*
Armando Saballos, INETER, Managua, Nicaragua; and Peter Webley, Martin Wooster

P3.16 *Advances in Ultraviolet Detection of Volcanic Eruption Clouds*
Stephen J. Schaefer, Joint Center for Earth Systems Technology UMBC, Baltimore, MD, USA; and Arlin J. Krueger, Simon A. Carn

P3.17 *Real-Time Monitoring of the Volcanic Ash Fallout Will Improve Airport Safety*
Simona Scollo, INGV, Catania, Italy; and Mauro Coltelli, Marco Folegani, Stefano Natali, Franco Prodi

P3.18 *Operational MODIS Volcanic Ash Products for Aviation Safety and Natural Hazards Mitigation*
George Stephens, OSDPD, NOAA/NESDIS, Camp Springs, MD, USA; and Gary P. Ellrod, Jun-Sun Im

P3.19 *Volcanic Ash Dispersion Modeling Research at NOAA Air Resources Laboratory*
Barbara Stunder, NOAA/ARL, Silver Spring, MD, USA

P3.20 *Operational Volcanic Ash Plume Prediction Model PUFF at the Japan Airlines*
H.L. Tanaka, Institute of Geoscience, University of Tsukuba and FRSGC, Japan; and Saburo Onodera, Daisuke Nohara

P3.21 *Correcting Ash Retrievals for the Presence of Atmospheric Water Vapor Using Foreward Modeling*
I.M. Watson, Michigan Technological University, Houghton, MI, USA; and W.I. Rose, G.J.S. Bluth

P3.22 *Eruption Cloud Echo Measured with C-band Weather Radar*
Yoshihiro Sawada, Hokkaido University, Sapporo, Japan

P4.1 *Operations of Washington Volcanic Ash Advisory Center (VAAC)*
Gregory M. Gallina, NOAA SSD, Camp Springs, MD, USA; and Davida Streett

P4.2 *Improvement of Ash Cloud Information by Tokyo VAAC*
Takeshi Koizumi, Japan Meteorological Agency, Tokyo, Japan; and Yoshihiko Hasegawa, Yasuhiro Kamada, Masamichi Nakamura

P4.3 *The Montreal VAAC Toolbox: When Every Second Counts*
Mark McCrady, CMC, MSC, Quebec, Canada; and Serge Trudel, Jean-Philippe Gauthier, Rene Servranckx

P4.4 *Eruption of Anatahan Volcano: Operations and Observations*
Michael G. Middlebrooke, NOAA/NWS, Barrigada, Guam

P4.5 *The Volcanic Ash Collaboration Tool (VACT)*
Jeffrey M. Osiensky, NWS Alaska Aviation Weather Unit, Anchorage, AK, USA; and Greg Pratt, David J. Schneider, Lynn Sherretz

P4.6 *Volcanic Ash Monitoring and Forecasting at the London VAAC*
Sarah Watkin, Met Office, Exeter, Devon, U.K.; and Derrick Ryall, Helen Watkin, Helen Champion, Stewart Wortley, Nigel Gait

P4.7 *Web Access to the Digital Archive of VAA Messages and VAFTAD Model Output*
Paula Dunbar, NOAA/NESDIS/NGDC, Boulder, CO, USA; and Grace Swanson

P5.1 *First 8 Hours of Volcanic Eruptions: A Northwest Airlines Example & Recommendation of Revised Flow of Ash Information for Aviation*
Tom Fahey, Northwest Airlines, Minneapolis/St. Paul, MN, USA

3:00 PM Afternoon coffee break (3:00-3:30)

3:30 PM **Breakout Sessions** (3:30-5:30)

Breakout Session 4: Improving Volcanic Eruption Reporting

Session Moderators: Ms. Christina Neal, U.S. Department of the Interior/U.S. Geological Survey/Alaska Volcano Observatory (DOI/USGS/AVO)

Ms. Cynthia Gardner, U.S. Department of the Interior/U.S. Geological Survey/Cascades Volcano Observatory (DOI/USGS/CVO)

Breakout Session 5: Technology Transfer from Research into Operations

Session Moderators: Mr. Mark Andrews, Department of Commerce/National Oceanic and Atmospheric Administration/National Weather Service/Aviation Weather Services (DOC/NOAA/NWS/AWS)

Ms. Debi Bacon, U.S. Department of Transportation/Federal Aviation Administration (DOT/FAA)

Breakout Session 6: Improving VAAC Operational Capabilities

Session Moderators: Mr. Raul Romero, International Civil Aviation Organization, Montreal, Canada (ICAO)

Ms. Grace Swanson, U.S. Department of Commerce/National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service/Volcanic Ash Advisory Center, Washington, D.C., USA (DOC/NOAA/NESDIS/VAAC)

Breakout Session 7: Meeting Aviation Needs

Session Moderators: Mr. William Phaneuf, Air Line Pilots Association (ALPA)

Mr. Richard Heuwinkel, Department of Transportation/Federal Aviation Administration

5:30 PM Sessions end for the day

OFCM Staff Meeting

6:30 PM Reception at the Smithsonian National Museum of Natural History (6:30 PM – 8:00 PM)

Thursday 24 June 2004

7:00 AM **Continental Breakfast**

8:00 AM **Regional Breakout Sessions** (8:00-10:00)

Breakout Session 8: North Asia Pacific (e.g., Alaska, Russia, Japan)

Session Moderators: Mr. Christopher Strager, U.S. Department of Commerce/National Oceanic and Atmospheric Administration (DOC/NOAA)

Ms. Terry Keith, U.S. Department of the Interior/U.S. Geological Survey/Alaska Volcano Observatory (DOI/USGS/AVO)

Breakout Session 9: The Americas and the Caribbean (excluding Alaska)

Session Moderators: Dr. Patricia Mothes, Instituto Geofísico de la Escuela Politécnica Nacional, Ecuador

J. Armando Saballos, Instituto Nicaraguense de Estudios Territoriales, Nicaragua

Richard Hernandez, Federal Aviation Administration

Breakout Session 10: Europe, Africa, and the Middle East

Session Moderators: Dr. Gerald Ernst, Department of Geology and Soil Science, University of Ghent, Belgium

Mr. Jean-Philippe Desbios, Volcanic Ash Advisory Center (VAAC), Toulouse, France

Breakout Session 11: South Asia Pacific (e.g., Indonesia, the Philippines, Australia, New Zealand)

Session Moderators: Mr. Rodney Potts, Australian Bureau of Meteorology Research Centre

Capt. David Innes, Air Niugini

10:00 AM Morning coffee break (10:00-10:30)

Closing Session

10:30 AM **ICAO's Commitment to Mitigating Volcanic Ash Hazard**
Mr. William Voss, Director, Air Navigation Bureau, International Civil Aviation Organization

10:45 AM **Conference Highlights**
Ms. Marianne Guffanti, DOI/USGS
Mr. Andrew Tupper, Bureau of Meteorology, Volcanic Ash Advisory Center (VAAC), Australia

11:30 AM **Building on Our Successes in Aviation Safety for the Next Decade**
Dr. Elbert W. (Joe) Friday, University of Oklahoma

Dr. Paul D. Try, Senior Vice President, Science and Technology Corporation

12:30 PM	**Closing Remarks/Next Steps** Mr. Samuel P. Williamson, Federal Coordinator for Meteorological Services and Supporting Research
1:00 PM	Adjourn

APPENDIX B

ATTENDEES

The 2nd International Conference on Volcanic Ash and Aviation Safety
Alexandria, Virginia
June 21-24, 2004

Ms. Cyndie Abelman
Meteorologist in Charge
National Weather Service
FAA Academy AMA-514
P.O. Box 25082
Oklahoma City, OK 73125-0082
USA
Phone: 405-954-6870
E-mail: cyndie.abelman@noaa.gov

Dr. Steven Ackerman
University of Wisconsin-Madison
1225 West Dayton Street
Madison, WI 53706
USA
Phone: 608-263-3647
E-mail: stevea@ssec.wisc.edu

Mr. Steven Albersheim
FAA
800 Independence Ave, SW
Washington, DC 20591
USA
Phone: 202-385-7704
Fax: 202-385-7701
E-mail: Steven.Albersheim@faa.gov

Mr. Mark Andrews
Aviation Weather Program Manager
NOAA
SSMC2, Rm 13308
1325 East-West Hwy
Silver Spring, MD 20910
USA
Phone: 301-713-1726 x109
Fax: 301-713-1520
E-mail: mark.andrews@noaa.gov

Ms. Debi Bacon
Air Traffic Control Specialist
FAA
800 Independence Ave., S.W.
Washington, DC 20591
USA
Phone: 202-385-7705
Fax: 202-385-7701
E-mail: debi.bacon@faa.gov

Mr. Antonio Bandaro
Catania Airport Director
Italian Civil Aviation Authority
Catania via Horosoli 13
Italy
E-mail: a.bardaro@enze.rupa.it

Mr. Kenneth Barnett
OFCM
Suite 1500
8455 Colesville Road
Silver Spring, MD 20910
USA
Phone: 301-427-2002
Fax: 301-427-2007
E-mail: Kenneth.Barnett@noaa.gov

Ms. Sara Barsotti
INGV
Via Della Faggiiola 32
Pisa, 56126
ITALY
Phone: 050-8311945
E-mail: barsotti@pi.ingv.it

Mr. Nigel Basheer
Senior Computer Systems Engineer
Tenix Defence Pty Ltd
Technology Park
Mawson Lakes, Second Ave
ADELAIDE 5095,
South Australia
Phone: +61 8 8300 4721
Fax: +61 8 8300 4510
E-mail: nigel.basheer@tenix.com

Mr. Chris Baum
Manager, Engineering and Accident Investigator
Air Line Pilots Assn, Intl.
535 Herndon Parkway
Herndon, VA 20170
USA
Phone: 703-689-4312
E-mail: chris.baum@alpa.org

Capt. Al Beerley
US Airways Airbus
1204 Old Forge Road
Oxford, PA 196363
USA
Phone: 610-932-8353
E-mail: albeerley@hotmail.com

Dr. Karen Bemis
IMCS, Rutgers University
71 Dudley Road
New Brunswick, NJ 08901-8521
USA
Phone: 732-445-1225
Fax: 732-445-3374
E-mail: bemis@rci.rutgers.edu

Mr. Saad Benarafa
World Meteorological Organization
7bis avenue de la Paix, case postale 2300
Geneva,
Switzerland
Phone: +41(0) 22 730 84 08
Fax: +41 (0) 22 730 81 28
E-mail: sbenarafa@wmo.int

Mr. Kevin Berberich
Summer Intern
NOAA-NESDIS
5200 Auth Road
Room 401
Camp Springs, MD 20746
USA
Phone: 301-763-8444
E-mail: w-vaac@noaa.gov

Mr. Charles Bergman
Manager, Air Safety and Operations
Air Line Pilots Association, Int'l
535 Herndon Parkway
Herndon, VA 20170
USA
Phone: 703-689-4188
Fax: 703-464-2104
E-mail: charlie.bergman@alpa.org

Dr. Cirilo Bernardo
CSIRO Atmospheric Research
PMB 1
Aspendale, Vic., 3195
Australia
Phone: (613) 9239 4669
Fax: (613) 9239 4400
E-mail: cirilo.bernardo@csiro.au

Mr. Ronald Birk
Director
NASA Earth Science Applications Division
Code YO
300 E Street SW
Washington, DC 20546
USA
Phone: 202-358-1701
Fax: 202-358-3098
E-mail: ronald.j.birk@hq.nasa.gov

Dr. Gregg Bluth
Michigan Technological University
1400 Townsend Drive
Houghton, MI 49931
USA
Phone: 906-487-3554
E-mail: gbluth@mtu.edu

Mr. Gary Bobik
FAA
800 Independence Ave. SW
Washington, DC 20591
USA
Phone: 202-267-9754
Fax: 202-493-5016
E-mail: gary.bobik@faa.gov

Ms. Betty Bollert
Dispatch Instructor
Alaska Airlines
P O Box 68900
Seattle, WA 98168
USA
Phone: 206-431-7655
E-mail: betty.bollert@alaskaair.com

Dr. Costanza Bonadonna
University of Hawaii
1680 East-West Road
POST Building 617a
Honolulu, HI 96822
USA
Phone: 808 956 5033
Fax: 808 956 5512
E-mail: costanza@hawaii.edu

Mr. Stephen Boulter
Screenwriter
Larimer Productions
5349 Promontory Circle
Ft. Collins, CO 80528
USA
Phone: 303-668-0515
E-mail: SKBoulter@msn.com

Mr. Alonzo Brown
Meteorologist
NOAA/NESDIS/SSD/SAB
5200 Auth Rd
Rm 401
Camp Springs, MD 20746
USA
Phone: 301-763-8444
E-mail: Alonzo.Brown@noaa.gov

Ms. Mary M. Cairns
Senior Staff Meteorologist
OFCM
8455 Colesville Road
Suite 1500
Silver Spring, MD 20910
USA
Phone: 301-427-2002
Fax: 301-427-2007
E-mail: Mary.Cairns@noaa.gov

Mr. Mike Campbell
Deputy Director/Chief International Operations
NWS/NCEP
Aviation Weather Center
Kansas City, MO 64153-2371
USA
Phone: 816-584-7203
Fax: 816-880-0650
E-mail: mike.campbell@noaa.gov

Dr. Bruce Carmichael
Manager of Aviation Weather Research
National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80301
USA
Phone: 303-497-8406
Fax: 303-497-8401
E-mail: brucec@ucar.edu

Dr. Simon Carn
University of Maryland Baltimore County
1000 Hilltop Circle
Baltimore, MD 21250
USA
Phone: 410-455-1454
Fax: 410-455-5868
E-mail: scarn@umbc.edu

Mr. Donald "Doc" Carver
FAA/OFCM
8455 Colesville Road
Silver Spring, MD 20910
USA
Phone: 301-427-2002
Fax: 301-427-2007
E-mail: donald.carver@noaa.gov

Mr. John Chadwick
Idaho State University
Pocatello, ID 83211
USA
Phone: 208-282-2949
E-mail: chadjohn@isu.edu

Mr. Peter Chen
Director, Operations
Canadian Meteorological Center
Environment Canada
2121 Trans-Canada Highway
Dorval, Quebec
Canada
Phone: 514-421-4622
Fax: 514-421-4679
E-mail: peter.chen@ec.gc.ca

The 2nd International Conference on Volcanic Ash and Aviation Safety
Alexandria, Virginia
June 21-24, 2004

Mr. Daniel Chrétien
Aviation Meteorologist
NAV Canada
77 Metcalfe #518
Ottawa, ON K1P 5L6
Canada
Phone: 613-563-5607
Fax: 613-563-5602
E-mail: chretid@navcanada.ca

Ms. Pam A. Clark
Acting Division Chief
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-CI-EE (P. Clark)
2800 Powder Mill Road
Adelphi, MD 20783
USA
Phone: 301-394-3447
Fax: 301-394-4797
E-mail: pclark@arl.army.mil

Col. Richard Clayton
Deputy Director of Weather
USAF
HQ USAF/XOO-W
1490 Air Force Pentagon
Washington, DC 20330-1490
Phone: 703-614-7258
Fax: 703-614-0055
E-mail: richard.clayton@pentagon.af.mil

Dr. Mauro Coltelli
Scientist
INGV
Piazza Roma 2
Catania, 95123
Italy
Phone: +39 095 7165850
E-mail: coltelli@ct.ingv.it

Dr. Bernadette Connell
Research Scientist
CIRA/CSU
1375 Campus Delivery
Fort Collins, CO 80523-1375
USA
Phone: 970-491-8689
Fax: 970-491-8241
E-mail: connell@cira.colostate.edu

Mr. Luigi Cornaglia
Investigation Manager
ALITALIA
Via P.P. Racchetti
Airport Fiumicino
Rome 50,
Italy
Phone: 0039-06-65638380
E-mail: cornaglia.luigi@alitalia.it

Dr. Antonio Costa
OV-INGV
Via Diocleziano, 328
Napoli, I-80124
Italy
Phone: 0039 0816108335
Fax: 0039 0816108351
E-mail: costa@ov.ingv.it

Captain John M. Cox
Executive Air Safety Chairman
Air Line Pilots Association
4463 - 39th Street South
St. Petersburg, FL 33711
USA
Phone: 727-515-1061 (cell)
Fax: 727-866-2268
E-mail: john.cox@alpa.org

Dr. Paola Del Carlo
INGV-Catania
Piazza Roma 2
Catania, 95123
ITALY
Phone: 0039 95 7165800
E-mail: delcarlo@ct.ingv.it

Mr. Peter Dempster
Intl Dispatcher
US Airways
173 industry Dr
Pittsburgh, PA 15275
USA
Phone: 412-747-5630
Fax: 412-747-1498
E-mail: peter_d_dempster@usairways.com

Mr. Larry Denton
The Weather Channel
300 Interstate N. Parkway
Atlanta, GA 30328
USA
E-mail: larry.denton@weather.com

Mr. Jean-Philippe Desbios
VAAC Representative
Meteo France
42 Avenue
G Coriolis
Toulouse, 31057 cedex
FRANCE
Phone: 33 561-07-83-30
Fax: 33-561 07 82 54
E-mail: jean-Philippe.desbios@meteo.fr

Mr. J. Gary DiNunno
Editor-in-Chief
Air Line Pilots Association
PO Box 1169
Herndon, VA 20172
Phone: 703-481-4460
Fax: 703-464-2114
E-mail: gary.dinunno@alpa.org

Prof. Eric Doten
Director
Embry-Riddle
600 Clyde Morris Blvd
Daytona Beach, FL 32114
USA
Phone: 386-323-5064
Fax: 386-226-6895
E-mail: ericsd@aol.com

Dr. Eliecer Duarte
Professor
Observatorio Vulcanologico y Sismologico de
Costa Rica
Campus, Universidad Nacional
Heredia,
Costa Rica
Phone: 506-261-0781
Fax: 506-261 0303
E-mail: eduarte@una.ac.cr

Mr. Paula Dunbar
Physical Scientist
National Geophysical Data Center
NOAA E/GC1
325 Broadway
Boulder, CO 80305
USA
Phone: 303-497-6084
Fax: 303-497-6513
E-mail: Paula.Dunbar@noaa.gov

Col. (Sel) Harold A. Elkins
Chief, Weather Plans Division
USAF
1490 Air Force Pentagon
Washington, DC 20330
USA
Phone: 703-696-4936
E-mail: afxowx@pentagon.af.mil

Mr. Gary Ellrod
Meteorologist
NOAA/NESDIS
Room 712, E/RA2, WWBg
5200 Auth Road
Camp Springs, MD 20746
USA
Phone: 301-763-8204 x 140
Fax: 301-763-8580
E-mail: Gary.Ellrod@noaa.gov

Ms. Dawn Erlich
STC
1010 Wayne Avenue, Suite 450
Silver Spring, MD 20910
USA
Phone: 301-565-8345
Fax: 301-565-8279
E-mail: stc.ss@stcnet.com

Dr. Gerald Ernst
University of Ghent
Krijgslaan 281-S8
Gent, B-9000
Belgium
Phone: +32.9264.4633
Fax: +32.9264.4943
E-mail: plumeman2000@yahoo.co.uk

Lt. Col. Frank Estis
OFCM
8455 Colesville Rd., Suite 1500
Silver Spring, MD 20910
USA
Phone: 301-427-2002
Fax: 301-427-2007
E-mail: frank.estis@noaa.gov

Mr. William "Bill" Euille
Mayor, Alexandria, Virginia
City of Alexandria
301 King Street
Alexandria, VA 22314
USA

Mr. John Ewert
U.S. Geological Survey
1300 SE Cardinal Ct., #100
Vancouver, WA 98683
USA
Phone: 360-993-8912
Fax: 360-993-8980
E-mail: jwewert@usgs.gov

Mr. Wayne Feltz
University of Wisconsin
1225 W. Dayton
Rm 235
Madison, WI 53706
USA
Phone: 608-265-6283
E-mail: waynef@ssec.wisc.edu

Ms. Gail Ferguson
Operations Manager
FAA
700 N Boniface Parkway
Anchorage, AK 99506
USA
Phone: 907-269-1250
Fax: 907-269-1343
E-mail: gail.ferguson@faa.gov

Mr. Gustavo Alberto Flores
Manager
VAAC Buenos Aires
25 de mayo 658
Capital Federal
Buenos Aires, 1002ABN
Argentina
Phone: 54-11-5-167-6707
Fax: 54-11-5-167-6709
E-mail: gflores@meteofa.mil.ar

Dr. Gregory S. Forbes
Severe Weather Expert
The Weather Channel
300 Interstate N. Parkway
Atlanta, GA 30328
USA
E-mail: greg.forbes@weather.com

Mr. Thomas Fraim
OFCM
8455 Colesville Road
Suite1500
Silver Spring, MD 20910
USA
Phone: 301-427-2002
Fax: 301-427-2007
E-mail: thomas.fraim@noaa.gov

Dr. Elbert W. Friday
Professor
University of Oklahoma
100 East Boyd St. SEC Suite 1310
Norman, OK 73019
USA
Phone: 571-215-8022
Fax: 202-334-3825
E-mail: joefriday@ou.edu

Mr. Nigel Gait
Met Office
B1-57
Fitzroy Road
Eastleigh, EX13PB
United Kingdom
Phone: -887616
E-mail: nigel.gait@metoffice.com

The 2nd International Conference on Volcanic Ash and Aviation Safety
Alexandria, Virginia
June 21-24, 2004

Mr. Gregory M. Gallina
Meteorologist
NOAA/NESDIS/SAB
5200 Auth Road
Rm. 401
Camp Springs, MD 20746-4304
USA
Phone: 301-763-8444
Fax: 301-763-8333
E-mail: Greg.Gallina@noaa.gov

Ms. Cynthia Gardner
U.S. Geological Survey
1300 SE Cardinal Ct.
Bldg 10
Vancouver, WA 98683
USA
Phone: 360-993-8914
Fax: 360-993-8980
E-mail: cgardner@usgs.gov

Mr. Alexander Giarrocco
Flight Dispatch Officer
Spirit Airlines Inc.
2800 Executive Way
Miramar, FL 33025
USA
Phone: 954 447 8051
Fax: 954 447 7852
E-mail: sallyc@spiritair.com

Mr. Ellis Godfrey
NOAA Coastal Services Center
2234 S. Hobson Avenue
Charleston, SC 29405
USA
Phone: 843-740-1257
E-mail: ellis.godfrey@noaa.gov

Capt. Richard Gonzalez
Air Force Weather Agency
Offutt AFB, NE 68113-4039
USA
Phone: 402-294-9759
Fax:
E-mail: richard.gonzalez@afwa.af.mil

Dr. Evgenii Gordeev
Director
Institute of Volcanology and Seismology
Piip Blvd. 9
Petropavlovsk-Kamchatsky, 683006
Russian Federation
Phone: 415-22-59530
E-mail: gord@emsd.iks.ru

Mr. Steve Graham
NASA/GSFC
Bldg. 33, Rm E112
Greenbelt, MD 20771
USA
Phone: 301-614-5561
Fax: 301-614-6530
E-mail: graham@pop900.gsfc.nasa.gov

Dr. David Green
NOAA/NWS
1325 East-West Highway
Silver Spring, MD 20910
USA
Phone: 301-713-3557
E-mail: david.green@noaa.gov

Mr. Thomas Grindle
Aerospace Engineer
NASA Dryden Flight Research Center
P.O. Box 273
MS: D-2708
Edwards, CA 93523-0273
USA
Phone: 661-276-2710
Fax: 661-276-3744
E-mail: tom.grindle@dfrc.nasa.gov

Dr. Charles G. Groat
Director
U.S. Geological Survey
2201 Sunrise Valley Drive
Reston, VA 20192
USA
E-mail: groat@usgs.gov

Ms. Marianne Guffanti
Geologist
U.S. Geological Survey
926A National Center
Reston, VA 20192
USA
Phone: 703-648-6708
Fax: 703-648-5483
E-mail: guffanti@usgs.gov

Dr. Reinaldo Gutierrez
Direccion Meteorologica de Chile
Casilla N 63 internacional
Santiago,
Chile
Phone: 56-02-6763461
E-mail: rgutierrez@meteochile.cl

Mr. Shahid Habib
NASA/GSFC
Code 900
Greenbelt, MD 20771
USA
Phone: 301-614-5392
Fax: 301-614-5620
E-mail: shahid.habib-1@nasa.gov

Mr. Keith Hagy
Assoc. Director
ALPA
535 Herndon Parkway
Herndon, VA 20170
USA
Phone: 703-689-4206
E-mail: keith.hagy@alpa.org

Mr. William Harrison
USA Aeronautical Services Agency
9325 Gunston Road, Bldg 1466
Suite N319
Fort Belvoir, VA 22060-5582
USA
Phone: 703-806-4871
Fax: 703-806-4409
E-mail: William_T_Harrison@belvoir.army.mil

Mr. Floyd Hauth
STC
Suite 450
1010 Wayne Avenue
Silver Spring, MD 20910
USA
Phone: 301-565-8345
Fax: 301-565-8279
E-mail: fhauth@netphd.net

Mr. John Haynes
Program Manager
NASA HQ
Code YO
300 E Street, SW
Washington, DC 20546
USA
Phone: 202-358-4665
Fax: 202-358-3098
E-mail: jhaynes@hq.nasa.gov

Mr. Jerome Heffter
NOAA-ARL (R-ARL)
1315 Eastwest Hwy
Silver Spring, MD 20910
USA
Phone: 301-713-0295
E-mail: jheffter@comcast.net

Dr. Rosalind Helz
U.S. Geological Survey
M.S. 926A
Reston, VA 20192
USA
Phone: 703-648-6086
E-mail: rhelz@usgs.gov

Mr. Richard Hernandez
FAA
5000 Carr 190
Carolina, PR 00979-7440
USA
Phone: 787-253-8707
Fax: 787-253-8709
E-mail: Richard.Hernandez@faa.gov

Mr. Sierra Herson
Meteorologist
Direccion General de Aeronautica Civil
Bloque B, casa 705
Tegucigalpa, Apdo 30145
Honduras
Phone: 504-233-8075
Fax: 504-233-8075
E-mail: hhsierras@latinmail.com

Dr. Paul Herzegh
Project Scientist
National Center for Atmospheric Research
PO Box 3000
Boulder, CO 80307
USA
Phone: 303-497-2820
E-mail: herzegh@ucar.edu

Mr. Richard Heuwinkel
FAA
1575 Eye St, NW
Washington, DC 20005
USA
Phone: 202-385-7696
E-mail: Richard.Heuwinkel@faa.gov

Dr. Catherine Hickson
Volcanologist
Natural Resources Canada
101 - 605 Robson Street
Vancouver, BC V6B 5J3
Canada
Phone: 604 666-9772
Fax: 604 666-7507
E-mail: chickson@nrcan.gc.ca

Mr. Charles Holliday
Chief, METSAT Applications Branch
Air Force Weather Agency
AFWA/XOGM
106 Peacekeeper Dr
Offutt AFB, NE 68113-4039
USA
Phone: 402-294-9756
Fax: 402-294-5872
E-mail: charles.holliday@afwa.af.mil

Mr. David Hook
Aircraft Dispatcher
Frontier Airlines
7001 Tower Rd
Denver, CO 80249-7312
USA
Phone: 720-374-4545
Fax: 720-374-4385
E-mail: dhook@flyfrontier.com

Dr. Linda Huey
Program Assistant
U.S. Geological Survey
904 National Center
Reston, VA 20192
USA
Phone: 703-648-6712
Fax: 703-648-5483
E-mail: lhuey@usgs.gov

Ms. Winnie H. Humberson
Outreach Coordinator
NASA/GSFC
Bldg. 33, Rm. E112
Greenbelt, MD 20771
USA
Phone: 301-6145560
Fax: 301-6146530
E-mail: winnie.h.humberson.1@gsfc.nasa.gov

Ms. Harmony Hunter
STC
10 Basil Sawyer Dr.
Hampton, VA 23666-1393
USA
Phone: 757-864-3297
Fax: 757-864-8810
E-mail: h.a.hunter@larc.nasa.gov

Capt. David Innes
Air Niugini
P.O Box 7186
Boroko
Port Moresby,
Papua New Guinea
Phone: (675)3273581
Fax: (675)3273454
E-mail: deejayinnes@yahoo.com

Mr. Pavel Izbekov
Alaska Volcano Observatory
903 Koyukuk Drive
Fairbanks, AK 99775
USA
Phone: 907-474-5269
E-mail: pavel@gi.alaska.edu

Mr. Douglas Jenkins
Operations Training and Standards
FedEx
Module F
3865 Airways
Memphis, TN 38116-0517
USA
Phone: 901-224-7429
E-mail: dgjenkins@fedex.com

Dr. David Johnson
National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80307
USA
Phone: 303-497-8370
Fax: 303-497-8401
E-mail: djohnson@ucar.edu

Dr. Sigrun Karlsdottir
Icelandic Meteorological Office
Bustadarvegur 9
Reykjavik, IS-150
Iceland
Phone: +354 522600
Fax: +354 522 6001
E-mail: sigk@vedur.is

Dr. Terry E. Keith
U.S. Geological Survey
4200 University Drive
Anchorage, AK 99508-4667
USA
Phone: 907-786-7456
Fax: 907-786-7425
E-mail: tkeith@doodlepig.com

Mr. Frank Kelly
NOAA/NWS
1325 East-West Highway
Silver Spring, MD 20910
USA
Phone: 301-713-7400 x126
E-mail: Frank.Kelly@noaa.gov

Mrs. Cathy Kessinger
NCAR/RAP
3450 Mitchell Lane
Boulder, CO 80301
USA
Phone: 202-497-8481
E-mail: kessinger@ucar.edu

Mr. Jamie Kibler
NOAA/SAB
5200 Auth Road
Room 401
Camp Springs, MD 20746
USA
Phone: 301-763-8444
Fax: 301-763-8333
E-mail: Jamie.Kibler@noaa.gov

Dr. Kisei Kinoshita
Professor
Kagoshima University
Korimoto 1-20-6
Kagoshima 890-0065,
JAPAN
Phone: 81-99-285-7803
Fax: 81-99-285-7735
E-mail: kisei@edu.kagoshima-u.ac.jp

Mr. Takeshi Koizumi
Deputy Director
Japan Meteorological Agency
Ote-machi, Chiyoda
Tokyo 1008122,
Japan
Phone: 81332841749
Fax: 81332123648
E-mail: t-koizumi@met.kishou.go.jp

The 2nd International Conference on Volcanic Ash and Aviation Safety
Alexandria, Virginia
June 21-24, 2004

Dr. Arlin Krueger
Professor
JCET/UMBC
1000 Hilltop Circle
Baltimore, MD 21250
USA
Phone: 410-455-8906
E-mail: akrueger@umbc.edu

Ms. Gloria Kulesa
FAA
475 School St, SW
Washington, DC 20024
USA
Phone: 202-267-7289
E-mail: Gloria.Kulesa@faa.gov

Mr. Kent Laborde
NOAA
14th and Constitution Ave, NW
Washington, DC 20230
USA
Phone: 202-482-5757
Fax: 202-482-3154
E-mail: kent.labored@noaa.gov

Dr. Judson Ladd
Chief
National Weather Service
819 Taylor St.
Room 10E09
Fort Worth, TX 76102
USA
Phone: 817-978-1100
Fax: 817-978-4920
E-mail: Judson.Ladd@noaa.gov

Mr. Marc Lamy
Manager, Investment Analysis
Tenix Investments Pty Ltd
100 Arthur Street
North Sydney NSW,   2060
Australia
Phone: 612 9963 9672
Fax: 612 9963 9691
E-mail: marc.lamy@tenix.com

Mr. Patrick Leahy
Associate Director for Geology
U.S. Geological Survey
12201 Sunrise Valley Drive
Mail Stop 911
Reston, VA 20192
USA
Phone: 703-648-6600
Fax: 703-648-7031
E-mail: pleahy@usgs.gov

Mr. Peter Lechner
Civil Aviation Authority of New Zealand
PO Box 31 441
Lower Hutt
Wellington,
New Zealand
Phone: +64 4 560 9593
Fax: +64 4 569 2024
E-mail: lechnerp@caa.govt.nz

Mr. Tenny Lindholm
Manager
National Center for Atmospheric Research
3450 Mitchell Lane
Boulder, CO 80301
USA
Phone: 303-497-8448
Fax: 303-497-8401
E-mail: mcgaffic@ucar.edu

Cpt. Franco Lodi
Ansv
Via Attilio Benigni, 53
Roma, 156
Italy
Phone: +39 06 82078 200
Fax: +39 06 8273672
E-mail: franco.lodi@ansv.it

Mr. Jim Luhr
Smithsonian Institution
P.O. Box 37012
NHB-119
Washington, DC 20013
USA
Phone: 202-357-4809
Fax: 202-357-2476
E-mail: luhr@volcano.si.edu

Dr. Giovanni Macedonio
Osservatorio Vesuviano
Via Diocleziano, 328
Napoli, I-80124
Italy
Phone: +39 081 6108 482
Fax: +39 081 6102 304
E-mail: macedon@ov.ingv.it

Dr. James R. Mahoney
Assistant Secretary of Commerce for Oceans and Atmosphere and NOAA Deputy Administrator
14th and Constitution Ave.
Washington, DC 20230
USA
E-mail: James.Mahoney@noaa.gov

Mr. Fausto César Mancero Jiménez
Subdirección de Aviación Civil del Ecuador
Simón Bolívar, Ave. Las Américas
Guayaquil, N/A
Ecuador
Phone: 593-4-2392712
Fax: 593-4-2283748
E-mail: fmancero@hotmail.com

Ms. Alexandra Matiella
Graduate Student
Michigan Technological University
630 Dow
1400 Townsend Dr.
Houghton, MI 49931
USA
Phone: 906-487-3097
E-mail: Mamatiel@mtu.edu

Dr. Mike Matson
Deputy Director, OSDPD
NOAA/NESDIS
FB4, Room 1069
Suitland, MD 20749
USA
Phone: 301-457-5120
E-mail: michael.matson@noaa.gov

Mr. Gari Mayberry
Geologist
U.S. Geological Survey
NMNH E-421
Washington, DC 20560-0119
USA
Phone: 202-357-2618
Fax: 202-357-2476
E-mail: mayberry@volcano.si.edu

Dr. Emily McCarthy
MTU-GMES
1400 Townsend Dr
Houghton, MI 49931
USA
Phone: 906-487-1761
E-mail: ebmccart@mtu.edu

Mr. David McCormack
Geological Survey of Canada
7 Observatory Crescent
Ottawa, ON K1A 0Y3
Canada
Phone: 613-992-8766
E-mail: cormack@seismo.nrcan.gc.ca

Mr. Mark McCrady
Environment Canada
2121 Transcanada Hwy
Dorval, QC H9P-1J3
Canada
Phone: 514-421-4635
Fax: 514-421-4679
E-mail: mark.mccrady@ec.gc.ca

Mr. Walter McKeown
Senior Scientist
U.S. Navy
9141 Third Avenue
Norfolk, VA 23511
USA
Phone: 757-445-2546
Fax: 757-444-7343
E-mail: walt.mckeown@nlmoc.navy.mil

Ms. Erin McNamara
OFCM
8455 Colesville Road
Suite 1500
Silver Spring, MD 20910
USA
Phone: 301-427-2002
Fax: 301-427-2007
E-mail: Erin.McNamara@noaa.gov

Dr. Stephen McNutt
AVO
P.O. Box 757320
Fairbanks, AK 99775-7320
USA
Phone: 907-474-7131
Fax: 907-474-5618
E-mail: steve@giseis.alaska.edu

Captain Terry McVenes
Executive Air Safety Vice-Chairman
Air Line Pilots Association
535 Herndon Parkway
Herndon, VA 20170
USA
Phone: 703-481-2432
Fax: 303-530-3608
E-mail: terry.mcvenes@alpa.org

Mr. Peter Meister
NASA Headquarters
Code Y
Washington, DC 20546
USA
Phone: 202-358-1557
Fax: 202-358-3098
E-mail: peter.g.meister@nasa.gov

Capt. Ed Miller
Air Line Pilots Association, Int'l
Herndon, VA 20170
USA
Phone: 703-689-4187
Fax: 703-464-2104
E-mail: millere@alpa.org

Dr. Thomas P. Miller
U.S. Geological Survey
4200 University Drive
Anchorage, AK 99508
USA
Phone: 907-786-7454
Fax: 907-786-7425
E-mail: tmiller@usgs.gov

Dr. Cecilia Miner
Senior Systems Analyst
AvMet Applications International
2300 Clarendon Blvd, Suite 1107
Arlington, VA 22201
USA
Phone: 703-351-5659
Fax: 703-351-5645
E-mail: miner@avmet.com

Capt. Eric Moody
British Airways (Ret.)
14 Crosby Hill Drive
Camberley, Surrey, GU15 3TY
United Kingdom
Phone: 01276 24562
Fax: 01276 24562
E-mail: eric@ericmoody.com

Ms. Patricia Mothes
Instituto Geofisico
Casilla 1701-2759
Quito, 1701-2759
Ecuador
Phone: (593-2)2225-655
(593-2)227-031
Fax: (593-2) 2567-847
E-mail: patriciamothes@hotmail.com

Mr. Greg Mullen
American Airlines
4601 Hwy 360
Md 875
Ft. Worth, TX 76155
USA
Phone: 817-967-7200
Fax: 817-967-7090
E-mail: lv2flyaa@earthlink.net

The 2nd International Conference on Volcanic Ash and Aviation Safety
Alexandria, Virginia
June 21-24, 2004

Mr. John Murray
Atmospheric Scientist
NASA
21 Langley Blvd
Hampton, VA 23669
USA
Phone: 757-864-5883
E-mail: John.J.Murray@nasa.gov

Dr. Tom Murray
Scientist in Charge
Alaska Volcano Observatory
4200 University Drive
Anchorage, AK 99508
USA
Phone: 907-786-7443
Fax: 907-786-7425
E-mail: tlmurray@usgs.gov

Ms. Christina Neal
U.S. Geological Survey
4200 University Drive
Anchorage, AK 99508
USA
Phone: 907-786-7458
Fax: 907-786-7425
E-mail: tneal@usgs.gov

Dr. Augusto Neri
Researcher
Instituto Nazionale di Geofisica e Vulcanologia
via della Faggiola 32
Pisa I-56126,
ITALY
Phone: 8311941
Fax:
E-mail: neri@pi.ingv.it

Mr. Gregory Neuman
Department of Defense
1000 6th St SW, Apt 512
Washington, DC 20024
USA
Phone: 202-285-2829
E-mail: greg@gregneuman.com

Mr. Chris Newhall
U.S. Geological Survey
Box 351310
Seattle, WA 98195
USA
Phone: 206-553-6986
Fax: 206-543-0489
E-mail: cnewhall@usgs.gov

Mr. John O'Brien
Airline Pilots Association
535 Herndon Parkway
Herndon, VA 20170
USA
Phone: 703-689-4200
Fax: 703-464-2104
E-mail: JOHN.OBRIEN@ALPA.ORG

Mr. Giles OKeeffe
President
ADF
2720 Ashbourne Rd
Wayzata, MN 55391
USA
Phone: 612-727-0295
Fax: 612-727-0382
E-mail: giles.okeeffe@nwa.com

Mr. Saburo Onodera
Manager, Flight Crew Training Dept.
Japan Airlines
JAL Technical Center 2
Haneda Airport
Ota-ku, Tokyo, 144-0041
Japan
Phone: 81-3-5756-3931
Fax: 81-3-5756-3596
E-mail: saburo.onodera@jal.com

Mr. Jeffrey Osiensky
Meteorologist in Charge
National Weather Service
6930 Sand Lake Road
Anchorage, AK 99645
USA
Phone: 907-266-5116
Fax: 907-266-5182
E-mail: jeffrey.osiensky@noaa.gov

Dr. Kenneth Papp
Alaska Volcano Observatory
903 Koyukuk Drive
Fairbanks, AK 99775
USA
Phone: 907-474-1925
E-mail: kpapp@gi.alaska.edu

Mr. Herman Patia
Rebaul Volcano Observatory
PO Box 386
Rebaul,
Papua New Guinea
Phone: 675-92-1699
E-mail: hguria@global.net.pg

Dr. Vincenzo Pennetta
ANSV
Via Attilio Benigni,53
Roma 156,
Italy
Phone: +39 06 82078238
Fax: +39 06 8293943
E-mail: vincenzo.pennetta@ansv.it

Mr. Rorik Peterson
University of Alaska, Fairbanks
903 Koyukuk Drive
PO Box 757320
Fairbanks, AK 99709
USA
Phone: 907-474-1519
E-mail: ffrap1@aurora.uaf.edu

Mr. Bill Phaneuf
Air Line Pilots Association, Intl
535 Herndon Parkway
Herndon, VA 20170
USA
Phone: 703-689-4388
Fax: 703-464-2104
E-mail: phaneufb@alpa.org

Mr. Errico Picciotti
University of L'Aquila (Italy)
via Vetoio No 1
67010 L'Aquila,
Italy
Phone: 39-0862-433708
E-mail: errico.picciotti@aquila.infn.it

Dr. Dave Pieri
JPL/Caltech
MS 183-501
4800 Oak Grove Dr.
Pasadena, CA 91109
USA
Phone: 818-354-6299
Fax: 818-354-0966
E-mail: dave.pieri@jpl.nasa.gov

Mr. Rodney Potts
Bureau of Meteorology Research Centre
GPO Box 1289K
Melbourne VIC, 3149
Australia
Phone: 61-3-96694584
Fax: 61-3-96694660
E-mail: r.potts@bom.gov.au

Dr. Fred Prata
CSIRO
107-121 Station Street
Aspendale, Vic 3195
Australia
Phone: +61 3 9239 4681
Fax: +61 3 9239 4444
E-mail: fred.prata@csiro.au

Mr. Greg Pratt
DOC/NOAA/FSL
325 Broadway, R/FS5
Boulder, CO 80305
USA
Phone: 303-497-7237
Fax: 303-497-6301
E-mail: Greg.Pratt@noaa.gov

The 2nd International Conference on Volcanic Ash and Aviation Safety
Alexandria, Virginia
June 21-24, 2004

Mr. Rudolfo Pua
Director
Commonwealth of the Northern Mariana Islands
PO Box 1007 CK
670-322-8001, 670-322-7743
96950 Saipan
E-mail: mpua@cnmiemo.gov.mp

Mr. Warren Qualley
Director, Aviation Services
Weathernews Americas
1218B West Rock Creek Rd
Norman, OK 73069
USA
Phone: 405-701-8922
Fax: 405-701-8901
E-mail: warren.qualley@wni.com

Dr. James Quick
Coordinator, Volcano Hazards Program
U.S. Geological Survey
12201 Sunrise Valley Drive
Mail Stop 904
Reston, VA 20192
USA
Phone: 703-648-6711
Fax: 703-648-5483
E-mail: jquick@usgs.gov

Mr. Dick Reynolds
Prin Systems Architect
Short and Associates
12 Woodlawn Ave
Annapolis, MD 21401
USA
Phone: 410-268-5630
E-mail: Dick.Reynolds@noaa.gov

Ms. Carmelitta Riley
STC
1010 Wayne Ave, Suite 450
Silver Spring, MD 20910
USA
Phone: 301-565-8345
Fax: 301-565-8279
E-mail: stc.ss@stcnet.com

Mr. Cliff Riley
International Flight Dispatcher
Continental Airlines
1600 Smith St.
HQSDC, 13th floor
Houston, TX 77002
USA
Phone: 713-324-7500
Fax: 713-324-4615
E-mail: criley02@coair.com

Mr. David Rodenhuis
FAA/ATCSCC
13600 EDS Drive, Ste 100
Herndon, VA 22170
USA
E-mail: david.rohenhuis@faa.gov

Mr. Humberto Rodriguez
SENEAM
Blvd. Puerto Aereo No. 485
Col. Moctezuma
Mexico, D. F., 7570
Mexico
Phone: (55) 5786-0804
Fax: (55) 5786-0820
E-mail: jrodrigu@sct.gob.mx

Mr. Raul Romero
Technical Officer MET
ICAO
999 University Street
Montreal, QC H3C5H7
Canada
Phone: (514) 9548219 Ext 70079
Fax: (514)9546759
E-mail: rromero@icao.int

Prof. William Rose
Michigan Technological University
Houghton, MI 49931
USA
Phone: 906 487-2367
Fax: 906 487-3371
E-mail: raman@mtu.edu

Mr. Robert Ruiz
AMTI/Supporting FAA AFS-410
470 L'Enfant Plaza
Suite 4102
Washington, DC 20024
USA
Phone: 202-385-4578
Fax: 202-385-4653
E-mail: Robert.M-CTR.Ruiz@faa.gov

Dr. Alexander Rybin
Volcanologist
Institute of Marine Geology and Geochemistry
Nauki Street
Yuzhno-Sakhalinsk, 693022
Russian Federation
Phone: (4242)791667
Fax: (4242)791517
E-mail: rybin@imgg.ru

Mr. Jose Saballos
INETER
Frente a Ploclinica
Oriental del INSS
Managua, 2110
Nicaragua
Phone: +505 2492761
Fax: +505 2491082
E-mail: asaballos.gf@ineter.gob.ni

Mr. Leonard Salinas
Manager, Q/A Flight Dispatch and Operations
United Airlines
P.O. Box 66100
Chicago, IL 60666
USA
Phone: 1-847-700-3707
Fax: 1-847-364-0717
E-mail: leonard.salinas@united.com

Mr. Eddy Sanchez
Instituto Nacional de Sismologia
Guatemala City,
Guatemala

Mr. Don Sarreals
USA
E-mail: dsarreals@aol.com

Dr. Yoshihiro Sawada
Hokkaido University
Higashi-ku
402-20-1,E20,N41
Sapporo, 007-0841
Japan
E-mail: yy-sawada@happytown.ocn.ne.jp

RADM James P. Schear
Vice President for Safety
FAA
800 Independence Avenue
Washington, DC 20591
USA
E-mail: james.schear@faa.gov

Dr. Dave Schneider
USGS-AVO
4200 University Drive
Anchorage, AK 99508
USA
Phone: 907-786-7037
Fax: 907-786-7425
E-mail: djschneider@usgs.gov

Mr. Simona Scollo
INGV-Catania
piazza Roma 2
Catania, 95123
ITALY
Phone: 957-165800
Fax: 954-35801
E-mail: scollo@ct.ingv.it

Mr. Bradley Scott
GNS
Private Bag 2000
Taupo,
New Zealand
Phone: 64-7-3748211
E-mail: b.scott@gns.cri.nz

Mr. Gianni Semenzato
Senior Flight Inspector
Italian Civil Aviation Authority
Via de Villa Ricotti 42
Rome,
Italy
Phone: 00390644185772
E-mail: g.semenzato@enac.rupa.it

Mr. Rene Servranckx
Meteorological Service of Canada
2121 North Service Road
Transcanada Highway
Dorval, QC H9P1J3
Canada
Phone: 514-421-4704
Fax: 514-421-4627
E-mail: rene.servranckx@ec.gc.ca

Mr. Alan Shaffer
Director, Plans and Programs
Office of the Secretary of Defense
3030 Defense
Pentagon
Washington, DC 20301
USA
Phone: 703-695-9604
Fax: 703-695-4885
E-mail: alan.shaffer@osd.mil

Dr. Lynn Sherretz
NOAA/FSL
325 Broadway
R/FS5
Boulder, CO 80305
USA
Phone: 303-497-5580
Fax: 303-497-6301
E-mail: Lynn.Sherretz@noaa.gov

Mr. Lee Siebert
Smithsonian Institution
NMNH, MRC-119
Washington, DC 20013
USA
Phone: 202-786-2404
E-mail: siebert@volcano.si.edu

Mr. Herson H. Sierra
Meteorologist
Tegucigalpa MWO
Colonia "Villa Centro Americana" Bloque "B"
Casa 705 Tegueigalpa
Honduras
Phone: 504-253-8075
Fax: 504-233-8075
E-mail: hhsierras@latin.mail.com

Mr. Matthew Simmons
Tenix Investments Pty Ltd
100 Arthur Street
North Sydney NSW,   2060
Australia
Phone: +612 9963 9611
Fax: -612 9963 9691
E-mail: matthew.simmons@tenix.com

Mr. Jim Skeen
National Transportation Safety Board
490 L'enfant Plaza East, SW
Washington, DC 20594
USA
Phone: 202-314-6356
Fax: 202-314-6404
E-mail: skeenj@ntsb.gov

Mr. George Stephens
NOAA/NESDIS
World Weather Building rm 510
5200 Auth Rd.
Camp Springs, MD 20910
USA
Phone: 301-763-8142 x129
Fax: 301-899-9196
E-mail: George.Stephens@noaa.gov

Dr. Christopher Strager
National Weather Service
222 West 7th Avenue
#23, Room 517
Anchorage, AK 99513-7575
USA
Phone: 907-271-5132
Fax: 907-271-3711
E-mail: Christopher.Strager@noaa.gov

The 2nd International Conference on Volcanic Ash and Aviation Safety
Alexandria, Virginia
June 21-24, 2004

Dr. Davida Streett
NOAA
5200 Auth Road
Camp Springs, MD 20746
USA
Phone: 301-763-8444
E-mail: davida.streett@noaa.gov

Ms. Barbara Stunder
Meteorologist
NOAA Air Resources Laboratory
1315 East West Highway (R/ARL)
Silver Spring, MD 20910
USA
Phone: 301-713-0295 x114
Fax: 301-713-0119
E-mail: Barbara.Stunder@noaa.gov

Ms. Grace Swanson
Senior Meteorologist
NOAA-NESDIS
5200 Auth Rd. ,Room 401
Camp Springs, MD 20746-4304
USA
Phone: 301-763-8444
Fax: 301-763-8333
E-mail: grace.swanson@noaa.gov

Mr. Michael Szkil
Meteorologist
National Weather Service
1325 East West Highway
OS23/Room 13322
Silver Spring, MD 20910-3283
USA
Phone: 301-713-1726, Ext. 144
Fax: 301-713-1520
E-mail: michael.szkil@noaa.gov

Mr. Francisco Taitano
Special Asst to the Governor
Commonwealth of the Northern Mariana Islands
PO BOX 2007 CK
96950 Saipan
Phone: 670-322-8001
Fax: 670-322-7743
E-mail: ftaitano@aol.com

Dr. Hiroshi L. Tanaka
Assoc. Professor
University of Tsukuba
1-1-1 Tenohdai
Tsukuba,
Japan
Phone: 81-29-857-4502
Fax: 81-29853-6879
E-mail: tanaka@nakura.cc.tsukuba.ac.jp

Mr. Steve Targosz
Air Line Pilots Association, Int'l
535 Herndon Parkway
Herndon, VA 20170
USA
Phone: 703-689-4210
Fax: 703-464-2104
E-mail: russoa@alpa.org

Mr. Hordur Thordarson
Metservice
PO Box 722
30 Salamanca Road
Wellington,
New Zealand
Phone: 00 64 04 470 0700
Fax: 00 64 04 473 5231
E-mail: thordarson@metservice.com

Mr. Noriyuki Todo
Japan Airlines International Co. Ltd.
3-3-2 Haneda Airport , West Passenger Terminal
Ota-ku
Tokyo, 144-0041
Japan
Phone: -8814
Fax: -9205
E-mail: noriyuki.todo@jal.com

Dr. Bennett Treadaway
US Airways
173 Industry Drive
Pittsburgh, PA 15275
USA
Phone: 412-747-5176
Fax: 412-747-3374
E-mail: bgt@usairways.com

Ms. Ahsha Tribble
NOAA
14th and Constitution Avenue, NW
Washington, DC
USA
Phone: 202-482-5920
E-mail: ahsha.tribble@noaa.gov

Dr. Paul Try
Sr. Vice President
STC
1010 Wayne Ave., Suite 450
Silver Spring, MD 20910
USA
Phone: 301-565-8345
Fax: 301-565-8279
E-mail: ptry@stcnet.com

Dr. Ted Tsui
Naval Research Lab
7 Grace Hopper Ave.
Monterey, CA 93943-5502
USA
Phone: 831-656-4738
Fax: 831-656-4769
E-mail: tsui@nrlmry.navy.mil

Mr. Andrew Tupper
Bureau of Meteorology
Met Bldg
13 Scaturchio St
Casuarina NT 812,
Australia
Phone: +61 8 8920 3867
E-mail: a.tupper@bom.gov.au

Mr. Louis Uccellini
Director, NCEP
NWS
5200 Auth Rd, Room 101
Camp Spring, MD 20746
USA
E-mail: louis.uccellini@noaa.gov

Ms. Sarah Watkin
Met Office
FitzRoy Road
Exeter,   EX1 3PB
United Kingdom
Phone: +44 1392 886443
E-mail: sarah.watkin@metoffice.com

Dr. Matthew Watson
MTU
1400 Townsend Drive
Houghton, MI 49931
USA
Phone: 906-487-2045
Fax: 906-487-3371
E-mail: watson@mut.edu

Dr. Daniel J. Watt
Aviation Meteorologist
United Airlines
PO BOX 66100
Chicago, IL 60666
USA
Phone: 847-700-3093
Fax: 847-7000-6054
E-mail: dan.j.watt@ual.com

Dr. Earle Williams
Research Scientist
Massachusetts Institute of Technology
MIT 48-211
Cambridge, MA 2139
USA
Phone: 781-981-3744
Fax: 781-981-0632
E-mail: earlew@ll.mit.edu

Mr. Samuel P. Williamson
Federal Coordinator for Meteorology
U.S. Dept. of Commerce, NOAA
Suite 1500
8455 Colesville Road
Silver Spring, MD 20910
USA
Phone: 301-427-2002
Fax: 301-427-2007
E-mail: Samuel.Williamson@noaa.gov

Mr. David Woods
NASA/GSFC
Code 900
Greenbelt, MD 20771
USA
Phone: 757-864-2672
E-mail: david.woods@nasa.gov

Mr. Bill Woolverton
Environment Canada
4999 98th Ave.
Room 200
Edmonton, AB T6B 2X3
Canada
Phone: 780-951-8830
Fax: 780-951-8602
E-mail: bill.woolverton@ec.gc.ca

Dr. Jerry Wright
Mgr. Security and Human Resources
ALPA
535 Herndon Pkwy
Herndon, VA 20170
USA
Phone: 703-689-4197
E-mail: jerry.wright@alpa.org

Mr. Rick Wunderman
Smithsonian Institution
10th & Constitution Ave, NW
MRC 119
Washington, DC 20560-0119
USA
Phone: 202-357-1511
Fax: 202-357-2476
E-mail: rwunder@volcano.si.edu

Dr. Jeff Wynn
Team Chief Scientist
U.S. Geological Survey
1300 SE Cardinal Ct.
Bldg 10
Vancouver, WA 98683
USA
Phone: 360-993-8919
E-mail: jwynn@usgs.gov

Col. Neil Wyse
USAF
1401 Constitution Ave NW
Rm 5807
Washington, DC 20230
USA
Phone: (202)482-2355
Fax: (202)482-4116
E-mail: neil.wyse@noaa.gov

Mr. Katsumi Yoshino
All Nippon Airways Co., Ltd
3-3-2 Haneda Airport
Ota-ku
Tokyo, 144-0041
Japan
Phone: 81-3-5757-5597
Fax: 81-3-5757-3270
E-mail: yoshinoka@ana.co.jp

Mr. William Young
Manager
Tenix Investments Pty Ltd
100 Arthur Street
North Sydney NSW, 2060
Australia
Phone: +61 2 9963783
Fax: 612 9963 9709
E-mail: bill.young@tenix.com

APPENDIX C

PAPERS

INDEX OF PAPERS

Session 3: Ash Cloud Observations, Modeling, and Forecasting **Session 3**

INDEX OF AUTHORS

* Abstract only

2003 CARIBBEAN VOLCANIC ASH ENCOUNTERS

Captain Albert M. Beerley, US Airways ALPA Training Committee, Philadelphia, PA USA

On March 17, 2003, Flight Operations received information from the National Weather Service that the Montserrat volcano had erupted, spewing ash and particulate into the atmosphere. East to west upper and lower atmospheric wind patterns shifted north by northwest and volcanic ash was transported into populated areas. Dispatch immediately all contacted all aircraft enroute to San Juan, Puerto Rico, St. Thomas, St. Croix, St. Maarten, Antigua and Santo Domingo in an attempt to divert aircraft away from the adverse effects of this meteorological condition. Flight operations were terminated for almost six hours in San Juan and its surrounding area until a volcanic ash pilot report and Notice to Airmen was rescinded. On July 12, 2003 significant volcanic activity occurred once again at Montserrat. The dome of the volcano collapsed sending ash and particulate into the atmosphere. An Airbus aircraft inbound to San Juan, Puerto Rico encountered an unforeseen cloud of ash at approximately 6000 feet. The encounter subsequently caused damage to the aircraft's engine fan blades and the forward flight deck windows.

ENGINE DAMAGE TO A NASA DC-8-72 AIRPLANE FROM A HIGH-ALTITUDE ENCOUNTER WITH A DIFFUSE VOLCANIC ASH CLOUD

Thomas J. Grindle, NASA, Edwards, CA, USA
Frank W. Burcham, Jr. NASA, Edwards, CA, USA

The National Aeronautics and Space Administration (NASA) DC-8 airborne sciences research airplane inadvertently flew through a diffuse volcanic ash cloud of the Mt. Hekla volcano in February 2000 during a flight from Edwards Air Force Base (Edwards, California) to Kiruna, Sweden. Although the ash plume was not visible to the flight crew, sensitive research experiments and instruments detected it. In-flight performance checks and postflight visual inspections revealed no damage to the airplane or engine first-stage fan blades; subsequent detailed examination of the engines revealed clogged turbine cooling air passages. The engines were removed and overhauled. This paper presents volcanic ash plume analysis, trajectory from satellites, analysis of ash particles collected in cabin air heat exchanger filters and removed from the engines, and data from onboard instruments and engine conditions.

AIRCRAFT ENCOUNTERS FROM THE 18 AUGUST 2000 ERUPTION AT MIYAKEJIMA, JAPAN

Andrew Tupper[1], Yasuhiro Kamada[2], Noriyuki Todo[3], Ed Miller[4]

[1] Bureau of Meteorology, Darwin, Northern Territory, Australia, and School of Mathematical Sciences, Monash University, Victoria, Australia
[2] Japan Meteorological Agency, Tokyo Volcanic Ash Advisory Center, Tokyo, Japan
[3] Japan Airlines International, Tokyo, Japan
[4] Air Line Pilots Association, Herndon, Virginia, USA

Corresponding author address: A.C. Tupper, Bureau of Meteorology Northern Territory Regional Office, PO Box 40050, Casuarina NT 0811, Australia. E-mail: A.Tupper@bom.gov.au

Abstract

Four large commercial aircraft are known to have encountered clouds produced by the 16-17 km high phreato-magmatic eruption of 18 August 2000 at Miyakejima, Japan, which lies close to Japan's two busiest airports at Haneda and Narita. Many other aircraft flew close by the eruption clouds. A near-new Boeing 737-800 and a Boeing 747 both suffered extensive damage and required engine replacement. Another 747 encountered ash and sulphur dioxide, was inspected for three days without any damage found, and a third 747 encountered the cloud approximately 800 km (430 nautical miles) to the southeast, smelt sulphur dioxide but suffered no damage. Costs to the aviation industry are known to exceed US $12,000,000, but this figure is probably a gross under-estimate. The eruption was very well observed from the air and from the ground, and initial warnings were issued quickly, however SIGMETs did not give sufficient detail of the ash cloud dispersion, air-traffic management decisions appear to have been made on the basis of superseded VAAC forecasts for the prior, low-level eruption, and the known encounters all happened to foreign airlines, while Japanese airlines had access to more information about the activity at Miyakejima and made appropriate flight plans. The Miyakejima incidents teach us about the importance of pre-eruption information and planning, of having worldwide rather than country-specific ash-avoidance procedures, of universal and consistent information distribution, and of rigorous post-event investigations. On the positive side, the rapid eruption observation and reporting and the pre-flight planning of local airlines probably contributed to the lack of fatalities from this extremely dangerous eruption.

Introduction

The phreato-magmatic eruption of Mount Oyama, Mikayejima, Japan, on 18 August 2000 was one of the most dangerous volcanic eruptions from the viewpoint of aviation safety in recent years. The eruption began on 8 July 2000 with a crater collapse. Several larger eruptions then occurred, on 10, 18[t] and 29 August (Kinoshita *et al.*, 2002). An evacuation order for Miyakejima residents was announced on 1 September 2000, and high SO_2 fluxes continue to affect the region.

The eruption of 18 August was sudden, but not completely unexpected in the context of the preceding activity. Researchers from the Earthquake Research Institute of Tokyo University had already set up a camera to record the eruptions (Kinoshita *et al.*, 2002), and since the volcano lies only 160 km south of Tokyo, public awareness was already very high. The event was well reported by pilots and ground observers, and seen remotely with hourly satellite imagery and radar (Iino *et al.*, 2001: Tupper *et al.*, 2004). Despite this, two aircraft suffered severe damage from the eruption cloud 90 minutes after the beginning of the eruption, and two other aircraft are known to have flown through the cloud.

Remote sensing issues associated with the eruption, and a brief chronology of events, are given in Tupper et al. (2004). The purpose of this paper is to focus on factors pertinent to the aircraft encounters. We are not seeking to apportion blame to individuals or agencies, but to examine issues associated with what is a complex and still developing warning International Airways Volcano Watch.

Location of Encounters

The 18 August 2000 eruption occurred at 0802 UTC (17:02 JST) Fig. 1 shows the location of Miyakejima, and of the four verified encounters, the first two of which occurred at about sunset:

i) A Boeing 747 had requested a diversion that was only partially allowed because of military airspace ("Octagon" on Fig. 1). The aircraft encountered ash cloud at 34,000 ft (10.3 km) at about 0930 UTC, and exited the cloud at 30,000 ft (9.1 km) 2 minutes later. The aircraft made an emergency landing at Narita. Three engines, the flight deck windshield, and some forward passenger windows were replaced. The fourth engine was to be replaced after 100 hours flying time. The airline made an initial cost estimate of at least US $5 million.

ii) A near-new Boeing 737-800 also encountered the cloud at about 0930 UTC, at 36,000 feet (10.9 km), having received no verbal warnings from Air Traffic Control or nearby aircraft. Just before penetration into the ash cloud, Air Traffic Control had given the flight a radar vector directing the aircraft 40NM (74 km) northeast of Airway B586, an action that was ineffective for avoidance. The flight management computer and electronic engine controls failed, but the engines still functioned. The cockpit filled with 'haze and dust'. The aircraft made an emergency landing. Both engines were damaged and had to be replaced, forward visibility was lost on the windscreen except for a small area under the windshield wiper. The leading edges and tail were abraded, and the radome, air data probes damaged. The cost was at least US $ 5 million.

iii) At 1235 UTC, a Boeing 747 encountered strong sulphuric smells and 'sparking' on the windshield, strongly indicative of an ash encounter. The aircraft had diverted from Airway B586 to Airway 337 in an attempt to avoid the ash, and was partially successful since satellite imagery suggests less ash in that area. The aircraft was removed from service and inspected for three days, but no ash or damage was found. Nevertheless, the cost to this airline of diversions and inspections exceeded US $2 million.

iv) At 2010 UTC, another 747 reported sulphuric smells. There was no evidence of ash in this encounter, although the aircraft was apparently not removed from service for a detailed inspection. This aircraft had diverted a considerable distance eastward from Airway 337, after receiving the report of the 1235 UTC encounter.

Other aircraft movements

The movement of other aircraft around the eruption cloud are incompletely known. A DC-10 transited the same airspace at almost the same time as the first two confirmed encounters, but made no report. Given the extent of the eruption clouds and their proximity to Narita and Haneda airports, it seems likely that other aircraft encountered ash.

Four Japan Airlines flights observed the eruption during the evening (from 0830 UTC to 0924 UTC), and successfully avoided the ash clouds, as did later night flights. It appears that the action taken was generally to fly to the northwest of the eruption, the only area unpolluted at cruising levels. This avoidance action appears quite contrary to the Air Traffic Control advice to the aircraft in encounter ii), and reflects the fact that the Japan Airlines flights were operating with superior information and were not reliant on the official warnings.

Performance of International Airways Volcano Watch

Fig. 2 summarises the time and stated cloud height of advisories and warnings. The eruption was exceptionally well observed by the Japan Meteorological Agency and by pilots, reports were made extremely quickly, and the speed of issue of warnings was probably the fastest of any major event in the history of the International Airways Volcano Watch. The time from eruption, to the issue of a volcanic ash advisory, then to the domestic 'Area Meteorological Advisory' (ARMAD) and then the international SIGMET, the official meteorological warning for the eruption, was still twenty-three minutes in total, reflecting a long chain of communication. However, the first SIGMET was still issued over an hour before the two most serious aircraft encounters.

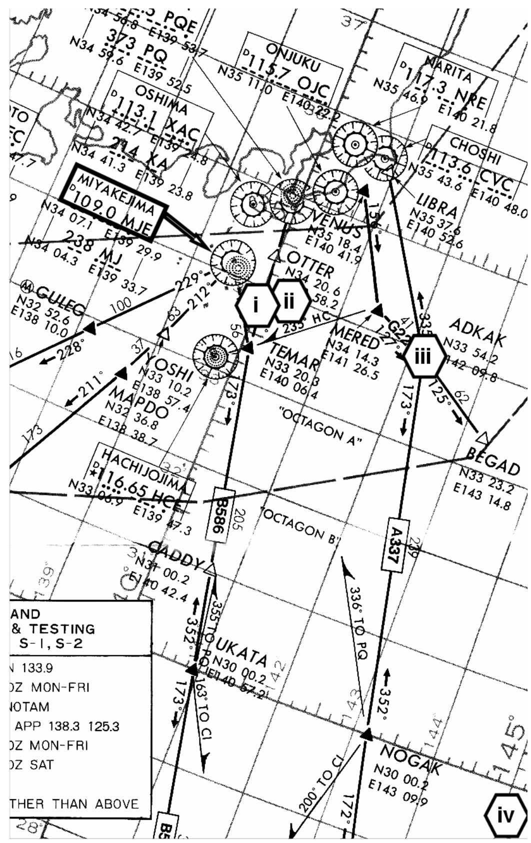


Figure 1 - Detail of air routes around Miyakejima. Hexagons labelled i-iv denote positions of reported aircraft encounters. The areas of restricted airspace are labelled 'Octagon A' and 'Octagon B'

A number of major problems can be identified. Firstly, the observation received by Tokyo VAAC at 0812 UTC of an eruption with tops ***greater than*** FL190 (5.8 km) was translated into tops ***to*** FL190 in the official NOTAM and SIGMETs (Fig 2, 'a'). The entire avoidance procedure during the critical first phase of the eruption was based on the incorrect assumption of a low-level eruption.

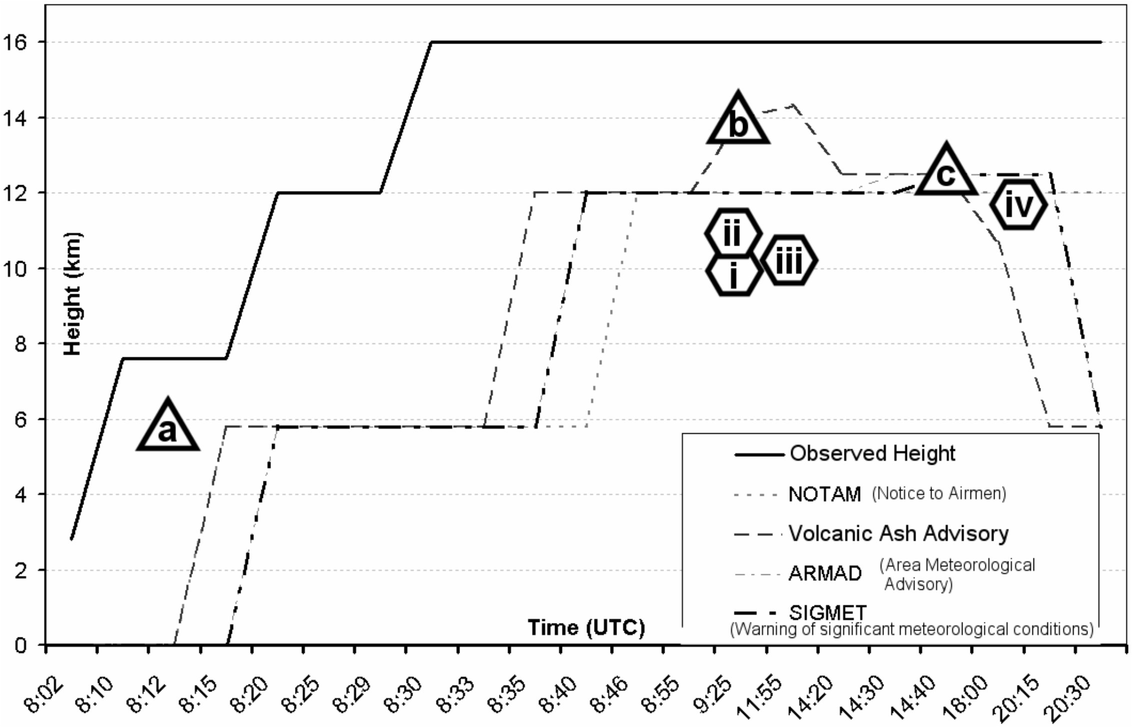


Figure 2 - Height of eruption reflected in observations, advisory and warning products. Lettered triangles show the time of key events described in the text, and hexagons show the time and height of confirmed aircraft encounters.

Even though these warnings were superseded around 0835 UTC, the misinformation continued to propagate through the warning system, as the initial information was passed on. This kind of height confusion is actually quite common: a useful guideline may be to assume that eruption clouds above 5 km extend to the tropopause until evidence is given to the contrary (Tupper and Kinoshita, 2003).

Secondly, the cloud dispersion at cruising levels was not well understood. The Tokyo VAAC was unable to prepare and issue a full dispersion forecast for the eruption until 0925 UTC ('b' in Fig.2), i.e. about the time of the encounters. The SIGMETs, the official warning product, never included a dispersion forecast and stated only that the ash was going to the southeast or east-southeast. The wind field in the area and likely dispersion of the plume was well known, with an upper air observation station just to the south, and an observation of eruption height over 45,000 ft (13.7 km) and spot wind observation of northwest winds at 50 knots (92 km/h) reported to Air Traffic Control by JAL at 0830 UTC. Despite this controllers apparently failed to grasp the extent of the cloud and were directing aircraft into the ash an hour after the JAL report and high-level SIGMET.

During the event, staff at Tokyo VAAC became concerned these issues, and took the initiative of distributing extra graphics showing a 'close-up' view of the eruption cloud.

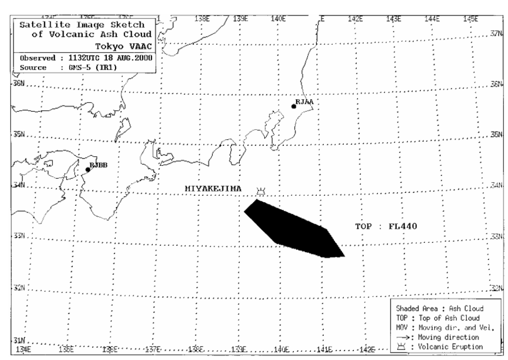


Figure 3 - Supplementary nephanalysis issued during the event by Tokyo VAAC.

Thirdly, as in many other volcanic ash events, the procedures for warning cessation at the stage where ash becomes difficult to detect were not defined. Encounter iv) occurred after the high level ash had become impossible to detect on satellite imagery and as Tokyo VAAC staff were beginning to concentrate on the lower level eruption clouds (Fig. 2, 'c').

Fourthly, it appears that, where local operators such as Japan Airlines were in direct receipt of graphical warnings, followed their own contingency plans, and were well aware of the situation at Miyakejima, foreign operators were not as well informed. All operators should receive the official warnings, and an arrangement exists where Japan Airlines redistributes graphical advices to other airlines. However it is evident from the written reports of airlines that suffered damage that justifiably or otherwise, they felt badly informed. As a consequence, the Tokyo VAAC was pressured with phone calls from several airlines, as well as the media, frustrating the VAAC's efforts to get information into the official warning system, and also frustrating the foreign operators who struggled with language issues.

Finally, despite the seriousness of the encounters and some direct complaints by airline operators, we have been unable to find any evidence of an investigation by the government agencies concerned. We assume that, because no post-analysis is explicitly mandated in the arrangements of the International Airways Volcano Watch, and no agreement was in existence between the responsible agencies in Japan that required an investigation in a situation where aircraft have been damaged but no fatalities have occurred, no process existed to trigger such an investigation.

<u>Discussion</u>

None of the issues identified above are uniquely Japanese. For example, in the Australian region, Qantas functions as a conduit for volcanic information to other international airlines in the same way that Japan Airlines does in Japan, and it is likely that any sudden eruption in Australian airspace would show that some airlines are far better informed than others.

Formally, Volcanic Ash Advisory Centres exist to advise Meteorological Watch Offices about the dispersion of volcanic ash cloud. However, airline dispatchers, who make critical decisions about their aircraft, are often desperate for information during crises and will use whatever resources are available to make their decisions. Personal relationships are also highly emphasised in meteorological / aviation relationships the world over; information flows much more freely where offices perceive a good working relationship.

A major challenge for the International Airways Volcano Watch is to ensure that enough information is distributed over *official* warning channels to allow all operators to avoid the ash cloud. Current initiatives, such as globally consistent volcanic ash graphics, universal SIGMET and NOTAM implementation, and better training, could substantially improve the information distribution. In turn, this will reduce the pressure on VAACs to provide telephone service to aviation operators.

There are substantial issues of workload. For example, the SIGMET 2 for this event was:

RJTG SIGMET 2 VALID 180845/181445 RJAA – TOLYO FIR VA MIYAKEJIMA (34.1N 139.5E) OBS at 0829 OVER MIYAKEJIMA VA TOPS MORE THAN FL400 DRIFTING TO E-SE BY B747 INTSF

This SIGMET, while informative, contains no explicit dispersion forecast. In today's coding, an appropriate SIGMET for that time may have been:

RJTG SIGMET 2 VALID 180845/181445 RJAA-TOKYO FIR VA ERUPTION MIYAKEJIMA LOC N31 E139 VA CLD OBS AT 0830Z SE OF MIYAKEJIMA SFC/FL460 N3415 E13925 - N3410 E13950 - N3345 E13955 - N3350 E13930 - N3415 E13925 MOV SE 40KT INTSF FCST 1445Z VA CLD APRX N3430 E13915 - N3420 E14105 - N3035 E14330 - N3155 E13850 - N3430 E13915 OTLK 012045Z VA CLD APRX N3435 E13905 - N3035 E13830 - N2855 E14505 - N3415 E14220 - N3435 E13905 020130Z VA CLD APRX N3440 E13905 - N2955 E13830 - N2730 E14700 - N3410 E14305 - N3440 E13905

Even this SIGMET is a simplification, as it treats all the ash as one layer in a situation where the wind changed markedly with height. Text SIGMETs will be necessary for some time yet, until graphical products are universal. When composing and then decoding SIGMETs such as those above, which are derived from even more complex Volcanic Ash Advisories, some delay is inevitable unless the whole process can be simplified and/or automated.

The deamnds of the media are unlikely to be reduced by informative warnings. It is difficult to keep operational contact numbers confidential, and every centre should have a firm policy for handling media enquiries during an event. Since there is virtually no public benefit in feeding extra information to the media during an event, responding these calls should be given a low priority at most.

Large volcanic eruptions in any particular area are relatively infrequent. The mistakes made in the VAAC, Meteorological Watch Office, airline offices and Air Traffic Control centres are likely to recur for future eruptions in other regions unless regular training is performed. Similarly, the sensitivities associated with any damage from a volcanic event are such that, unless a clear protocol is already in place for post-analysis, it is possible that no effective investigation would be performed.

A final point of interest is that no damage was found to the aircraft involved with encounter (iii), despite three days of inspections. When compared to the Hekla 2000 incident (Grindle and Burcham, 2003), this suggests that further research is necessary to determine the danger threshold of ash clouds.

Following the Miyakejima eruptions, the Tokyo VAAC has had substantial experience with other eruptions. Volcanic SIGMETs, previously restricted to heights around 5 km, are now issued for all altitudes. Numerous case studies have been conducted for training purposes, a VAAC web site has been created, and the Japan Meteorological Agency provides a representative to the ICAO International Airways Volcano Watch Operations Group, which is shaping the future warning system.

Conclusions

The eruption of Miyakejima provides us with a remarkable example of a major eruption of a monitored volcano, in airspace serviced by highly sophisticated aviation and meteorological services. The eruption therefore gives us an insight into the issues that are likely to be prominent over the rest of the world once the basic technological challenges of monitoring are sorted out.

In this case, despite rapid observation of the eruption and a relatively rapid issue of warnings, two aircraft were seriously damaged, and at least two others encountered the cloud. To address these challenges, we suggest:

1) Further development of the International Airways Volcano Watch to ensure that information before and during an eruption is adequate for international aviation operators.
2) Regular training and drills to ensure operational readiness.
3) The development of internationally agreed post-analysis procedures for improvement of the International Airways Volcano Watch.

Acknowledgements

We gratefully acknowledge the help of the airlines who anonymously provided information about their encounters with the Miyakejima eruption clouds, Dr. A. Terada of Hokkaido University for providing a video of the eruption, and Prof. K. Kinoshita of Kagoshima University for much related discussion and materials. We also acknowledge the operational efforts of the staff on duty during the eruption, which was the first major eruption in Japanese airspace since the creation of the Tokyo VAAC.

References

Grindle, T. J. and F. W. Burcham, 2003, Engine damage to a NASA DC-8-72 airplane from a high-altitude encounter with a diffuse volcanic ash cloud. Technical Memorandum NASA/TM-2003-212030, 22 pp.

Iino, N., K. Kinoshita, M. Koyamada, S. Saitoh, K. Maeno, and C. Kanagaki, 2001, Satellite imagery of ash clouds of the 2000 eruption of Miyake-jima volcano. *CEReS International Symp. on Remote Sensing of the Atmosphere and Validation of Satellite Data*, Chiba, Japan, 13-8.

Kinoshita, K., C.Kanagaki, N.Iino, M.Koyamada, A.Terada, and A.Tupper, 2002, Volcanic plumes at Miyakejima observed from satellites and from the ground. *Optical Remote Sensing of the Atmosphere and Clouds III*, H.-L. Huang, D. Lu, and Y. Sasano, Eds., SPIE, 227-36.

Tupper, A. and K. Kinoshita, 2003. Satellite, air and ground observations of volcanic clouds over islands of the Southwest Pacific. South Pacific Study, *23*, 21-46.

Tupper, A., S. Carn, J. Davey, Y. Kamada, R. Potts, F. Prata, and M. Tokuno, 2004. An evaluation of volcanic cloud detection techniques during recent significant eruptions in the western 'Ring of Fire'. Remote Sens. Environ., ***91***, 27-46, doi:10.1016/j.rse.2004.02.004.

VOLCANIC ASH CLOUDS POSE A REAL THREAT TO AIRCRAFT SAFETY

Leonard J. Salinas *
United Airlines, Chicago, Illinois

1. ABSTRACT

Volcanic ash clouds pose a real threat to aircraft safety. More than 100 jet aircraft have encountered volcanic ash clouds in the past 25 years often resulting in damage to the aircraft. The ash is abrasive and capable of causing serious damage to aircraft engines, control surfaces, windshields, and landing lights. The ash can clog the pitot-static systems, which determine airspeed and altitude, and can damage sensors that deliver electronic data to automated systems used to fly the aircraft. Seven of these encounters caused in-flight loss of jet engine power.

The ash cloud, transported by atmospheric winds, can drift over great distances causing disruption to air traffic and is a potential hazard to aircraft hundreds of miles from its source.

The hazard is compounded by the fact that volcanic ash clouds are not detectable by the present generation of radar instrumentation carried aboard aircraft. Complete avoidance of volcanic ash clouds is the only procedure that guarantees flight safety.

Addressing the threat of volcanic ash to aircraft safety has brought together Governments, University Scientists, Pilots, Dispatchers, Meteorologists, Air Traffic Controllers, and many representatives of the aviation industry to work collaboratively to reduce the hazards caused by volcanic ash. The First International Symposium and recently the Second International Conference on Volcanic Ash, Aviation Safety, The International Civil Aviation Organization, (I.C.A.O.), The World Meteorological Organization (W.M.O.), The Airline Pilots Association (A.L.P.A.), The Airline Dispatchers Federation (A.D.F.), and many others identified the need for specialized air carrier operations, procedures, communications, routings, and training are essential in maintaining a high level of flight safety.

* Corresponding author address:
Leonard J. Salinas, United Airlines, Program Manager Dispatch, Flight Safety and Operations-WHQFS
P.O. Box 66100, Chicago, IL 60666;
E-mail: leonard.salinas@united.com

2. INTRODUCTION

The first notable encounter was the British Airways 747 near Galunggung, Indonesia, in 1982. It showed that, in such encounters, we might expect a loss of engine power, problems with airspeed indications, and extensive abrasion damage, including a loss of windshield transparency. The encounter placed the flight in great danger, and it required heroic and persistent efforts by the crew to restart the engines and bring the flight to a safe conclusion (Tootell, 1985).

During the eruption of Redoubt Volcano in Alaska on 15 December 1989, a new B747-400 on a flight from Amsterdam to Anchorage flew into the plume and lost power from all four engines. The crew was able to restart the engines and land the aircraft safely. The initial estimate of damage to the aircraft was $80 million, including the replacement of all four engines (Brantley, 1990).

3. WARNING-SYSTEM

To ensure aviation safety, it is necessary that reports of eruptions be processed without delay into warnings to Pilots, Air Traffic Control Centers, and Air Carrier Operations Centers. Volcanoes are a threat to air safety from the moment that they erupt. A warning system should be capable of a 5-minute response time once an eruption has been detected. The Mount St. Helens ash took approximately 5 minutes to reach aircraft-cruising altitudes (Rosenbaum and Waitt, 1981) at a rate of climb of approximately 5,000 ft per minute. A modern jet aircraft is traveling over 500 mph and advancing 6-8 miles per minute.

Winds play the dominant role in the distribution of volcanic ash. The agency for subsequent ash-location advisories should be the meteorological office. The computerized model of winds over the eruption site can be used, in conjunction with the dispersion models, to predict ash trajectories, as an aid to flight path planning for avoiding airborne volcanic ash, such as, the NOAA Air Resources Laboratory Volcanic Ash Forecast Transport And Dispersion (V.A.F.T.A.D.) model (Heffter and Stunder, 1998).

4. VOLCANIC ASH ADVISORY CENTERS

The Volcanic Ash Advisory Centers (V.A.A.C.s) were established in September 1995 in Darwin at a meeting of the I.C.A.O. At this meeting it was decided that in an effort to ensure that volcanic cloud hazards were addressed there must be an interface between Volcano Observatories, Meteorological agencies, Air Traffic Control Centers, and Air Carrier Operations. In order to meet their goal they decided the world should be divided into different regions differentiated by their volcanic activity and volcano observatories. The designated V.A.A.C. would be in charge of keeping track of the activity by analyzing satellite imagery in their designated region.

The V.A.A.C.s operate advanced science-based tools for detecting, identifying, tracking and projecting the movement of airborne volcanic ash. Because many of the world's active volcanoes are located in uninhabited regions, the rapid detection and location of volcanic eruptions are often problematic (Chen, 1998).

The Volcanic Ash Advisory Statement (V.A.A.S.) is issued by the V.A.A.C.s. The V.A.A.C.s must provide the required advisory information to the various M.W.O.s for a timely issuance of the SIGMETS.

The nine V.A.A.C.s are the contacts meteorologists can utilize for many of the details regarding a volcanic eruption. They are Anchorage, Buenos Aires, Darwin, London, Montreal, Tokyo, Toulouse, Washington, and Wellington.

The I.C.A.O. International Airways Volcano Watch publication of Operational Procedures and List of Operational Contact Points Between Vulcanological Agencies, Meteorological Watch Offices and Area Control Centers provides areas of responsibilities on a global scale, the phone numbers, fax numbers, e-mail addresses, and electronic addresses.

5. STATUS OF ACTIVITY OF VOLCANO

A color code for the "Level of Alert" indicates the status of activity of the volcano. A group representing many agencies, meeting in Anchorage, Alaska shortly after the Redoubt Eruption in 1989 developed this. It was determined this would be a simple method by which all could immediately understand the current condition of the volcano.

RED	Volcanic eruption in progress. Ash plume/cloud reported above FL250.
ORANGE	Volcanic eruption in progress but ash plume/cloud not reaching FL250.
YELLOW	Volcano known to be active from time to time and volcanic activity has recently increased significantly, volcano not currently considered dangerous but caution should be exercised.
GREEN	Volcanic activity considered to have ceased and volcano reverted to its normal state.

6. SIGMETS, NOTAMS, AND ASHTAMS

The operational requirements for the issuance of SIGMETS and NOTAMS have been part of the relevant Annexes for a number of years. The requirements for ASTAMS were included in Annex 15 - Aeronautical Information Services in November 1997. The SIGMET and NOTAM are excellent sources of information for the Pilot, Dispatcher, Air Traffic Control Facility, and Meteorologist.

7. AIR CARRIER OPERATIONS

Pilots are the last link in the chain of safety actions to avoid or mitigate encounters with volcanic ash. In order for pilots to be effective, it is necessary that the rest of the system meet the needs of the pilots. Pilots view the sky in terms of routes, fixes, and (or) coordinates. The Air Traffic Controller and Dispatcher are best equipped to provide this information to the Pilots in aviation language.

Approximately 600 of the 1,500 potentially active volcanoes are classified as active (Foreman, 1991). Volcanoes are not generally marked on aeronautical route charts. The Dispatcher or Air Traffic Controller will provide a statement of where an eruption is occurring expressed in aeronautical terminology, a bearing and distance from a navigational fix, or a latitude and longitude. Statements of distance will be expressed in nautical miles, rate of movement in knots, and plume heights in flight levels. References to time should always be in Universal Coordinated Time.

8. PLUME AVOIDANCE

Before operating in a region of known potential volcanic activity Pilots and Dispatchers (Jointly Responsible for Flight Safety by Federal Air Regulations under 121) should check Significant Meteorological Information Reports (SIGMETs), Notices to Airmen (NOTAMs), ATC directives, and Pilot Reports (PIREPs) for that region. To aid in identifying regions that are potentially active at a particular time United Airlines has developed procedures that provide flight safety (Hinds and Salinas, 1998). Since volcanic eruptions can seriously impact operational routes and destinations the United Airlines Weather Center has been designated as the initial point of contact in the Operational Control Center (O.C.C.) to gather pertinent data and information and issue a United Airlines Volcano Advisory (UVA). The Meteorologists will research sources such as, but not limited to, VAAC's, SIGMETS, NOTAMS, PIREPS, Volcano Observatories, ATC, VAFTAD's, Local Station Managers, and Civil Emergency Agencies. The Air Carrier issues a text and graphic Alert noting the volcanic eruption. This advisory will appear on documents that are sent to the Pilots and Dispatchers. The United Volcano Advisory UVA will be updated continuously during the event and will only expire after no activity is evident and VAAC concurs.
The advisory will contain the following:

- Advisory Number
- Valid Time (UTC)
- Volcano Name and Location
- Summit Height
- Winds at Summit
- Height of Eruption in Flight Levels
- Winds at Flight Levels
- Estimate Ash Coverage lat./long.
- Comments (Plain Language)

This information will be provided in both text and graphical form that is much easier to use and are more compelling in terms of amending flight plans for the purpose of avoidance. The standard graphic product will utilize the internationally recognized symbol to represent a volcanic eruption in progress on the graphical display.

9. MITIGATION FOLLOWING AN INADVERTENT ENCOUNTER

Emphasis must be placed on the avoidance of volcanic ash. Avoid flight at night in areas of known volcanic activity or in instrument meteorological conditions (IMC), when volcanic ash may not be visible. Plan the flight to remain well clear of reported activity. If possible, stay upwind of volcanic ash. But, if ash penetration occurs, crews should know what to do. Criteria for recognizing that one's airplane is in a volcanic ash plume and suggested procedures for escaping from a plume, are covered in the paper Recommended Flight-Crew Procedures if Volcanic Ash is Encountered (Campbell, 1991).

10. RECOGNITION

Volcanic ash may be difficult to detect at night or during flight through clouds; however, flight crews have observed the following conditions:

- At night, heavy static discharges (St. Elmo's fire) around the windshield, accompanied by a bright white glow in the engine inlets.
- At night, landing lights cast sharp, distinct shadows in volcanic clouds (unlike the fuzzy, indistinct shadows that are cast against weather clouds).
- Volcanic ash and dust appearing in the cockpit and cabin.
- An acrid odor or the smell of sulfur.
- Multiple engine malfunctions, such as surge, increasing exhaust-gas temperature, torching from tailpipe, and flameouts.
- Decrease in indicated airspeed.

11. ENCOUNTER PROCEDURES

If volcanic ash is encountered, accomplish the following (Campbell, 1991):

- Immediately reduce thrust to idle.
- Auto throttles off (if engaged).
- Exit volcanic cloud as quickly as possible. Volcanic ash may extend for several hundred miles. The shortest distance/time out of the ash may require an immediate, descending 180-degree turn.
- Engine and wing anti-ice on. All air conditioning packs on. Turn on engine and wing anti-ice.
- Start the auxiliary power unit (APU), if available.
- Oxygen mask on and 100 percent, if required.
- Ignition on.
- Monitor EGT.
- Close outflow valves.
- Do not pull fire switches.
- Leave fuel boost pump switches "on" and open cross feed valves.
- Do not use fuel heat.
- Engine restart may be required. Successful engine start may not be possible until airspeed and altitude are within the air start envelope.
- Monitor airspeed and pitch attitude.
- Land at the nearest suitable airport.

12. SPECIAL AIR REPORT OF VOLCANIC ACTIVITY

Pilot observations of volcanic activity are of use to others. The Volcanic Ash Working group has produced a special air report of Volcanic Activity Form (VAR), which is carried by United Airlines pilots and most other Air Carrier pilots. The form is a guide. The form should be delivered to the local meteorological office on arrival. This form provides a detailed and useful tool for others in accurate reporting. The ICAO standard for the contents include:

- Aircraft identification
- Position
- Time
- Flight level or altitude
- Volcanic activity observed
- Air temperature
- Winds
- Supplementary information

13. CONCLUSIONS

There are 1,500 known volcanoes worldwide, and about 600 of these volcanoes are considered active. An average of 55-60 volcanoes erupt each year, and about 8-10 of these eruptions produce ash clouds that reach flight altitudes. Volcanic Ash can reach aircraft cruise altitudes in 5 minutes and considering jet aircraft are traveling at 5-8 miles per minutes a 5-minute communications warning system is imperative.

Pilot and Dispatcher training is a priority. Both must understand that volcanic ash is not like sand or dust, and they must know how to recognize inadvertent entry into an ash cloud. The Boeing Company in cooperation with the Air Line Pilots Association and the U.S. Geological Survey has developed a Volcanic Ash Training Video. In addition Pilots, Dispatchers, and Air Traffic Controllers must be aware of any potential volcanic activity affecting their area of operation. Should an inadvertent penetration of a volcanic ash cloud be made, flight crews must be aware of potential problems and be prepared to deal with the arising flight conditions.

Prompt communication among Volcano Observers, Meteorologists, Air Traffic Controllers, Flight Dispatchers, and Pilots regarding location of drifting ash clouds will maintain a high level of flight safety.

The detection and tracking of ash-cloud movement using remote-sensing techniques and atmospheric transport models continue to provide the graphical data required in long-range flight planning. Enhanced monitoring of the

Earth's active volcanoes, especially in the remote regions of the world, such as the new communication links with the Russians for warning and information about Kamchatkan volcanoes (Miller and Kirianov, 1993), now provides prompt notification of an eruption.

Location of a volcano has been simplified by using the Global Planning Chart showing the position of known active volcanoes relative to air routes and air navigation aids. (U.S.G.S. Casadevall and Thompson, 1994).

Avoidance requires the coordinated efforts of a broad group of technical specialists. The goal of these efforts is to avoid an area or airspace that has been contaminated by volcanic ash. Avoidance of Volcanic Ash Clouds is the only procedure that guarantees flight safety

14. Acknowledgments

The author would like to thank Ed Miller, ALPA Retired, Steven Albersheim, FAA, Marianne Guffanti, USGS, Samuel Williamson Office of Federal Coordinator of Meteorologists, Raul Romero, I.C.A.O, Nouhou Tata Diallo, World Meteorological Office, Barbara Stunder, NOAA-ARL, Christopher Strager, DOC/NOAA Alaska Region, Grace Swanson, NOAA-NESDIS, Tom Miller, Scientist Emeritus, USGS AVO, Christina Neal, USGS/AVO, Gary Hinds and Dan Watt, UAL Meteorologists, and Captain Hank Krakowski VP Flight Safety, Security and Quality Assurance, United Airlines, for their continued support, recommendations, and technical expertise, in the interest of Aviation Flight Safety in regard to the Hazards of Volcanic Ash.

15. REFERENCES

Brantley, S.R., ed., 1990, The Eruption of Redoubt Volcano, Alaska: U.S.G.S. C-1061, 33 p.

Campbell, E.E., 1991, Recommended Flight-Crew Procedures If Volcanic Ash Is Encountered: 1st International Symposium, Bull.-2047, 151 p.

Casadevall, T.J. & Thompson, T.B., 1994, Volcanoes and Air Navigation Aides-A Global Planning Chart: U.S.G.S.-Map GP-1011.

Chen, P., 1998, Issues Facing The Volcanic Ash Advisory Centres: Workshop on Volcanic Ash, Toulouse, France.

Foreman, P.M., 1991, Warning Systems And Pilot Actions: 1st International Symposium, Bull.-2047, 163 p.

Heffter, J.L. & Stunder, B.J., 1998, Modeling Volcanic Ash Transport and Dispersion: Workshop on Volcanic Ash, Toulouse, France.

Miller, T.P., & Kirianov, V.Y., 1993, Notification Procedures For Kamchatkan Volcanic Eruption: U.S.G.S. Open -File Report 93-569, 9 p.

Rosenbaum, J.G., & Waitt, R.B., Jrl, 1981, Summary O Eyewitness Accounts of The May 18 Eruption of Mount St. Helens, Washington: U.S.G.S. Professional Paper 1250, p. 53-67.

Tootell, E., 1985, All 4 Engines Have Failed; The True and Triumphant Story of Flight BA 009 and the Jakarta Incident: Auckland, Hutchinson Group Ltd., 178 p.

AIR NIUGINI AND THE VOLCANIC ASH THREAT

Captain David Innes, Flight Safety Office
Air Niugini, Papua New Guinea

ABSTRACT

Air Niugini is the national airline of Papua New Guinea, operating international services to Asia, Australia and the South West Pacific as well as domestic ports in the New Guinea Islands region. The airline operates a small fleet of turboprop and jet aircraft in an area notable for its high number of active volcanoes, some situated near major centre's and airport's, many situated directly beneath major international air route's. Air Niugini's experience with volcanic activity and airborne ash has resulted in a heightened state of awareness of the phenomena and we have developed in house methods for maintaining crew awareness of the threat as well as standard operating procedures designed to better enable crews to manage ash encounters. Papua New Guinea's unusual reliance on air transport for commerce and communication mean's that the airline is continually seeking out those solutions best suited for our operating environment in order to maintain services in an area prone to volcanic activity.

INTRODUCTION

Papua New Guinea is an island chain stretching from Indonesia in the west to the Solomon Island's in the east, a distance of approximately nine hundred nautical miles. Most of the population lives on the main island but significant population centres exist on the outlying islands of New Britain, New Ireland, Manus and Bougainville. Air Niugini as the national carrier is tasked with servicing these communities as well as providing international connection's to neighbouring states. Many of the major population centres happen to be situated near active or dormant volcanoes, which are concentrated in a line reaching from the north coast of the main island across to New Britain and the island of Bougainville.

ENCOUNTERS

Air Niugini crews fly in the vicinity of active volcanoes on a daily basis, but as yet we have been fortunate when it comes to actual ash encounters. The most significant encounters have involved Fokker F28 aircraft operating close to erupting volcanoes at Rabaul (Tavurvur) in 1994 and Manus Island in 1996. In the first case, an F28 on the ground at Rabaul Airport was effectively scrambled in the midst of a volcanic eruption only a few kilometre's from the airfield. In the second example, an aircraft enroute between the towns of Wewak and Madang reported passing close by Manus Island as it erupted. Other airborne encounters have been limited to observations only from a safe distance. Operational procedures from ash contaminated runways exist but given the lack of suitable ground equipment at many outport's for clearing ash and towing aircraft to clear areas for engine operations, company policy is to simply cease operation's to affected ports until the ash contamination has been cleared. Apart from Rabaul Airport, such ash deposits have been light coverings only.

DAMAGE

Air Niugini has had no significant report of damage to its aircraft resulting from in flight ash encounters. Aircraft suspected to have flown in the vicinity of ash are removed from service while they are inspected and cleaned, and because of our restrictive operating procedure's, we find our aircraft serviceability and engine overhaul cycles are comparable to industry standards for our fleet type and type of operations. While our aircraft have fared well, the same cannot be said of some of the airstrips we operate into. Rabaul Airport was effectively destroyed by the 1994 eruption, along with much of the town, and while Air Niugini was fortunate enough to manage to extract its aircraft during the eruption, several companies lost both fixed and rotary wing aircraft to heavy ash falls.

SOCIO-ECONOMIC CONSEQUENCES

In regard to passenger services, the islands of New Guinea, New Britain, New Ireland and Bougainville are serviced almost exclusively by air. Sea transportation is relatively slow and infrequent and the country has no railway network. The mountainous terrain, up to 14000 feet or more in places, has limited road access to the coastal areas and one rough road into the Highlands region of the main island. Any major disruption to the countries regular air services has an immediate and severe impact on the communities involved, and it should be noted that apart from small numbers of commuter size aircraft, Air Niugini holds a virtual monopoly on regular public transport. Tourism is a major source of foreign income, as is small scale high value seafood and agricultural produce. The presence of volcanic ash near major centres invariably causes major disruptions to these industries with flow on effect's that run into weeks if not month's. When airstrips are closed due to volcanic activity, communities are reduced to travelling long distances to alternate airfields where the only service available is usually a small commuter aircraft of nine to nineteen seats capacity.

Air Niugini's guidelines for operating in regions prone to volcanic activity are simple and effective, but result in frequent schedule delay's and cancelled flights. One example is the Rabaul area, where night operations are banned even though facilities exist for full night time operations. Aircraft do not overnight at this port due to the possibility of ash damage from the nearby volcano and flight in Instrument Meteorological Conditions (IMC) is not permitted. In the wet season, between November and April, flight's operating into Rabaul/Tokua frequently divert to Kavieng if there is cloud cover over Simpson harbour. If the flight is an early evening one, the designated alternate is Port Moresby, a seventy minute flight. Air Niugini and the communities it serve's are adversely affected by even the risk of volcanic ash due to the difficulty of establishing whether or not ash is actually present in area's of high risk.

CONCLUSIONS

Air Niugini has to date successfully managed to minimise the risk of exposure to volcanic ash through the use of a restrictive set of standard operating procedures. The negative consequence of this has been the disruption of services to communities almost wholly reliant on our scheduled services for commerce and communication's. We believe the best way of improving our schedule maintenance while maintaining our record for ash avoidance would be the adoption of volcanic ash detection technology suited to our particular needs. Ground based ash detection at certain airfields coupled with appropriate procedures would allow crews to make more informed decisions, thereby enabling the airline to better service the community while ensuring aircraft are protected from exposure to airborne ash.

REDUCING ENCOUNTERS OF AIRCRAFT WITH VOLCANIC-ASH CLOUDS

Marianne Guffanti, U.S. Geological Survey, Reston VA 20192, USA (guffanti@usgs.gov)
Thomas J. Casadevall, U.S. Geological Survey, Denver CO 80225, USA
Gari C. Mayberry, U.S. Geological Survey, Washington DC 20560, USA

Introduction

The volcanic-ash hazard to aviation is not a rare possibility on a worldwide scale, given that many major air routes traverse the world's most volcanically active regions (Casadevall et al., 1999; Ewert and Newhall, this volume). Miller and Casadevall (2000) estimate that volcanic ash can be expected to be in air routes at altitudes greater than 9 km (30,000 ft) for roughly 20 days per year worldwide. Numerous instances of aircraft flying into volcanic ash clouds have demonstrated the life-threatening and costly damages that can be sustained. Upon impact with aircraft traveling at speeds of several kilometers per minute, airborne ash particles abrade forward-facing surfaces, including windscreens, fuselage surfaces, and compressor fan blades in turbine engines. Moreover, the melting temperature of the glassy silicate rock material that comprises ash is lower than the operating temperatures of modern jet turbine engines; consequently, ash particles ingested into such engines can melt in hot sections and then accumulate as re-solidified deposits in cooler parts of the engine. The overall result of an encounter of an aircraft with an ash cloud can be immediately degraded engine performance (including flame out and loss of thrust power), loss of visibility, and failure of critical navigational and operational instruments (Dunn and Wade, 1994).

Systematic collection of information about ash/aircraft encounters is important to substantiate the nature and extent of the risk to aviation and to improve the multi-faceted mitigation strategy of ash avoidance. To that end, the U. S. Geological Survey (USGS) and Smithsonian Institution, in collaboration with the Darwin Volcanic Ash Advisory Center, are compiling a summary of reported encounters in the form of a database that includes information about the source volcanoes that produced the ash clouds and conditions during the encounters. This paper presents a preliminary analysis of information about encounters from 1973 through 2003. The bulk of the encounter data is published in the Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds by the International Civil Aviation Organization (ICAO, 2001). An updated summary of encounters will be provided to ICAO for publication in a future update of the 2001 Manual.

Overview of Known Encounters

Appendix I of the Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds (ICAO, 2001) identifies 83 ash/aircraft encounters from 1935 to 1993 and provides information about the source volcanoes, eruption dates, aircraft types, and severity of the encounters; preliminary mention of another ~17 encounters from 1994 to 2000 is given in an accompanying table. An additional 9 encounters are known through 2003 that are not included in the Manual. The most recent reported incident occurred in July 2003 in the Caribbean region (see Beerley, this volume).

From 1973 through 2003, 105 encounters of aircraft with airborne volcanic ash have been documented (Figure 1); this is a minimum value because encounter incidents are not consistently reported. The highest annual encounter rate (25 incidents) occurred in 1991, mostly due to the eruption of Mt. Pinatubo in the Philippines. Since 1991, 26 encounters are documented through 2003, an average of two per year, again a minimum value.

The encounter database does not include information about aircraft caught on the ground at airports affected by ash; a separate database is being compiled for airport disruptions resulting from volcanic activity (see Guffanti et al., this volume).

Aircraft have been damaged by ash clouds from eruptions ranging from small, recurring episodes (e.g., at Soufriere Hills Volcano, Montserrat, 1996) to very large, singular events (e.g., at Pinatubo, 1991). Thirty source volcanoes have produced ash clouds encountered by aircraft (Table 1). (For a few encounters, the source volcanoes are not known.) Six volcanoes are associated with highest number of encounters (≥5): Pinatubo in the Philippines, Sakura-jima in Japan, Galunggung in Indonesia, and St. Helens, Augustine, and Redoubt in the United States.

To quantify the effects of reported encounters on aircraft, a severity index for ash encounters (Table 2) has been formulated (ICAO, 2001). The criteria for each class in the severity index are based on the actual types of damage or conditions reported. Severity of encounters ranges from minor Class 0 incidents (acrid odor in cabin, electrostatic discharge on windshield) to very grave Class 4 and 5 incidents (engine failure). Fortunately, no Class 5 encounters (those resulting in crashes) have occurred.

In the database, most encounters (roughly 75%) are Class 0-2. Accurately documenting the extent of Class 0 encounters is problematical. Some likely occur that not publicly reported because no significant damage is involved. Smelling sulfur does not necessarily indicate the presence of damaging ash, given that separation of the gas and ash components of volcanic clouds is known to occur (Bluth et al., 1994; Guffanti et al., in press). Moreover, the human nose very sensitive to sulfur dioxide (R. Wunderman, written communication, 2004) and may sense it at levels that are undetectable by remote-sensing methods.

A significant percentage (~25%) of encounters comprises serious Class 3-4 incidents. Eight Class 4 encounters involving temporary engine failure occurred from 1980-1991 (Table 3). These encounters occurred 240 to 960 km (150 to 600 miles) from the source volcanoes (St. Helens, Galunggung, Redoubt, Pinatubo, Unzen). The encounters lasted from 2 to 13 minutes at altitudes ranging between 4.6-11.3 km (15,000-37,000 ft) above sea level.

Some recent documented encounters in August 2000 did not involve engine failure, but were nevertheless very dangerous. A Boeing 737-800 nearing Japan's Narita Airport flew into an ash cloud produced during an eruption about an hour earlier at Mijake-jima volcano, located about 100 miles from the airport. The engines continued to function, but the flight management computer and electronic engine controls failed. Handicapped further by severe loss of visibility due to abrasion of all but a small part of the windscreen, the crew managed a safe landing. Shortly thereafter, a 747 had a similar experience. Three additional aircraft also are thought to have encountered the Miyake-jima cloud. Costs to the aviation industry, including replacement of engines, exceeded US $12 million (see Tupper et al., this volume).

ICAO recommends that information on ash clouds and encounters be documented by having pilots complete the Volcanic Activity Report (VAR) when appropriate. The VAR can be found in Annex 3 and ICAO Doc 4444. Pilots and Air Traffic Services should complete these reports and forward them to appropriate services and agencies for operational use and historical record-keeping by the USGS and Smithsonian. In addition, encounter information can be sent to any of the authors of this paper or by email to gvn@volcano.si.edu. Such information does not need to be received by the USGS and Smithsonian in an operational, real-time mode. Furthermore, information identifying the airlines or aircraft operators involved in encounters will not be included in the USGS/Smithsonian database.

Discussion

Under the auspices of ICAO's International Airways Volcano Watch, operational procedures for ash avoidance have been formulated. Avoidance requires that dispatchers, pilots, and air-traffic controllers quickly learn of explosive eruptions and the locations of ash clouds. Accordingly, mitigation involves elements of: (a) real-time volcano monitoring and rapid eruption reporting, (b) detecting ash clouds in a timely manner, (c) forecasting expected cloud dispersion, (d) ensuring communication among the diverse parties responding to the hazard, and (e) not least, educating key operational personnel such as volcanologists, meteorologists, pilots, dispatchers, and air-traffic controllers about the hazard and how to respond to it (Guffanti and Miller, 2002). Arguably, implementation of these mitigation elements has reduced the likelihood of aircraft encounters with ash clouds. Fewer encounters have been reported since 1991 (Figure 1), while at the same time the amount of air traffic in volcanic regions grew (and the level of eruptive activity remained more-or-less constant).

But encounters do continue to occur for a variety of reasons. Unexpected eruptions occur at unmonitored volcanoes, and timely eruption reporting by volcanological agencies to the aviation sector sometimes is overlooked. Inherent limitations exist in remote-sensing methods of detecting ash clouds, including the time it takes to receive and analyze processed satellite data at ground facilities. Models for forecasting cloud dispersion also have significant limitations, such as incomplete input parameters describing the initial eruption plume and sparse wind-field data. Breakdowns occur in the multi-step process of information dissemination. Training and hazard awareness may be inadequate, especially as new personnel enter into critical positions.

Only as the above problems are identified and rectified can encounters be minimized or, ideally, eliminated altogether. Perversely, effective mitigation can give the erroneous perception that the hazard has been eliminated, leading to dangerous complacency. As our ability to prevent encounters improves to the point that even fewer incidents occur, we must not mistakenly conclude that no threat exists, but rather call for continued vigilance and support of proven, broad-based mitigation efforts.

References Cited

Beerley, A., this volume, 2003 Caribbean volcanic ash encounters.

Bluth, G.J.S., Casadevall, T.J., Schnetzler, C.C., Doiron, S.D., Walter, L.S., Krueger, A.J., and Badruddin, M., 1994, Evaluation of sulfur dioxide emissions from explosive volcanism – the 1982-1983 eruptions of Galunggung, Java, Indonesia: Journal of Volcanology and Geothermal Research, v. 63, p. 243-256.

Casadevall, Thomas J., Thompson, Theodore B., and Fox, Tom, 1999, World Map of Volcanoes and Principal Aeronautical Features: U.S. Geological Survey Map I-2700, scale 1:34,268,000, reprinted 2001.

Dunn, Michael G., and Wade, Douglas P., 1994, Influence of volcanic ash clouds on gas turbine engines: U.S. Geological Survey Bulletin 2047, p. 107-118.

Ewert, John W., and Newhall, Christopher, G., Status of volcano monitoring worldwide, this volume.

Guffanti, Marianne, Casadevall, T.J., and Mayberry, G.C., this volume, Effects of volcanic activity on airports.

Guffanti, Marianne, Ewert, J. W., Swanson, G., Gallina, G., and Bluth, G., in press, The volcanic-ash hazard to aviation during the eruptive activity in 2003-2004 of Anatahan Volcano, Commonwealth of the Northern Mariana Islands: Journal of Volcanology and Geothermal Research.

Guffanti, Marianne, and Miller, E. K., 2002, Reducing the threat to aviation from airborne volcanic ash: Proceedings of the 55th Annual International Air Safety Seminar, Dublin, Nov. 4-7, 2002. Flight Safety Foundation, Alexandria, Virginia, p. 283-293.

International Civil Aviation Organization, 2001, Manual on Volcanic Ash, Radioactive Material, and Toxic Chemical Clouds: ICAO Doc 9691-AN/954, Montreal, Canada.

Miller, Thomas P., and Casadevall, Thomas J., 2000, Volcanic Ash Hazards to Aviation: Encyclopedia of Volcanoes, Sigurdsson, H., editor, Academic Press, San Diego, California, USA, p. 915-930.

Tupper, A., Kamada, Y., Todo, N., Miller, E., this volume, Aircraft encounters from the 18th August 2000 eruption of Miyakejima, Japan.

Figure 1. Frequency of reported encounters of aircraft with volcanic ash, 1973-2003.

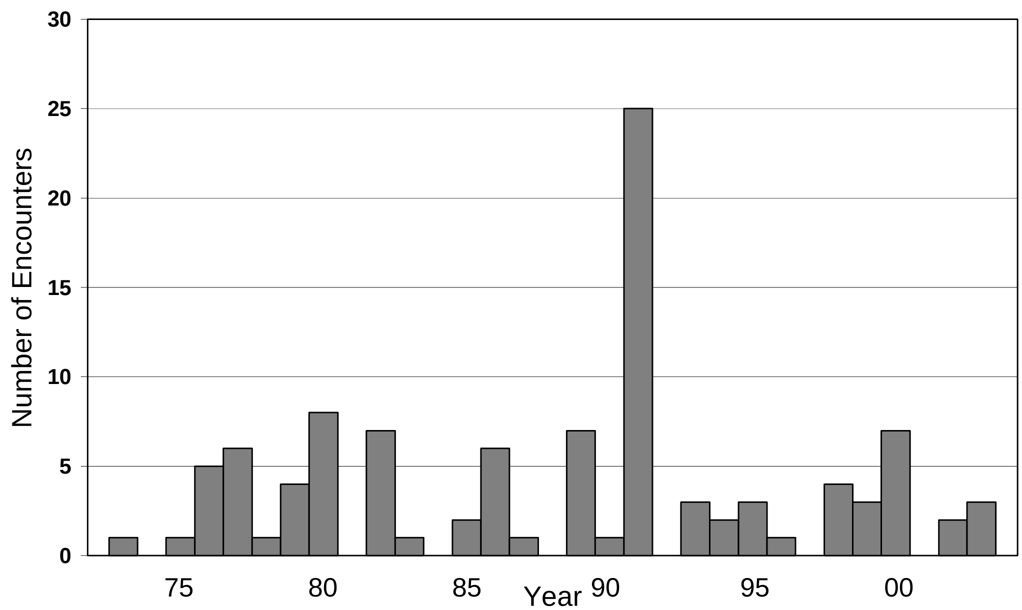


Table 1. List of volcanoes that produced ash clouds encountered by aircraft, 1973-2003. Volcanoes are organized by country, eruption year in parentheses.

Chile: Hudson (1991)

Colombia: Nevado del Ruiz (1985)

Dem. Rep. of Congo: Nyamuragira (1991)

Ecuador: Guagua Pinchincha (1999), Tungurahua (1999)

Guatemala: Fuego (1998), Pacaya (1987, 1993, 1998)

Iceland: Hekla (2000)

Indonesia: Colo (1983), Galunggung (1982), Langila (1997), Soputan (1985)

Italy: Etna (1989, 2000)

Japan: Asama (1973), Izu-Oshima (1986), Miyakejima (2000), Sakurajima (1975, 1977, 1978, 1979, 1982, 1986, 1991, 1994), Unzen (1991), Usu (1997)

Mexico: El Chichon (1982), Popocatepetl (1998)

Philippines: Pinatubo (1991, 1993)

Papua New Guinea: Manam (1993), Rabaul (1995)

Russia: Kliuchevskoi (1994)

United Kingdom: Soufriere Hills (1996, 2003)

United States: Anatahan (2003), Augustine (1976, 1986), Redoubt (1989, 1990), St. Helens (1980)

Table 2. Severity Index for Ash Encounters, from ICAO (2001, Appendix I, p. I-6).

Class	Criteria
0	Acrid odor (e. g. sulfur gas) noted in cabin Electrostatic discharge (St. Elmo's fire) on windshield, nose, engine cowls No notable damage to exterior or interior
1	Light dust in cabin; no oxygen used Exhaust gas temperature (EGT) fluctuations with return to normal values
2	Heavy cabin dust; "dark as night" in cabin Contamination of air handling and air conditioning systems requiring use of oxygen Some abrasion damage to exterior surface of aircraft, engine inlet, & compressor fan blades Frosting or breaking of windows due to impact of ash Minor plugging of pitot-static system; insufficient to affect instrument readings Deposition of ash in engine
3	Vibration of engines owing to mismatch; surging Plugging of pitot-static system to give erroneous instrument readings Contamination of engine oil hydraulic system fluids Damage to electrical system Engine damage
4	Temporary engine failure requiring in-flight restart of engine
5	Engine failure or other damage leading to crash

Table 3. Summary of Class 4 encounters, modified from ICAO (2001)

Encounter Date	**Source Volcano**	**Encounter Altitude**	**Encounter Duration**
25 May 1980	Mt. St.Helens, USA	15,000-16,000 ft	~4 minutes
24 June 1982	Galunggung, Indonesia	37,000 ft	13 minutes
24 June 1982	Galunggung, Indonesia	33,000-35,000 ft	unknown
13 July 1982	Galunggung, Indonesia	33,000 ft	unknown
15 December 1989	Redoubt, USA	25,000 ft	~8 minutes
17 June 1991	Pinatubo, Philippines	37,000 ft	2 minutes
17 June 1991	Pinatubo, Philippines	unknown	unknown
27 June 1991	Unzen, Japan	37,000 ft	unknown

AIRCRAFT ENCOUNTERS WITH VOLCANIC CLOUDS OVER MICRONESIA, OCEANIA, 2002/03

Andrew Tupper[1], Jason Davey[1], Paul Stewart[2], Barbara Stunder[3], Rene Servranckx[4].

[1] Northern Territory Regional Office, Bureau of Meteorology, Darwin, Northern Territory, Australia, and School of Mathematical Sciences, Monash University, Victoria, Australia
[2] National Meteorological and Oceanographic Centre, Bureau of Meteorology, Melbourne, Victoria, Australia
[3] NOAA Air Resources Laboratory, Silver Spring, Maryland, U.S.A.
[4] Canadian Meteorological Centre, Meteorological Service of Canada, Montreal, Quebec, Canada

Corresponding author address: A.C. Tupper, Bureau of Meteorology Northern Territory Regional Office, PO Box 40050, Casuarina NT 0811, Australia. E-mail: A.Tupper@bom.gov.au

Abstract

Three aircraft encounters with volcanic clouds were reported over the Micronesia area, northeast of Papua New Guinea; two in November 2002 and one in March 2003. Satellite analysis was performed using standard techniques, but no detectable ash was found in the area. Back and forward trajectories were then performed, to attempt to identify the source of the volcanic clouds. For the March 2003 encounter, the volcanic cloud most likely derived from Rabaul, Papua New Guinea, and was probably lofted from low altitudes to aircraft cruising levels during extensive convection in the area. The two aircraft in November 2002 appear to have encountered parts of a cloud approximately 350 km (190 nautical miles) across, and about 12 hours apart. One aircraft, an Airbus 340, reported intense St Elmo's Fire, and light white 'smoke' with 'burn smells'. Three pitot probes were replaced because of ash inside, some light abrasion was found on the engine air inlets but no damage on the windscreen or the nose, and no internal engine damage was reported. The second aircraft observed the ash cloud and smelt a slight odour but found no damage. In this case, the volcanic cloud almost certainly did not come from a local source, but was advected over a great distance. The most likely source of the cloud is the eruption of Reventador (Ecuador) twenty days earlier, but trajectory analysis is inconclusive.

Introduction

It is important that every aircraft encounter with volcanic clouds be investigated, even when the damage is relatively minor, and the available information is incomplete. Here, we discuss three such encounters over or near Micronesia, north and northeast of Papua New Guinea.

For these events, we produced forward and backward trajectories for the events described using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1998), implemented at the Australian Bureau of Meteorology and at NOAA (Draxler and Rolph, 2003), and the Canadian Meteorological Centre trajectory model (CMC, 2004), hereafter 'CMC trajectory model'. We also conducted reverse absorption and visible analysis using GMS, GOES and MODIS data.

Aircraft encounter on 8 March, 2003

On 8 March, 2003, at 1745 UTC an aircraft reported volcanic ash at FL330 (approximately 10 km altitude) to the Oakland, U.S.A., air traffic control centre. The position was given as within 60 nautical miles (111 km) of the equator at 156E, at the border of the Port Moresby (Papua New Guinea) and Oakland Oceanic Flight Information Regions. The information was passed on by telephone to the Guam Weather Forecast Office, which then issued a SIGMET for volcanic ash cloud.

The report was passed to Washington Volcanic Ash Advisory Centre (VAAC), who immediately contacted the Darwin VAAC, as the report originated within Darwin's area of responsibility (ICAO, 2004). Washington and Darwin meteorologists discussed the satellite analyses (no ash detected, no known major eruption, no obscuring factors such as cloud in the area), and both VAACs issued advisories to alert Meteorological Watch Offices in the area to the situation. The SIGMET issued from Guam was not found in Darwin VAAC communications traffic, indicating either an addressing problem or a problem in the message handling within the Australian Bureau of Meteorology.

No hard copy of the report was received in Guam, nor was any further information logged at Oakland (Frank Wells (NOAA), Steven Albersheim (US FAA), personal communications). Enquiries to various airlines have also proved fruitless; accordingly, we have no knowledge of damage caused or of any characteristics of the ash encounter, which is somewhat frustrating. Our analysis here is based on the assumption that the information received was correct, if sketchy.

Under this assumption, we surmise that the encounter did not cause severe on-board systems failure (from the lack of media reports), and that, as the encounter occurred on a moonless night, that visible or other sensible indications of volcanic ash were close to the aircraft in order to be observed by the crew.

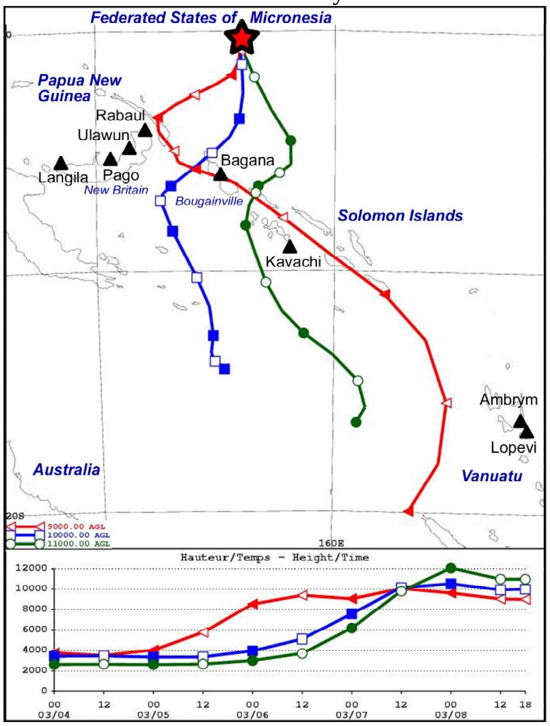


Figure 1-CMC backward trajectories for 8 March 2003 encounter, for endpoints at 9, 10 & 11 km at 18 UTC on 8 March 2003, beginning 4 March 00 UTC. Volcanoes with known or assumed activity during the period are indicated, and the star indicates the encounter location.

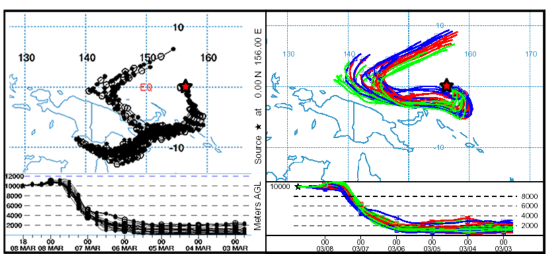


Figure 2 - 27-member ensemble HYSPLIT back-trajectories for 8 March 2003 encounter using (left) Bureau of Meteorology TLAPS analyses, and (right) NOAA FNL data. End-point separation 1 grid-point (horizontally), 0.01 grid point (vertically).

Figs. 1 & 2 show CMC trajectory model and HYSPLIT back-trajectories from the location of the encounter. Of the active volcanoes indicated in Fig. 1, explosive eruptions were most likely from Rabaul, Ulawun, Langila, Ambrym, and Lopevi. However, the only explosive activity actually observed (most of these volcanoes are not constantly monitored) was from Tavurvur cone at Rabaul, which fluctuated between 'white vapour' and 'convoluted pale grey ash clouds' rising a few hundred metres above the 223 m summit (Rabaul Volcano Observatory, 2003). This height is well below aircraft cruising levels, but the vertical motion shown in both figures suggests of the possibility of ash rising in convection or synoptic scale ascent.

The differences in the ensemble trajectories, and the differences between these trajectories and the CMC trajectory model, reflect the input analyses. In this case, TLAPS has probably captured the low-mid level monsoon trough slightly better because of the higher resolution. These ensemble trajectories suggest a more westward source than the CMC output, with many of the TLAPS ensemble members showing a source south of Papua New Guinea. This area is, however, not volcanically active: the most likely candidate volcanoes are in the New Britain region of Papua New Guinea, where the three models have all indicated a possible source region.

Satellite imagery at 1745 UTC on 6 March (not shown), indicates a deep layer cloud mass with embedded convection near Rabaul, associated with the convergence north of a strong monsoon trough and Coral Sea low near 15ºS (Darwin Regional Specialised Meteorological Centre, 2003). The cloud mass moved over a wide area, with cumulonimbus tops advecting slowly towards the northeast (and toward the position of the aircraft encounter) and dissipating. The situation two days later, at the time of the aircraft encounter, had another period of deep cloudiness beginning near New Britain, while skies near the encounter were relatively clear of cloud. This satellite analysis supports the strong vertical motion indicated by the model analyses.

The location of the suspected encounter is consistent with ash from eruptions at Rabaul, New Britain, several days earlier, transported in the vertical by enhanced ascent associated with an active monsoonal cloud mass. We presume that the concentration of ash at this time would have been quite low, given the effects of over 3 days of dispersion, enhanced for a period of at least 12-24 hours by moisture deposition and fallout within the precipitating cloud mass.

Aircraft encounters, 23/24 November, 2002

Fig.3 shows the locations of the two encounters discussed here. Three pilot reports were received, shown here with our comments in italics.

Encounter 1:

1. IDENTIFIER - *(removed for confidentiality)*
2. POSITION - 80NM NORTH W/P DOHRT-AWY B452 *(DOHRT is at 0N, 156.83E)*
3. TIME - 23.1728Z
4. FLT LEVEL - FL330 *(about 10 km)*
5. VOLC ACTIVITY OBSERVED AT - NOT REPORTED
6. AIR TEMP - M35C
7. SPOT WIND - 150/10

SUPP INFO - VOLCANIC ASH REPORTED AS FLYING IN CB *(cumulonimbus)* CLOUD
ACI RQST ANY REPORTS THAT U MAY HAVE RCVD.

In post-flight briefing, the aircraft crew reported intense St Elmo's Fire, and light white 'smoke' with 'burn smells'. These symptoms are characteristic of moderate severity ash encounters. The report was not transmitted during the flight because the crew were unable to establish contact with either Port Moresby or Oakland; radio interference is another characteristic of volcanic ash encounters. The aircraft, an Airbus 340, had three Pitot probes replaced because of ash inside, some light abrasion on the engine air inlets but no damage on the windscreen or the nose. The encounter lasted about one minute at cruising speed (≈900 km/h), suggesting an area of distinct ash cloud of the order of 15 km wide.

Eight hours later, a report was received from an aircraft on the ground at Rabaul:
LOCAL DATE - 24NOV2002
TIME (UTC) - 240330Z
A/C POSITION - ON THE GROUND TOKUA (AYTK) *(Tokua airport)*
A/C - P2-ANI
FLT NO. - PX204
VOLCANO NAME – TAVURVUR *(note: a cone at Rabaul)*
DIRECTION OF ASH DRIFT - VERY HEAVY ASH FRM VOLCANO GOING STRAIGHT INTO CLOUD (BASE 3000FT) *(about 900 metres)*
WIND - LIGHT NORTH WESTERLY

Four hours after this, a second encounter report was made:

Encounter 2:

1. IDENTIFIER - *(removed for confidentiality)*
2. POSITION - 0320N 15210E
3. TIME - 24.0717Z
4. FLT LEVEL - FL360 *(about 11 km)*
5. VOLC ACTIVITY OBSERVED AT - NOT REPORTED
6. AIR TEMP - NOT REPORTED
7. SPOT WIND - NOT REPORTED
8. SUPP INFO - PLAIN LANGUAGE QUOTE NOT CONCLUSIVE BUT POSS SLIGHT HAZE AND A LITTLE SMELL AT FL360 UNQUOTE

Additional information was also obtained from this airline: 'The pilot in charge of that flight acknowledges that the signs were inconclusive and not agreed by all flight crew. The time and location were his recollection of actual event. He added that looking down-sun the haze was evident, and looking up-sun there was a "corona" around the sun. They flew into clearer air without these signs a bit later.' Further inquiries elaborated on the phrase 'a bit later': 'they could discern a different "haze" below them for about 20 minutes before the sulphurous smell was noticed. That lasted for "2-3 minutes, less than 5 anyway"'. These additional data emphasise the importance of obtaining complete information at the time of a report. At cruising speed, a cloud observed for 20-25 minutes corresponds to an approximate cloud width of 300 – 375 km, with the area where the smell of sulphur was noticed about 30-45 km across.

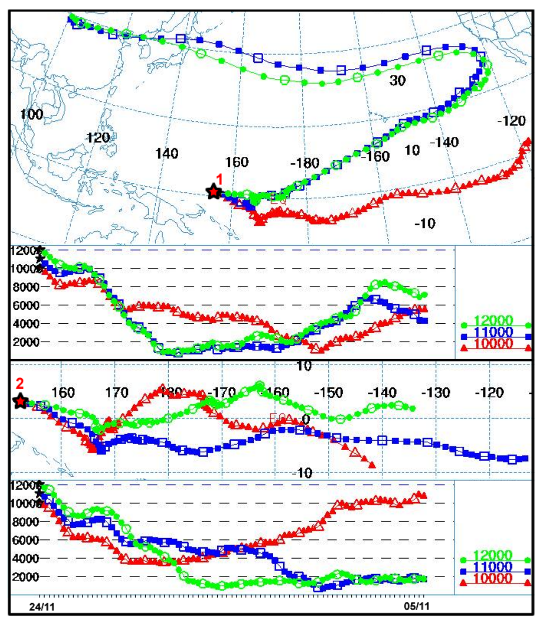


Figure 3 - 20-day back trajectories for Encounter 1 in November 2002, using HYSPLIT/GASP, ending 00 UTC 24 November 2002 (top), and for Encounter 2, ending 12 UTC (bottom). The positions of encounters 1 & 2 on 23/24 November are marked with stars.

Analysis of GMS-5/VISSR, EOS/MODIS and NOAA/AVHRR data (not shown) did not indicate any ash in the area. Back trajectories (Fig.3) show that the cloud at the position of Encounter 2 was near approximately 2N 157E at the time of Encounter 1 (that is, within 50 km of Encounter 1), and at altitude of 10 km. It is therefore highly likely that the aircraft encountered parts of the same cloud. Because Encounter 1 occurred during the night, any haze or corona (suggesting ash or sulphate aerosols) would probably not be observed, and the cloud was probably only noticed when a less diffuse area affected the aircraft for a short period. At the time of Encounter 2, the sun was low in the sky (4 degrees elevation), which would make the haze more visible. Had the flight been slightly later, it is possible that no report would have been made at all, since the smell of sulphur was not a mandatory reporting element for aircraft (this is expected to change in the near future).

One possible source of this ash cloud was, the entrainment of volcanic ash into deep convection. The report from Tokua airport gives a strong indication of this phenomenon. However, this event occurred after the first encounter, and some distance away. Moreover, satellite, manual and model analysis prior to the encounters (not shown) all had light and variable winds at the surface and strong easterlies in the upper levels, suggesting that advection of ash from Rabaul to the encounter location was virtually impossible. The active volcanoes in the vicinity of the encounters were the same as those shown in Figure 1, but short-term back-trajectories (not shown) indicate little chance of ash from these volcanoes being responsible for the encounters.

If the ash did not derive from a local source, then it must have originated in a major eruption some distance away. This would be consistent with the sizeable width of the diffuse cloud. Encounters with ash at a great distance from the source have occurred before (Casadevall, 1994). Fig. 3 shows an extended 20-day backward trajectory from the position of Encounter 1, using HYSPLIT-4 with GASP analysis data. This and other back-trajectories performed (not shown) initially came from the east, giving a high degree of confidence to the diagnosis of a remote eruption source. At a greater distance from the encounters, there is significant divergence in both position and altitude. Many trajectories meander along the equator, while others go near Hawaii, North America, and Japan. One CMC back-trajectory (not shown) reached as far as Italy, where Mt Etna was in eruption with ash being emitted at low levels.

However, by far the biggest eruption globally in November 2002 was the eruption of El Reventador, in Ecuador, South America, on 3-5 November. The eruption column was at least 17 km high, with approximately 53 kilo-tonnes of sulphur dioxide released, and an unknown quantity of ash (Smithsonian Institution, 2004). El Reventador is almost exactly east of the encounters (albeit 13950 km east!). Since the tropospheric portion of the eruption cloud was observed to drift westwards in equatorial easterlies, and the clouds associated with the encounters twenty days later came from the east, El Reventator is a potential source of the ash clouds.

Twenty-day forward trajectories from the last observed position of the Reventador ash were performed to further investigate the possibility of Reventador being the source of ash for the Micronesia encounters. Fig. 4 shows the CMC trajectory result for this case; the ash initially heads westwards for several to many days, reaching as far eastwards as 160W, then tracks southwards in the Southern Hemisphere. HYSPLIT trajectories also show a number of possible tracks, including into the Northern Hemisphere. In general the speed of movement of the ash is a little too slow to reach Papua New Guinea in twenty days, although of course this is very sensitive to altitude in the models. Therefore, although the circumstances remain suggestive, we are not able to definitively verify Reventador as the source using either satellite techniques or trajectory forecasts. On the other hand, we are unable to suggest any other likely sources.

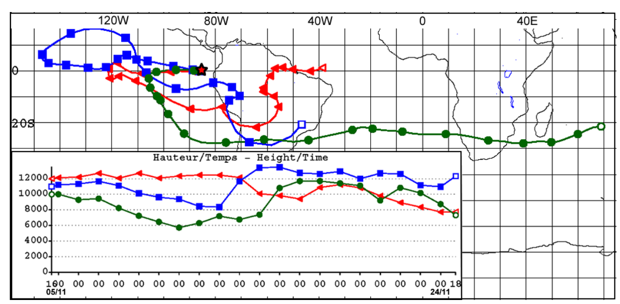


Figure 4 - 20-day CMC forward trajectories from the last known position of the Reventador eruption cloud, 5 November 2002.

Discussion

These cases show some of the more frustrating aspects of operational monitoring, detection and forecasting of volcanic ash for aviation:

- Pilot reporting is intermittent, sometimes not in real-time, and is often haphazard. The information obtained for November 2002 was remarkably good and reflects on the efficient operation of the airlines involved; on the other hand, the pilot report from March 2003 was vague and impossible to clarify.

- Volcanic eruption information in areas like the South Pacific is often difficult to obtain, due to resource and communication difficulties (Tupper and Kinoshita, 2003). Our analysis assumptions here have rested partly on the lack of major eruption reports from Bougainville, the Solomon Islands, and Vanuatu, all of which have inadequate volcanic monitoring.

- Satellite analysis was unable to identify volcanic clouds at the time of the encounters. This is not a new issue; satellite-based monitoring in the tropics is frequently problematic (Tupper *et al.*, 2004), increasing our reliance on ground-based reporting.

- For the March 2003 encounter, comparisons between trajectories based on different meteorological datasets show some significant divergence after 1-2 days. The trajectories suggest differences in the analyses of the three-dimensional wind field (e.g. strengths and/or positions of the monsoon trough, Coral Sea low, etc) and are an example of the increased uncertainty of trajectories in complex meteorological situations.

Conclusions

The volcanic ash from a reported aircraft encounter in March 2003, if reported correctly, most likely came from low level eruptions at Tavurvur, Rabaul, Papua New Guinea, after being advected to high levels during an active monsoon. In November 2002, an aircraft was significantly damaged by ash from an unknown source, and another aircraft flew through a part of the same cloud twelve hours later. The source of this cloud almost certainly was not local, and therefore originated from a major eruption elsewhere in the world. The most likely candidate source of the ash was El Reventador in Ecuador, but we are unable to prove this hypothesis to our satisfaction using either satellite or trajectory analysis. The volcanic clouds at the time of these encounters were not detectable by current satellite techniques.

Acknowledgements

We gratefully acknowledge the comments of Geoffrey Garden (Bureau of Meteorology) and two anonymous NOAA reviewers, and the participation of colleagues from the Toulouse, Darwin and Washington VAACs in analysis of these events. We thank Steve Albersheim (FAA, USA), Frank H. Wells (Guam Weather Forecast Office), Marianne Guffanti (US Geological Survey), the airlines who anonymously provided details of the November 2002 encounters, and the Rabaul Volcano Observatory and Air New Guinea for their provision of volcanic activity reports.

References

Casadevall, T. J., 1994. The 1989-1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations. J. Volc. Geoth. Res., ***62***, 301-16.

CMC, cited 2004, Atmospheric Transport Models for Environmental Emergencies. [Available online from http://www.msc-smc.ec.gc.ca/cmc_library/protected/PREVISIONS/e_8.pdf (user: librarian; password: Books8).]

Darwin Regional Specialised Meteorological Centre, 2003, Archived manual analyses.

Draxler, R. R. and G. D. Hess, 1998. An Overview of the Hysplit_4 Modeling System for trajectories, dispersion, and deposition. Aust. Met. Mag., ***47***, 295-308.

Draxler, R. R. and G. D. Rolph, cited 2003, HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website (http://www.arl.noaa.gov/ready/hysplit4.html). NOAA Air Resources Laboratory, Silver Spring, MD.

ICAO, cited 2004, International Civil Aviation Organization Handbook on the International Airways Volcano Watch (IAVW), 2nd edition. [Available online from http://www.icao.int/icao/en/anb/met/index.html.]

Rabaul Volcano Observatory, 2003, Volcano Information Bulletins.

Smithsonian Institution, cited 2004, Volcanic Activity Reports of the Global Volcanism Program, http://www.volcano.si.edu/gvp

Tupper, A., S. Carn, J. Davey, Y. Kamada, R. Potts, F. Prata, and M. Tokuno, 2004. An evaluation of volcanic cloud detection techniques during recent significant eruptions in the western 'Ring of Fire'. Remote Sens. Environ., ***91***, 27-46, doi:10.1016/j.rse.2004.02.004.

Tupper, A. C. and K. Kinoshita, 2003. Satellite, air and ground observations of volcanic clouds over islands of the Southwest Pacific. South Pacific Study, ***23***, 21-46.

SULFUROUS ODORS: A SIGNAL OF ENTRY INTO AN ASH PLUME—BUT PERHAPS LESS RELIABLE FOR ESCAPE

Richard Wunderman, Global Volcanism Program, Smithsonian Institution, Washington, D.C.

Although our understanding of odorous gases associated with volcanic ash plumes is incomplete, available reports indicate that during aircraft-ash encounters the pilots smelled sulfurous odors. Many people can smell the volcanic gases hydrogen sulfide (H_2S, "rotten egg") and sulfur dioxide (SO_2, "struck-match") at low concentrations—just a few parts per million (ppm). When subjects are exposed to sulfurous gases at slightly higher concentrations their smell receptors become saturated (undergoing 'olefactory fatigue'). Unless trained otherwise, pilots could arrive at the false sense that the gas is gone. Thus, pilots' sense of smell should reliably signal entry into (or proximity to) an ash plume; in contrast, once in a plume with significant regions above the saturation threshold, pilots' sense of smell could also mislead, providing a false sense of having emerged from the plume. Can such high concentrations occur? The few public records of aircraft-ash encounters suggest are inconclusive. Scientists have long known that large quantities of sulfurous gases escape during an eruption, but it is difficult to assess the gas concentrations of most ash plumes. Small droplets containing condensed sulfurous acids might also play a role. Thus, olefactory fatigue could plausibly present a very dangerous situation in the absence of other signs of entry into a plume (electrical discharges, clogged pitot tubes, etc.). Moreover, one could imagine the confusion induced by the perceived disappearance of the odor, as the aircraft penetrated into zones of higher or fluctuating H_2S concentrations. Pilots training might include brief exposure to low concentrations of sulfurous gases, with discussion of the strengths and limitations of the sense of smell, the range of observations that might confirm the presence of an ash cloud, and procedures leading to reliably escaping a plume. Scientists need to establish whether critical concentration thresholds are likely to be exceeded in eruptive plumes.

A GLOBAL PERSPECTIVE ON VOLCANOES AND ERUPTIONS

Richard Wunderman, Lee Siebert, James Luhr, Tom Simkin, Ed Venzke,
Smithsonian Institution, Washington, D.C. 20560 USA

Geologists have identified ~1500 volcanoes worldwide as probably active in the past 10,000 years. Many form conspicuous, lofty cones; others include depressions, fissures, and areas peppered with vents. Most of these volcanoes reside on land or protrude above water. An additional, much larger number remain unwatched at depth beneath the sea, but their eruptions seldom break the surface. Towards the poles in places like Iceland, eruptions under thick glacial ice can melt an opening, allowing energetic discharges directly into the atmosphere. Volcanoes often occur in linear belts or chains; those along the Pacific Rim tend to erupt explosively. Many Asian air routes pass portions of Indonesia, the Philippines, and Japan, countries collectively home to over one-third of the known active volcanoes. Earth's active volcanoes include ~10-15 erupting (discharging solid material) nearly continually. At any one time, these are joined by several others, often those that have erupted in the recent past. During each year of the 1990s, ~50-60 volcanoes erupted. Across the spectrum of explosive eruptions, smaller eruptions predominate. Many noteworthy eruptions started suddenly (over one-third reached climax within the first day; one-fifth in the first hour); however, in noteworthy cases years of milder eruptions preceded a climactic one. Such factors as the erupted material's volume, discharge rate, viscosity, and volatile content influence the eruption's size, character, and ash column height. No one phenomenon spawns large ash clouds. It is often difficult to gauge the ultimate size of an eruption at the onset. Although a growing ash column would hopefully trigger an immediate report to a VAAC, factors may thwart this effort (e.g., bad weather, darkness, limited infrastructure, damage, lack of diagnostic satellite coverage), thus halting clear, timely assessments. Half the world's 1500 active volcanoes reside in developing nations; many of the world's volcanoes lack dedicated monitoring instruments.

PROMISE AND PITFALLS IN ERUPTION FORECASTING

Chris Newhall, US Geological Survey
Box 351310, Univ. of Washington, Seattle, WA 98195 cnewhall@usgs.gov

"The problem with weather forecasting is that it's right too often for us to ignore it and wrong too often for us to rely on it." (Patrick Young) The same holds true for eruption forecasting.

Weather forecasting, though not perfect, has improved greatly in recent decades. Volumes of data from ground, air, and space based sensors and sophisticated numerical models complement older methods. Daily trials in every forecast area help to refine the models. Hurricane (typhoon) and tornado forecasting carry greater uncertainties, limited by fewer data and opportunities for testing forecasts.

Volcanic eruption forecasting has also improved in recent decades. Though uncertainties remain high, probably even higher than uncertainties in hurricane and tornado forecasts, dozens of successful eruption forecasts have been made since 1980 that saved tens of thousands of lives. True, volcanologists are handicapped by being limited to proxy or indirect measurements at the earth's surface rather than having direct measurements of the rising magma. True, only a few trials per year allow us to refine forecast methods. True, numerical forecast models are a dream of the future. However, today's and certainly tomorrow's eruption forecasts are important wake-up calls for plume detection and the variety of other ash-hazard mitigation measures described elsewhere in this volume.

In this paper I'll say a few words about why volcanoes erupt, the basis for eruption forecasts, the relative reliability of various types of eruption forecasts, and some potential pitfalls of which you should be aware.

First, what are eruptions? Eruptions are ejections of molten or solid rock, as flows or fragments, into the air or onto the earth's surface. In most cases the starting material of eruptions is molten rock (magma) that has risen from many miles depth, through the crust of the earth. If magma and its hot gases heat groundwater in the surrounding crust to sufficiently high temperatures and pressures, natural steam explosions will pulverize the older crust around the magma and cause that already solid rock to erupt as well. Many eruptions begin with such steam ("phreatic") explosions and then become "magmatic" if magma itself reaches the surface.

Phreatic explosions generate ash by pulverizing the rock through which they explode. Magmatic explosions generate ash by fragmenting the magma itself. Gases that are dissolved comfortably in magma at depth exsolve (i.e., un-dissolve) near the earth's surface, pressurize, and blow the magma into tiny sand- and silt-size fragments that we know as volcanic ash *(fig. 1)*. Aside from minor differences in composition and shape, phreatic ash and magmatic ash are the same, i.e., tiny rock fragments, lofted into the air in thermals generated by the heat of exploding steam and magma. Small explosions may loft ash a few hundred or a few thousand feet above a vent; giant eruptions like that of Mount St. Helens in 1980 or Pinatubo in 1991 loft ash 60,000-100,000 feet. A curtain of ash then rains out of an eruption plume, back down through all elevations.

Ideally, forecasts of eruptions would specify their location, onset date, explosive magnitude, and duration or ending date. The most important for aviation safety are location, onset, and explosive magnitude (eruption column height, ash concentrations), joined soon after by ash trajectories. Current forecasts of duration or ending date are too imprecise to be helpful to the aviation community.

To forecast the location of volcanic eruptions is relatively simple if there is an adequate network of monitoring instruments. Nearly all eruptions are from preexisting volcanoes, and most though not all volcanoes that have erupted in recent history are monitored well enough to detect signs that might lead to an eruption (see Ewert and Newhall, this volume). As magma pushes its way toward the surface, it breaks the crust to make way. This process is recorded as tiny earthquakes by nearby seismometers. It also causes the earth's surface to bow slightly upward, detectable by sensitive surveying instruments including high-precision GPS stations. As gases that are dissolved in the magma at depth begin to exsolve, some leak out and can be detected by a variety of "gas sniffers"

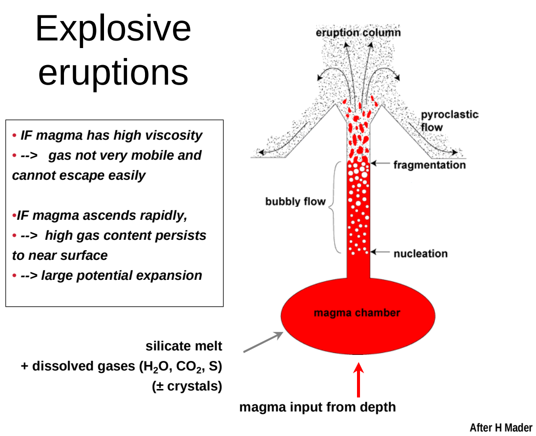


Fig. 1. From Magma to Ash. Molten rock that contains dissolved gases (mostly, CO2 and H2O) rises buoyantly through a volcanic conduit. As it rises, confining pressure decreases (as when the cap of a carbonated drink is opened), bubbles form, expand, and eventually turn the top of the magma column into a magma foam. Rapid depressurization causes the foam to explode and pulverize tiny minerals and quenched (glass) bubble walls into volcanic ash. Heat from the hot ash causes the cloud to rise like a strong thermal.

at the surface. Nearly always, we know which monitored volcanoes are restless and COULD erupt.

To forecast the onset of an eruption is more difficult but sometimes possible. Some volcanoes exhibit exponentially escalating unrest and the onset of an eruption can be forecast to within a few hours or days (small eruptions of Mount St. Helens after the famous May 18 1980 events, a moderate-size initial eruption of Redoubt in December 1989, and progressively larger and eventually giant Pinatubo eruptions of June 1991). Sometimes, volcanoes also show a sudden, distinctive cessation of seismicity or gas emission, or a sudden tilting of ground very near a vent, that are extra signs that an eruption is imminent. Fortunately, volcanoes that have been quiet for many years and that are the most dangerous are usually the easiest at which to forecast eruption onset. Unfortunately, volcanoes that erupt frequently can erupt again with little notice, and volcanoes that have already been restless for an extended period can also erupt with little further notice (e.g., Mount St. Helens, May 18 1980).

Forecasts of the explosive magnitude of an eruption are fraught with uncertainty. Two approaches are usually combined. The first is to review prior eruptions of that volcano and to assume that future eruptions will be of similar magnitude(s). Because many volcanoes erupt with a wide range of explosive magnitudes, we may have only statistical odds of one explosive magnitude vs. another. These odds can be refined slightly by factoring in the number of years the volcano has been quiet and the degree to which long quiescence at that volcano makes subsequent eruptions more explosive. Not all volcanoes behave alike, though, and some volcanoes even change their general eruptive style from decade to decade or century to century.

A second way to forecast explosive magnitude looks for telltale indications in precursory unrest. Some indicators include the speed with which magma is rising (faster speed correlates with higher eventual explosivity), recent gas emissions (to judge whether the new magma remains gas-charged or has already lost its fizz and explosive potential), and, perhaps, the apparent volume of rising magma as indicated by bowing up of the ground surface. Truth be told, though, we have had very few opportunities to test the consistency and thus reliability of these indicators.

At best, explosive magnitude can be forecast to the nearest order of magnitude of how much magma will be fragmented into ash (e.g., 0.01, 0.1, 1, 10, or 100 cubic miles of magma) and the nearest 20,000 or 30,000 feet of eruption column height. Many volcanologists use a shorthand index of explosive magnitude, called the Volcanic Explosivity Index or VEI (Newhall and Self, 1982). Successively higher VEI values refer to roughly one order of magnitude greater ash volume and successively higher maximum column heights. Of the 60 or so non-submarine volcanoes around the world that are active each year (Wunderman and others, this volume), most are producing VEI 2 eruptions from which ash rises between 3,000 and about 20,000 feet. VEI 2 eruptions generally don't threaten commercial jet traffic at cruise altitude but can certainly cause problems for low-flying aircraft, planes on ascent or descent, and for airports themselves. VEI 3 and higher eruptions, of which there are typically several per year worldwide, generally do send ash to cruise altitudes and are serious aviation hazards. If a volcano is expected to erupt and is known to produce VEI 3 and larger eruptions, it would be prudent to assume that the impending eruption could be that large until proven otherwise. Satellite imagery combined with a measure of seismic tremor associated with an eruption (McNutt, 1994) can often give an estimate of column height within an hour after eruption onset, supplanting whatever was forecast, but be aware that eruptions often increase or decrease in VEI from hour to hour and day to day. In more than 90 % of eruptions, the climax (maximum explosive magnitude) is reached in the first 24 hours (Simkin and Siebert, 1984), but tall eruption columns can also pop up later in eruptions!

What determines the ultimate explosive magnitude of an eruption? In a word, gas! More precisely, explosivity is controlled by how much gas was originally contained in the magma and how much of that has bled off before the magma reached near the earth's surface. The analogy between magmas and soda pop is actually quite good. Gas-charged soda pop will explode if opened suddenly, but if opened slowly its gas will just bleed off. Without trying here to quantify these parameters, we can generalize that if magma is relatively fluid and/or is rising slowly, most of its gas may be able to bleed off before that magma nears the surface. Its resulting explosive potential will be low. This is true of fluid Hawaiian magmas and of very viscous magmas beneath some lava domes. In contrast, if gas-rich magma is too viscous to let gases escape easily and if it rises fast enough that the gases can't bleed off before nearing the surface, the explosive potential will be high. This is characteristic of most volcanoes of the Circum-Pacific "Ring of Fire" and most volcanoes in Italy, Greece, and Iceland. Some volcanoes like Soufrière Hills on Montserrat exhibit both behaviors -- non-explosive dome growth when the supply and ascent rate of magma is slow and explosive eruptions when it is high. At a few volcanoes like Stromboli in Italy, the ascent rate is just right to maintain constant small explosions -- high enough to not lose all of its gas enroute to the surface yet low enough to lose enough gas to keep explosions small.

I should add words of caution about “non-explosive” dome building eruptions and secondary explosions. Even though lava domes may grow without explosions, those that are actively growing, especially if on steep slopes, tend to collapse and produce what we call dome-collapse pyroclastic flows. These are hot avalanches and have significant dust (ash) clouds. Because the lava is hot, these winnowed ash clouds can rise in thermals to thousands, even several tens of thousands of feet, i.e., up into cruise altitudes. Dome collapse and associated ash clouds are very difficult to forecast and, at this point, the best that can be done for warning of these is near-real time detection and tracking, alerted by the seismicity of the collapse. “Secondary explosions” occur where pyroclastic flow deposits are thick and remain hot for months or even years and groundwater seeps into the deposit, is heated, and flashes into steam. Most such events are too small for aviators to worry about, e.g., lofting ash only a few hundred feet at Redoubt Volcano in 1990, but the largest secondary explosions from thick deposits on the slopes of Mount Pinatubo occurred months after the main eruption, with only rainfall as warning, and sent ash 80,000 feet into the air and damaged at least one commercial jet.

Conventional wisdom is that after an eruption, magma that remains in the volcano's conduit cools and solidifies ("freezes"), forming a plug that will have to be cracked or blasted out before the volcano can erupt again. Such "closed-vent" behavior is characterized by infrequent, often explosive eruptions. However, many volcanoes exhibit "open-vent" behavior in which magma in the conduit does not solidify between eruptions but, instead, churns in a kind of lava-lamp-like convection. Rising, gas-rich magma grows less and less dense as gas bubbles grow in it, eventually turning into a magma foam not far below the surface. Foams are permeable and most of the gas escapes, feeding persistent gas plumes from such volcanoes. The degassed foam collapses, becomes dense, and sinks back down through the fresh rising magma, driving the convection process. If the reservoir of gas-rich magma is large enough, this activity can persist and feed small eruptions for years or even decades, e.g., Stromboli, Italy and Yasour, Vanuatu. Some volcanologists think the same is occurring beneath other volcanoes that in recent years have produced a lot of gas and not much else, e.g., Popocatépetl in Mexico.

Closed-vent behavior makes eruptions relatively easy to forecast. Fresh magma working its way to the surface must break through the plug or surrounding rock, generating earthquakes and swelling of the ground. Gas leaks may or may not be detected at the surface. The most easily measured gas, sulfur dioxide, may be absorbed into and hidden in groundwater and thus not reach gas instruments on the surface. Fortunately, most VEI 3 and larger eruptions are going to follow closed-vent behavior and thus will give at least some warning of reawakening.

Open-vent behavior tends to bleed off the gas and thus reduce explosive potential. Thus, most eruptions during this behavior will be VEI 2 and smaller. However, be careful, because there are some cases in which either the convection speeds up (increasing explosive potential) or is temporarily stopped (trapping gas and thus also increasing explosive potential). Eruptions from volcanoes in open-vent behavior are generally difficult to forecast because there is virtually no plug to break through. Seismic and ground deformation precursors will be minimal.

Emission of CO_2, SO_2, and other volcanic gases may increase notably, but these don't indicate likely onset time very precisely. Ground deformation (e.g., tilt) measurements right on crater rims can warn of fresh-arriving slugs of magma and thus of explosions or dome collapse to follow within hours to a few days, but very few volcanoes have instruments close enough to their vents to detect such changes. So, in general, eruptions during open-vent behavior will be difficult to forecast. As an example, after the vent of Mount Spurr, Alaska, was opened in June 1992, a second eruption in August began without clear seismic precursors.

Throughout this paper I have been referring to eruption forecasts as if they are issued in a standard format. In reality, they are not. Three related formats illustrate.

One format of eruption forecasts explicitly states one or several progressively narrower time windows, e.g., 2 weeks, 1 day, etc., within which an eruption is expected to begin (e.g., Swanson and others, 1983; Punongbayan and others, 1996). Very few forecasts are this explicit, although one successful one from Pinatubo (1991) was instrumental in saving many lives. Equally few specify the exact magnitude of an impending eruption; more often, forecasts give a range of likely magnitudes.

A second format estimates relative and absolute probabilities of all likely outcomes, usually in the form of a probability tree that applies to a specified timeframe (Aspinall and others, 2002; Newhall and Hoblitt, 2002; Marzocchi and others, *in press*).

The third, most common format (with many variants) is a color or numerical code that is shorthand for the intensity of seismic and other unrest, level of volcanologists' concern, OR proximity of the onset of an eruption. Most such codes have 3-6 levels of which the lowest is background activity and the highest is a dangerous explosive eruption in progress. Steps between these two extremes represent increasing hazard but may not specifically "forecast" an eruption. Rather, they represent DECREASING ASSURANCE that an eruption will NOT occur. Although this might seem like a fine distinction I think it is an important one, as there are still many instances in which we know that present unrest COULD presage an eruption but could equally well stop without eruption. Volcanologists try very hard to avoid false alarms, i.e., to not "cry wolf," and color codes that can be raised or lowered are more flexible than forecasts of when a volcano WILL erupt. The International Civil Aviation Organization (ICAO, 2004) describes its color-code scheme, and task groups within the US Geological Survey (Gardner, *this volume)* and the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) are exploring whether wider standardization is possible.

The three formats of forecasts are broadly related. Yellow or similar codes indicate elevated but not intense unrest, and generally do not imply that an eruption will occur. Indeed, more often than not, yellow unrest will stop without an eruption. Many instances of orange or similar unrest typically are followed by an eruption within days to weeks, so there is an implication, tacit or explicit, that an eruption could and in some cases probably will begin within that timeframe. The highest level of alert, red or similar, may indicate that an eruption is likely within hours or has already begun. Please note use of the terms "could" and "likely," rather than "will occur." Observatories may use different formats for different audiences or to emphasize time of onset, type of eruption, or simplicity and possible relation to response plans, respectively.

Weather forecasters track how often their forecasts are correct or incorrect. Can we do the same for eruption forecasts? Of 224 moderate-size explosions during a 1987-1991 test period at Sakurajima Volcano, 162 were successfully forecast and 62 were missed (Kamo and others, 1994). An automated algorithm produced only a few false alarms. Twenty (20) post-climactic, mostly dome-building eruptions of Mount St. Helens were successfully forecast between 1980 and 1986 without false alarms or misses (Swanson and others, 1983; Swanson, 1990).

Color-code or numerical alerts do not specifically forecast dates of eruptions but, at higher levels, usually imply a timeframe of weeks or less. Within the past 20 years but not including Sakurajima and Mount St. Helens events, 60 orange, red, or similar alerts were followed by eruptions within weeks or less, 8 orange or red alerts were “false alarms,” i.e., NOT followed shortly by eruptions, and 48 eruptions were missed. Many in the last group were anticipated with a yellow alert but not with a more urgent orange or red alert.

Of roughly 150 VEI $\geq$3 eruptions that occurred from mid-1984 to mid-2004 – eruptions that are always of concern to aviation -- about 30 were successfully forecast with an orange or red alert and 50-100 were loosely anticipated by a yellow or equivalent alert, but at least several tens were not anticipated at all.

The last group occurred where volcanoes were not monitored or where the observatory failed to issue an alert. These unforetold VEI ≥3 eruptions are worrisome and unacceptable, and their source volcanoes are slowly being brought under monitoring surveillance.

Eruption forecasting is improving slowly but surely. Part of the improvement comes from expanded and better monitoring and a growing body of experience about what precursors to expect. Another part comes from improving conceptual models of how magma rise and degas, or, if not, explode. Clearly, not all eruptions are being forecast yet, but are the forecasts that are issued reliable? Since volcano observatories are careful to not issue false alarms, most orange, red, or equivalent warnings are likely to be correct and can help you to be ready for ash as soon as an explosive eruption does begin.

References:

Aspinall WP, Loughlin SC, Michael FV, Miller AD, Norton GE, Rowley KC, Sparks RSJ, Young SR, 2002, The Montserrat Volcano Observatory: its evolution, organization, role, and activities, *in* Druitt TH, Kokelaar BP, eds., The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. London, Geol Soc London, p. 71-91

Ewert JW, Newhall CG, *this volume,* Status of volcano monitoring worldwide

Gardner CA, Guffanti MC, Heliker CC, Hill DP, Lowenstern JB, Murray TL, *this volume*, A proposed alert-level notification scheme for aviation and ground-based hazards at U.S. volcanoes.

ICAO (International Civil Aviation Organisation), 2004, Handbook on the International Airways Volcano Watch, ICAO Document 9766-AN/968, http://www.icao.int/icaonet/dcs/9766_2_en.pdf

Kamo K, Ishihara K, Tahira M, 1994, Infrasonic and seismic detection of explosive eruptions at Sakurajima Volcano, Japan, and the PEGASUS-VE early-warning system, *in* Casadevall TC, ed., Volcanic Ash and Aviation Safety, Proceedings of the First Intl Symposium on Volcanic Ash and Aviation Safety, US Geological Survey Bull 2047, p. 357-365

Linde AT, Sacks S, 2000, Real time predictions of imminent volcanic activity using borehole deformation data (abstr.), EOS, v. 81:48, p. F1253

Marzocchi W, Sandri L, Gasparini P, Newhall C, Boschi E, in press, Quantifying probabilities of volcanic events: the example of volcanic hazard at Mt. Vesuvius. J Geophys Res

McNutt SR, 1994, Volcanic tremor amplitude correlated with volcano explosivity and its potential in determining ash hazards to aviation, *in* Casadevall TC, *op. cit.,* p. 377-385

Newhall CG, 2000, Volcano Warnings. In Sigurdsson H, Houghton, B, McNutt, SR, Rymer H, and Stix J, eds., Encyclopedia of Volcanoes, Academic Press, San Diego, p. 1185-1197

Newhall CG, Hoblitt RP, 2002, Constructing event trees for volcanic crises. Bull Volcanol, v. 64, p. 3-20

Newhall CG, Self S, 1982, The Volcanic Explosivity Index (VEI): an estimate of explosive magnitude for historical volcanism. Jour Geophysical Research, v. 87, p. 1231-1238

Punongbayan RS, Bautista MLP, Harlow DH, Newhall CG, Hoblitt RP, 1996, Pre-eruption hazard assessments and warnings, *in* Newhall CG, Punongbayan RS, eds., Fire and Mud, PHIVOLCS, Quezon City and Univ. of Washington Press, Seattle, p. 67-85

Scott B, *this volume*, Volcanic alert systems: an overview of their form and function.

Simkin T, Siebert L, 1984, Explosive eruptions in space and time, *in* Explosive Volcanism: Inception, Evolution, and Hazards, National Academy Press, p. 110-121

Simkin T, Siebert L, 1994, Volcanoes of the World, 2nd ed., Geoscience Press, Tucson, 349 p.

Swanson DA, Casadevall TJ, Dzurisin D, Malone SD, Newhall CG, and Weaver CS, 1983, Predicting eruptions at Mount St. Helens, June 1980 through December 1982: Science, v. 221, p. 1369-1376

Swanson DA, 1990, A decade of dome growth at Mount St. Helens, 1980-90: Geoscience Canada, v. 17, p. 154-157.

Wunderman R, Siebert L, Luhr J, Simkin T, Venzke E, *this volume*, A global perspective on volcanoes and eruptions

STATUS AND CHALLENGES OF VOLCANO MONITORING WORLDWIDE

John W. Ewert, U.S. Geological Survey, Vancouver, WA 98683, USA (jwewert@usgs.gov)
Christopher G. Newhall, U.S. Geological Survey, Seattle, WA 98195 USA

Introduction

Volcanoes exhibit precursory activity that may occur hours to years before an eruption and thus allow an eruption forecast. Accurate forecasts and real-time detection of volcanic eruptions are essential to keep pilots, passengers, and planes out of ash clouds. Timely eruption reporting by volcano observatories, beginning with information about the premonitory build-up phase, allows more time for flight planning and improves response time of satellite-based ash-cloud detection. Here we describe in general terms the most commonly used volcano-monitoring techniques, and report where obvious gaps in monitoring exist, particularly with respect to aviation safety.

Most volcano-monitoring networks and observatory operations have been designed to mitigate hazards to people on the ground rather than in the air. Consequently, most volcano observatories and hence most monitored volcanoes are found where the risks to people on the ground are greatest. Notable exceptions are the monitoring of Alaskan volcanoes by the Alaska Volcano Observatory (AVO) (Murray, this volume), Kamchatkan and Kurile volcanoes by KVERT (Gordeev and others, this volume), and Anatahan volcano by the U.S. Geological Survey and the Commonwealth of the Northern Mariana Islands. At the present time, volcano-monitoring operations are conducted by about 60 institutions globally. However, of the more than 1500 active volcanoes in the world, less than a quarter have any kind of real-time monitoring, and only a few (numbering less than 50) would be considered adequately monitored for both hazard and research purposes.

Why is ground-based monitoring critical?

A recent eruption at Anatahan volcano in the Commonwealth of the Northern Mariana Islands (CNMI) in 2003, gives an example of the time lag between eruption onset and ash cloud detection that can occur in a remote area if only remote sensing is employed. On 10 June 2003, approximately five hours elapsed from the unexpected onset of eruptive activity at Anatahan and subsequent ash plume to 11 km, to the issuance of the first Significant Meteorological Advisory (SIGMET) and Volcanic Ash Advisory by the Guam Meteorological Watch Office (MWO) and Washington-Volcanic Ash Advisory Center (W-VAAC), respectively (Guffanti and others, in press). Arguably, had Anatahan been seismically monitored in real time before the start of eruptive activity, this delay likely could have been much shorter and dissemination of ash-hazard information to the aviation sector could have been more rapid. Luckily, no damaging encounters appear to have occurred.

Subsequently, real-time seismic monitoring was installed on Anatahan by the U.S. Geological Survey and the CNMI Emergency Management Office, and in March and April of 2004 notices of new eruptive activity at Anatahan were passed to the W-VAAC and Guam MWO within minutes of seismic detection (R.White, written communication).

When ground-based monitoring is in operation at a volcano, and communication links are in place between the volcano observatory and the regional MWO and VAAC, notices of heightened eruption potential and notification of eruption onset are typically more rapid than if no ground-based monitoring is in place. The eruption of remote Bezymianny Volcano, Kamchatka in June, 2004, illustrates this case. On June 16, 2004, based on increasing seismicity, the Kamchatkan Volcanic Eruption Response Team (KVERT) raised the concern color code for Bezymianny from yellow to orange (indicating an eruption is possible within a few days and may occur with little or no warning). On June 18, 1940 UTC an explosive eruption was detected seismically, and an ash column to 8-10 km was observed by a remotely operated video camera at 2040 UTC. KVERT issued an eruption notification at 2055 UTC, a little more than one hour after the eruption began. In contrast, owing to a lack of satellite coverage, the ash column was first spotted in satellite imagery approximately 4 hours after the seismically-determined eruption onset. (D. Schneider, personal communication).

Although the eruption notification was not made within five minutes of the eruption onset as airline representatives to the 2nd International Conference on Volcanic Ash and Aviation Safety suggested as a goal, the notification was much more timely than would have been possible with only satellite remote sensing owing to the ground-based monitoring by the KVERT. No damaging encounters were reported from this eruption.

Real-time volcano monitoring

An adequately monitored volcano has continuous multiparametric (a combination of seismic, deformation, geochemical, etc.) data streams that are available in real-time to an observatory facility. More commonly in the world today, if a volcano has any monitoring at all, it is by a single seismometer, standalone or within a regional network.

For the purposes of this discussion, we classify volcano monitoring techniques into two general classes; those useful for eruption forecasting and prediction, and those useful for eruption detection. We limit our discussion to those techniques and instruments that can be used in real time or near-real time, generally in a telemetered configuration. A combination of monitoring techniques and sensor types yields the most reliable results.

Eruption forecasting tools

Seismic monitoring is the mainstay of volcano monitoring operations around the world. The typical telemetered seismic station used to monitor a volcano is a single (vertical) component , short-period type, data from which are sent via analog telemetry to a central recording site. This class of instrumentation has been employed to monitor volcanoes since the early 1970s, is robust even in marginal field conditions, and the technology is accessible in developing countries. To locate seismicity, a minimum of four telemetered instruments spread around the volcano is necessary. In many cases though, only one or two instruments may be deployed close enough to a volcano to reliably detect and track the subtle changes in seismicity prior to eruption. Fortunately, useful information about the status of a volcanic system can be gleaned from one or two stations if an experienced seismologist is on hand with appropriate data processing software (McNutt, 1996).

At well-monitored volcanoes, which number less than 50 worldwide, focused, small-aperture seismic networks are arrayed within a larger aperture regional network and may consist of a mix of single and three-component stations. Focused seismic monitoring techniques can be used to infer the presence of magma as a cause of seismicity, to track the ascent of magma and other fluids toward the surface, and to determine the onset of explosive eruptions.

Other monitoring techniques used to forecast and predict eruptions include methods to measure ground movement (deformation), gas emissions, and changes in thermal characteristics. Telemetered deformation instrumentation includes (in order of increasing sensitivity) Global Positioning System (GPS) installations, which measure surface displacement in three dimensions; tiltmeters, which measure changes in near-surface ground inclination; and strainmeters, which measure minute compressional or tensional changes in strain in boreholes that are 10s to 100s of meters deep. Monitoring ground movement by remote sensing over broad areas is sometimes possible with Interferometric Synthetic Aperture Radar (InSAR). The InSAR technique lends itself to tracking slow, long-term changes that may occur months to years ahead of an eruption. Together, these deformation-monitoring techniques can detect accumulation of magma beneath a volcano and the passage of magma toward the surface (Dvorak and Dzurisin, 1997).

Carbon dioxide, sulfur dioxide and hydrogen sulfide gas fluxes can be determined by flying monitoring instruments beneath and through the volcanic gas plume near the volcano. Sulfur dioxide flux can be measured from the ground in daylight hours and the data telemetered. Changes in concentrations of gas species in soil or fumaroles can also be measured, and the data telemetered to a central receiving site. Though not measurements of the total gas flux from the magmatic system, these types of data can be useful in tracking a volcanic system moving toward eruption. These techniques can confirm the presence of an active, degassing magma body and be used to infer rise of magma to shallow levels beneath a volcano and/or boiling and disappearance of groundwater in response to increased thermal flux (Symonds and others, 1994).

The extent and intensity of thermal emissions from a volcanic source can be measured in a variety of ways including satellite, aircraft, and ground based measurements. Used in conjunction with other monitoring techniques, thermal monitoring can aid in diagnosing whether a restless volcano is progressing toward eruption.

Eruption detection tools

Explosive volcanic eruptions can create a sudden ash hazard to aircraft, necessitating the shortest possible delay between eruption detection and issuance of warnings. While satellite remote sensing offers attractive eruption detection capabilities owing to broad areal coverage and multi-spectral capabilities, uncertainties in cloud cover, eruptive column height, orbital timing of Polar Operational Environmental Satellites and scan timing of Geostationary Operational Environmental Satellites make timely detection of eruptions from space a hit or miss proposition (Mouginis-Mark and Domergue-Schmidt, 2000). Ground-based instrumental monitoring, used in conjunction with satellite remote sensing offers a much higher probability of timely detection of eruption onsets.

As with eruption forecasting, seismic monitoring is the mainstay of eruption detection at volcano observatories. Other techniques used to detect and confirm eruptions include infrasonic and lightning detection, direct human observations, weather radars and video surveillance. A combination of different sensors coupled with effective communication between observers and the aviation community offer the best chance of timely ash cloud avoidance by aircraft.

Current Status

The number of monitored volcanoes has increased in most regions since the First International Symposium on Volcanic Ash and Aviation Safety in 1991 (Casadevall, 1994). About 270 of 470 explosive volcanoes that have erupted in past 2000 years have some form of continuous monitoring in place (fig. 1). The majority have only seismic monitoring—in many cases a single sensor. Well-monitored volcanoes tend to be in wealthy countries, exhibit some level of unrest, have erupted recently, and/or pose a clear hazard to densely populated areas. The corollary is that there are about 200 recently active volcanoes with explosive potential that remain unmonitored.

With the exception of the monitoring being carried out in the Aleutian Islands by the Alaska Volcano Observatory Murray, 2004), Kamchatkan and northern Kurile volcanoes by KVERT (Gordeev, this volume), and Anatahan volcano by the U.S. Geological Survey and the CNMI, aviation risk has not been the determining factor in where volcano networks are established. Usually the first priority of the institution doing the monitoring is the safety of people in hazardous areas nearby the volcano. Volcano observatories typically issue public notifications of conditions at monitored volcanoes, but again, the focus is typically on warnings about ground hazards.

Although more volcanoes are monitored now than ever before, there are still large portions of volcanic arcs that remain un-monitored, including volcanoes that seriously threaten airways (fig. 1). The most under-monitored volcanic areas include the Northern Mariana Islands, the Kurile Islands and parts of Kamchatka, the central and southern Andes of South America, and Africa. Not surprisingly, these are areas with the smallest ground populations at risk.

Challenges

More volcanoes along busy air routes are continuously monitored now than at the time of the first Volcanic Ash and Aviation Safety Conference 13 years ago. Encounters are fewer today than 13 years ago (Guffanti and others, this volume). Yet, encounters with ash still occur. We in the volcanological community are proud of our improvements in monitoring, but we're still not satisfied and the aviation community shouldn't be either. Here are several targets toward which volcanologists, meteorologists, air traffic control, pilots, and airlines *together* should strive:

1) Add monitoring as quickly as possible to the ~200 volcanoes that are potentially active and may pose a threat to aviation, but are still unmonitored. Can we halve that number of unmonitored within the next 10 years?

2) Strengthen monitoring at minimally-monitored volcanoes, so that no eruption will be missed.

3) Ensure that communications between volcano observatories and VAACs are fast, clear, and robust. One way to improve this communication and awareness of each others' work would be to increase near-real-time data sharing. Through the internet, volcano observatories could share graphic seismic data with their VAAC(s) and VAACs could share selected satellite imagery (e.g., GOES or GMS images) with their cooperating volcano observatories.

4) A clear and worthy target is to notify pilots of an ash-producing eruption within 5 minutes of its onset. Work together to ensure adequate funding for these efforts. Specifically, pilots, airline companies, and those in air traffic control need to help volcanologists and meteorologists tally (a) encounters and details of their consequences, (b) diversions (avoided encounters) and probable savings (c) the volume of air traffic in under-monitored volcanic areas. These data are sorely needed to justify measures and expenses that each of the abovementioned players would make in the overall mitigation effort.

References Cited

Casadevall, T.J., *ed*., 1994, Volcanic ash and aviation safety: Proceedings of the first international symposium on volcanic ash and aviation safety: U.S. Geological Survey Bulletin 2047, 449 p.

Casadevall, T.J., Thompson, T.B., and Fox, T., 1999, World map of volcanoes and principal aeronautical features: U.S. Geological Survey Geologic Investigations Series Map I-2700

Dvorak, J.J. and Dzurisin, D., 1997, Volcano Geodesy: The search for magma reservoirs and the formation of eruptive vents: Reviews of Geophysics, v. 35, no. 3, p. 343-384.

Gordeev, E., Senjukov, S., and Girina, O., 2004, Monitoring and reporting of Kamchatkan volcanic eruptions: this volume.

Guffanti, M.C., Casadevall, T.J., and Mayberry, G.C., Reducing Encounters of aircraft with volcanic-ash clouds: this volume

Guffanti, M.G., Ewert, J.W., Gallina, M., Bluth, G. S. J., and Swanson, G.L., in press, The Volcanic-Ash Hazard to Aviation During the 2003-2004 Eruption of Anatahan Volcano, Commonwealth of the Northern Mariana Islands: Journal of Volcanology and Geothermal Research.

McNutt, S.R., 1996, Seismic monitoring and eruption forecasting of volcanoes: a review of the state-of-the-art and case histories, *in* Scarpa, R. and Tilling, R.I., eds., Monitoring and mitigation of volcano hazards: New York, Springer-Verlag, p. 99-146.

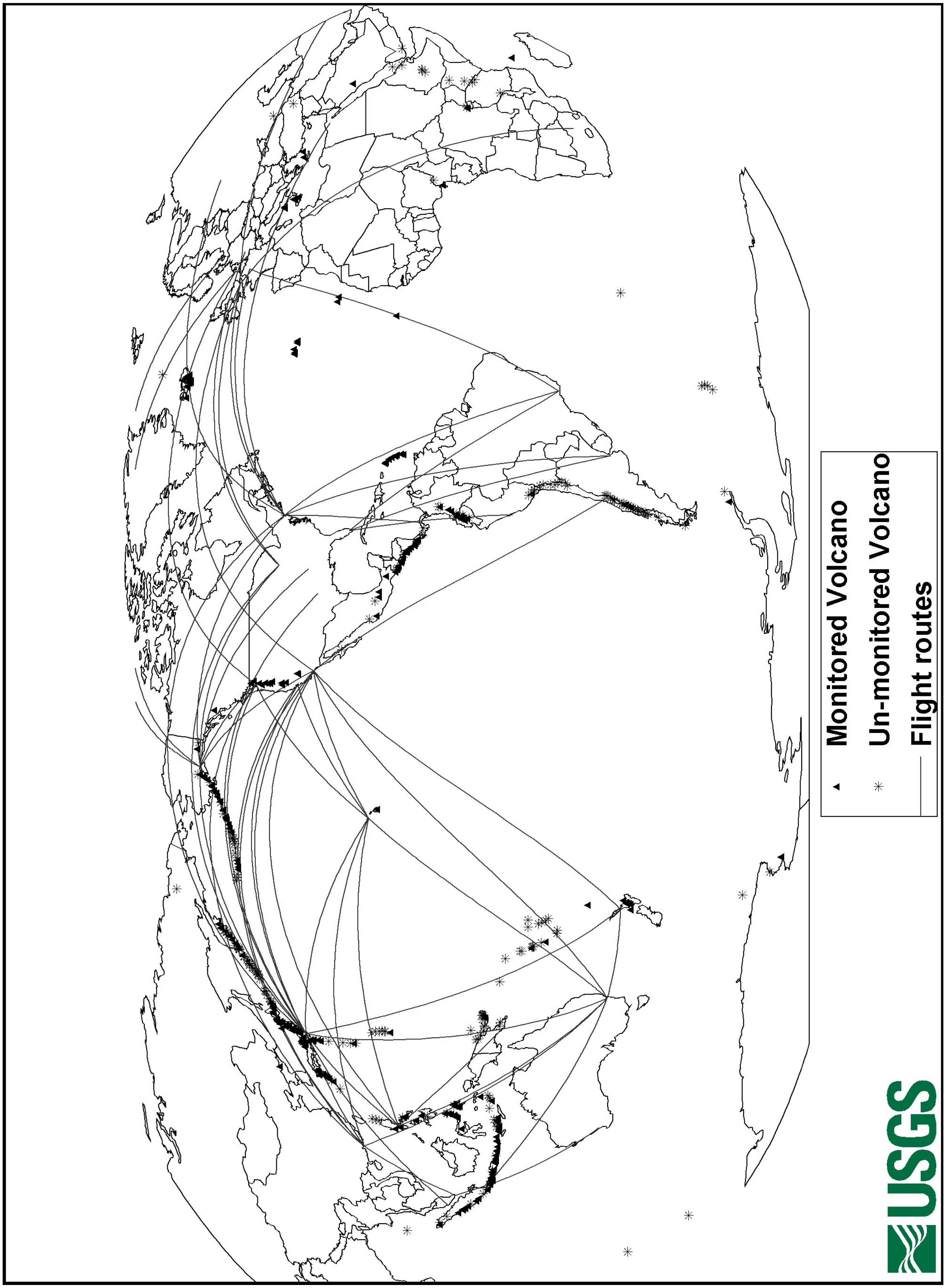
Mouginis-Mark, P.J., and Domergue-Schmidt, N., 2000, Acquisition of satellite data for volcano studies, *in* Mouginis-Mark, P.J., Crisp, J.A., and Fink, J.H., eds., Remote sensing of active volcanism: American Geophysical Union Geophysical Monograph 116, p.9-24.

Murray, T.L., 2004, The Alaska Volcano Observatory – Fifteen years of working to mitigate the risk to aviation from volcanic ash in the North Pacific: this volume.

Siebert, L., and Simkin, T., 2002-, Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and their Eruptions. Smithsonian Institution, Global Volcanism Program Digital Information Series, GVP-3, (http://www.volcano.si.edu/gvp/world/).

Symonds, R.B., Rose, W.I., Bluth, G.J.S., and Gerlach, T.M., 1994, Volcanic-gas studies: Methods, results, and applications, *in* Carroll, M.R. and Holloway, J.R. eds., Volatiles in Magmas: Mineralogical Society of America Reviews in Mineralogy, v. 30, p. 1-66.

Figure 1. Map showing 468 volcanoes that have erupted explosively in the last 2000 years. Monitored volcanoes indicated by solid triangles. Un-monitored volcanoes indicated by open circles. Volcano data from Siebert and Simkin, 2002-. Flight routes from Casadevall and others, 1999. Monitoring status compiled by the authors.


Monitored Volcano
Un-monitored Volcano
Flight routes

VOLCANIC ALERT SYSTEMS: AN OVERVIEW OF THEIR FORM AND FUNCTION

Bradley Scott, Institute of Geological and Nuclear Sciences, Wairakei, New Zealand

Volcanic activity world wide is monitored by over 60 Volcano Observatories. Individual volcano observatories can be responsible for anywhere from one to over 40 volcanoes. They are typically set up to advise national, regional or local governments, emergency responding agencies, industry and the population. This advice is usually communicated by 'volcano alert bulletins' and 'volcano alert levels'. A wide variety of needs are catered for in these systems. Two basic styles of volcano alert/warning systems have developed which relate to the status of a volcano, i.e. is it frequently in eruption or is it reawakening? Systems dealing with frequently active volcanoes have steps in them that are typically linked to the 'current' status of the volcanic activity, especially ongoing eruptive activity. They can carry any element of prediction, forecasting or warning and some indication of the degree of risk that the public are placed in while undertaking normal (non-restricted) activity on or about the volcano. In contrast, systems based on expected activity (reawakening) are often based on time-windows to the next expected level of unrest or the commencement of eruptive activity. The window durations are typically years, months, days or hours. The structure and responses to the alert systems vary between countries, resulting in a lack of international uniformity in our alert-warning systems, however this does not undermine the important function they achieve.

EXPLOSIVE ERUPTIONS OF ETNA VOLCANO SERIOUSLY THREATEN AVIATION SAFETY IN THE CENTRAL MEDITERRANEAN REGION

Mauro Coltelli and Paola Del Carlo

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Piazza Roma 2, 95123, Catania, Italy

Etna is a basaltic volcano located in eastern Sicily (Italy). Although it is worldwide known for lava flow eruptions that often threat the populated areas on its slopes, in the last decades explosive eruptions represent its more frequent activity either at summit craters or along fissures opened on its flanks, making Etna volcano a serious source of risk for aviation in central Mediterranean region (Fig. 1).
The frequency of Etna's eruptive phenomena in the last four centuries has increased, and particularly the explosive eruptions since 70's years (Branca and Del Carlo, 2004a). From 1979, we surveyed a large number of violent explosive events (Fig. 2) produced by summit craters, including more than 150 lava fountain episodes, characterized by: i) eruptive columns from 2 to 15 km high above the vent, ii) tephra volumes ranging from 10^4 to 10^7 m^3 and iii) magnitude from violent strombolian to subplinian. They often produced tephra fallout over eastern Sicily and the city of Catania.

Fig. 1: 2001 eruption plume of Etna in the Mediterranean Sea (NOAA courtesy).

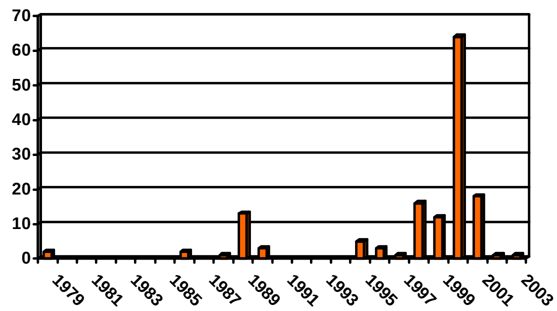


Fig. 2: Frequency of Etna's explosive eruptions occurred in the last 25 years.

At summit craters the prolonged explosive activity is generally weaker and produces limited dispersed tephra fallout, whereas violent strombolian and subplinian types episodes from summit craters are short-lived eruptions (from less than one hour to few hours) that produce widely dispersed deposits up to a few hundred km from the volcano. Due to the small volume of magma erupted they are not able to produce serious damages to the infrastructures also close to the volcano but they produce or induce several collateral damages mainly to the human health (lung ingestion of very small particles), to agriculture (lost of harvests), to the aviation (in-flight encounters with the drifting ash cloud and airport's runway contaminated with ash) and to the surface mobility (slippery roads due to a continuous ash mantle). These events are often repeated in a short time as in September 1989, when 14 episodes occurred during 16 days; in 1990 when other five episodes occurred; between November 1995 and June 1996 when ten strong fire fountain episodes were produced by North East Crater; during 1997 with other 14 episodes mainly from South East Crater; in 1998-9 when 4 episodes occurred, and finally the extraordinary activity of 2000 when 64 episodes occurred during five months causing the first serious problems to the population of eastern Sicily for the damages to aviation, to agricultures, and to roads and villages around Etna covered by an ash-mantle and almost daily cleared.

During this period, the most relevant air accident occurred on April 2000 when a commercial airplane (Airbus 320) departing from Catania airport encountered Etna's ash cloud damaging cockpit windshields.

During the last flank eruptions, occurred in 2001 and 2002-03, an exceptional and prolonged explosive activity originated from vents opened on the upper slopes of Etna was observed for the first time in the last century (INGV Research Staff, 2001; Andronico et al., 2004). Lava fountaining activity formed an ash plume 1-3 km high above the 2800 m vent (Fig. 3), causing a continuous tephra fallout for almost two months during the 2002-03 eruption.

Fig. 3: 2002-03 eruption ash plume dispersed eastward from the 2800 m vent in the S slope of Etna (Photo UFVG-INGV Sezione di Catania).

Copious lapilli and ash covered the volcano slopes and fine particles reached Rome and central Italy, western cost of Greece at and the northern coast of Libya. Because the effects of this *unusual* flank activity have been very serious on both health and economy, particularly for the respiratory diseases widely reported, and for the frequent disruption of the flight operations at Catania and Reggio Calabria airports, the explosive activity of Etna has started to draw the attention of local administrators and national politicians (Fig. 4).

Fig. 4: 2002-03 eruption plume and ash fall on Catania airport (Photo UFVG-INGV Sezione di Catania).

The critical revision of the historical reports from the last four centuries (Branca and Del Carlo, 2004b) shows that eruptions characterised by long-lasting explosive activity, such as the 2001 and 2002-03, are not so unusual. The report by abbot Recupero (1985) describes a copious tephra fallout of 4 kg per square meter in Catania in about ten days during the La Montagnola eruption in 1763, whereas during the 2002-03 eruption, we measured 2.5 kg per square meter in two days. In the 19th century, the occurrence of this type of eruption is more frequent. Eruptions occurred in 1811, 1852, 1886 and 1892 caused abundant ash fallout in the distal areas of the volcano. Therefore, the eruptive behaviour of Etna during the 2001 and 2002-03 eruptions is not a frequent phenomenon, yet at the same time it does not represent any anomaly in the eruptive history over the past centuries.

The thick volcaniclastic successions, that blanket the eastern slope of the Etna edifice, record a history of important explosive activity in Late Pleistocene and Holocene times characterised by plinian, phreatoplinian and subplinian central eruptions and violent strombolian lateral eruptions (Coltelli et al., 1998; 2000; Del Carlo et al., 2004).

The discovery of these explosive eruptions raises important issues for hazard assessment of basaltic volcanoes in almost persistent activity such as Etna, indicating that even a volcano, commonly considered non-hazardous for humans, can become very dangerous for aviation safety.

In summary, Etna's explosive eruptions observed and quantitatively described, historically reported and stratigraphically studied, represent a severe threat for aviation and economy of Sicily.

INGV staff in Catania, is in charged of the monitoring of the eruptive activity of Sicilian volcanoes, in response to this source of hazard, up to a few years ago completely ignored. It worked with Catania International Airport Direction, Italian Agency for Civil Aviation (ENAC), Meteorological Office of Italian Air Force and Italian National Civil Protection for warnings continuously the aviation authorities about the incidence of ash clouds on Sicilian airspace and the ash fallout on Catania airport depending on the intensity of the eruptive plume and the wind direction. With this aim, INGV is organizing an articulate strategy for studying in depth these eruptions, for setting an instrumental network to observe ash-cloud formation and developing, and finally for forecasting by mean of simulating computer models the ash dispersion in atmosphere and its fallout on the ground.

The lesson learned during the 2001 and 2002-03 crises was used to improve our volcanic ash cloud monitoring system, and transferred to ENAC for editing an official procedure for air-traffic and airport operations management in case of future crises at Etna, and in any case, to have a broad applicability worldwide.

References

Andronico D, Branca S, Calvari S, Burton MR, Caltabiano T, Corsaro RA, Del Carlo P, Garfì G, Lodato L, Miraglia L, Muré F, Neri M, Pecora E, Pompilio M, Salerno G, Spampinato L (2004) A multi-disciplinary study of the 2002-03 Etna eruption: insights for a complex plumbing system. Bull Volcanol, DOI: 10.1007/s00445-004-0372-8

Branca S, Del Carlo P (2004a) Eruptions of Mt Etna during the past 3,200 Years: a revised compilation integrating the historical and stratigraphic records. In: Bonaccorso A, Calvari S, Coltelli M, Del Negro C, Falsaperla S (eds) Mt Etna Volcano Laboratory. AGU Geophysical monograph series 143, 1-27

Branca S, Del Carlo P (2004b) Types of eruptions of Etna Volcano AD 1670-2003: Implications for short-term eruptive behavior. Bull. Volcanol., in press

Coltelli M, Del Carlo P, Vezzoli L (1998) The discovery of a Plinian basaltic eruption of Roman age at Etna volcano (Italy). Geology, 26:1095-1098

Coltelli M, Del Carlo P, Vezzoli L (2000) Stratigraphic constrains for explosive activity for the past 100 ka at Etna volcano, Italy. Int. J. Earth Sciences, 89:665-677

Del Carlo P, Vezzoli L, Coltelli M (2004) Last 100 ka tephrostratigraphic record of Mount Etna. In: Bonaccorso A, Calvari S, Coltelli M, Del Negro C, Falsaperla S (eds) Mt Etna: Volcano Laboratory. AGU Geophysical monograph series 143, 77-89

INGV Research Staff Sezione di Catania (2001) Multidisciplinary Approach Yields Insight into Mt Etna 2001 Eruption. EOS Transactions, American Geophysical Union 82:653-656

Recupero G (1815) Storia naturale e generale dell’Etna. Ed. Dafni, Tringali Editore, Catania, 1970

RECENT ERUPTIVE ACTIVITY IN ECUADORIAN VOLCANOES AND ITS THREAT TO AVIATION SAFETY

Hugo Yepes A., Instituto Geofísico, Escuela Politécnica Nacional, Quito-ECUADOR
hyepes@igepn.edu.ec

Recently, Ecuadorian volcanoes have been unusually active. They are huge, tall volcanoes whose edifices rise more than 15.000 ft asl, therefore their eruptions start close to the flight corridors used by local commercial airlines. Guagua Pichincha (GGP) and Reventador (REV) have produced short lived but powerful eruptions (VEI $\geq$ 3), which generated superbuoyant eruptive columns and stratospheric injections of volcanic material. A distinctive characteristic is that these eruptive columns split at about the tropopause due to a 180º change in wind direction at the equatorial regions. This creates a virtual E-W ash shade for commercial routes flying N-S along the pacific coast of South America. Tungurahua (TUNG) is generating thermals since 1999 within two altitude ranges: 1) quiescent plumes related to weak strombolian activity and/or permanent gas emissions that are being propagated by prevailing westerly winds between 15.000-20.000 ft; and 2) stronger strombolian or vulcanian explosions which have been tracked by satellites to altitude levels higher than 25.000 ft. Sangay (SANG) sent its most recent ash cloud, 50 km long and traveling East at 18.000 ft, at the beginning of 2004. Thanks to the geophysical monitoring of the volcanic activity, the onset of the eruption period at GGP and TUNG was anticipated by the IG and transmitted to the responsible authorities, including commercial aviation (DAC). Once that eruption activity was correlated with seismic signals, it was possible to inform DAC about expected ash clouds or thermals beforehand. In some cases, especially during TUNG's open system venting, no seismic signals are generated and information flows in opposite direction: from ground observers and pilots to the IG through DAC. REV's eruption was sudden but the working relationship already established between IG and Washington VAAC greatly helped to establish the size and potential threat during early stages of the eruption. SANG is not monitored by the IG due to its remote location, but it poses a major threat to Guayaquil Airport and commercial routes.

THE ALASKA VOLCANO OBSERVATORY - FIFTEEN YEARS OF WORKING TO MITIGATE THE RISK TO AVIATION FROM VOLCANIC ASH IN THE NORTH PACIFIC

Thomas L. Murray, Alaska Volcano Observatory, U.S. Geological Survey,
Anchorage AK, USA

On December 15, 1989, a passenger wide-body jet encountered an ash cloud erupted from Alaska's Redoubt Volcano. All four engines of the aircraft ceased operation and it descended almost 15,000 feet before the engines were restarted, enabling the aircraft to land safely in Anchorage. This near disaster was a defining moment for the then year-old Alaska Volcano Observatory (AVO). Almost all of Alaska’s volcanoes lie along the 1500-mile-long Aleutian volcanic arc which parallels the busy North Pacific air routes between North America and Asia. Generally, the main threat to life and property posed by explosive eruptions of Aleutian arc volcanoes is to aircraft. Thus, most of AVO's efforts have focused on limiting the risk to aviation in the North Pacific from volcanic ash, including (1)installing new seismic monitoring networks on remote volcanoes along the Aleutian arc to provide advanced notification of volcanic activity, (2)expanding the satellite remote sensing capability of AVO and developing this into an integral part of volcano monitoring and research, (3) undertaking geologic studies of Alaskan volcanoes to determine their eruptive histories and hazards, (4) working with other Federal and State agencies in Alaska to establish protocols and procedures that enable AVO to quickly notify the aviation industry of volcanic activity and volcanic ash clouds,(5) coupling the monitoring efforts with a strong research program to better understand volcanic processes in order to provide better forecasts of volcanic activity, and (6) working with Russian scientists to establish the Kamchatkan Volcanic Eruptions Response Team (KVERT)in order to insure reports of volcanic activity in Kamchatka are broadly distributed.

GROUND-BASED REAL TIME MONITORING OF ERUPTION CLOUDS IN THE WESTERN PACIFIC

Kisei Kinoshita[1], Satoshi Tsuchida[1], Chikara Kanagaki[1], Andrew C. Tupper[2], Ernesto G. Corpuz[3] and Eduardo P. Laguerta[3]

[1] Faculty of Education, Kagoshima University, Kagoshima, Japan

[2] Darwin Volcanic Ash Advisory Centre, Bureau of Meteorology, Northern Territory, Australia

[3] Philippine Institute of Volcanology & Seismology, Quezon City, Philippines

Abstract: Ground-based observation of eruption clouds, combined with satellite imagery, is very important for understanding their properties under various volcanic and meteorological conditions. Real time monitoring contributes greatly to aviation safety, since height information is essential for dispersion model prediction. The near-infrared camera serves to improve the observation because it is less sensitive to atmospheric haze and able to detect hot anomalies. We report here the monitoring of eruption clouds at Mayon volcano in the Philippines, and Suwanosejima, Satsuma-Iojima and Sakurajima volcanoes in southwest Japan. We also discuss volcanic clouds and gas at Miyakejima near Tokyo.

1. Introduction

Volcanic clouds are often obscured on satellite imagery by meteorological cloud, or are too small-scale to detect. For aviation safety, a ground-based observation network is very useful for detecting ash ejections, and obtaining the vertical structure of the clouds. The flow and dispersion of volcanic clouds can be clarified by combined studies of ground observation and satellite images. Here we report our works in this direction concerning volcanoes in Japan and the Philippines. More details are described in the papers in a booklet of Kagoshima group [1].

2. Methods of ground-based observation

2-1. Near-infrared and visible observations

The near-infrared (NIR) band is widely used in satellite imagery, as it has quite different properties of surface reflection and atmospheric transportation compared with visible bands. The use of visible-cut filter in the cameras with CCD or CMOS sensor enables us to get NIR images in ground-based observation [2]. We are using a film type filter IR-84, which shields the light with wavelength < 840 nm. There are the following advantages for NIR over conventional visible observations, though the colour information is lacking: (i) The images are not so obscured by haze and mist. (ii) They may distinguish aerosols more clearly than visible images. (iii) They may detect very hot anomalies. (iv) They may detect vegetation damage by ash, gas and lava.

Fig. 1 shows a comparison of NIR and visible images of Takachiho peak at Kirishima volcanoes 48 km away. We may see topographic features owing to the shading in NIR image, while we only see the outline of the mountain in visible image.

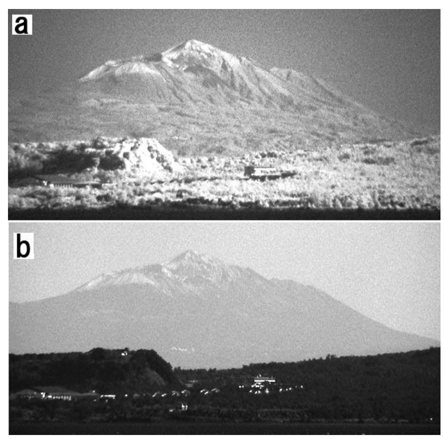


Fig. 1. Takachiho peak in Kirishima volcanoes observed from 48 km away in Kagoshima City on 14 Jan. 2004. (a) NIR image with IR-84 and ND400 filters in night-shot mode of SONY DCR-TRV30. (b) Conventional visible image.

2-2. Methods of automatic recording and monitoring

Since the features of volcanic clouds change with day and time, long period recording is necessary. Time-lapse recordings may be appropriate for the phenomena, except for very quick ones such as lightning. For this purpose, there are basically two alternatives [2] as follows.

(A) Long-time automatic camera recordings: Video camera recording for 100 days is possible in a two hour videocassette by recording 0.5 sec. with 10 min. interval. Memories with large capacity are able to store quite large number of digital camera photos for a few to several months with an hourly interval.

(B) Camera-computer system for monitoring and archiving: A web-camera with a personal computer or a network-camera alone is able to serve as a real time monitor accessible remotely via an Internet connection. For time-lapse recording and archiving, a server with enough storage capacity is necessary in the system.

For both *(A)* and *(B)*, a stable electric power supply is essential, and an uninterrupted power supply (UPS) must be used.

3. Mayon volcano

After the gigantic Pinatubo eruption in 1991, Mt. Mayon (2462 m) near Legaspi in southeast Luzon has been the most active volcano in the Philippines (Fig. 2). It erupted in 1993 and 1999-2001 with pyroclastic and lava flows, as seen by the lack of vegetation in Fig. 3. In the latter eruptions, the appearance of hot lava in nighttime was detected by a video camera by using night-shot mode.

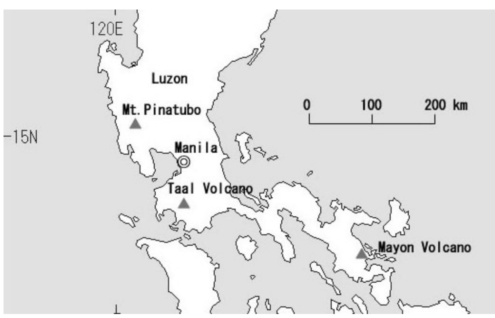


Fig. 2. Location of Mayon volcano.

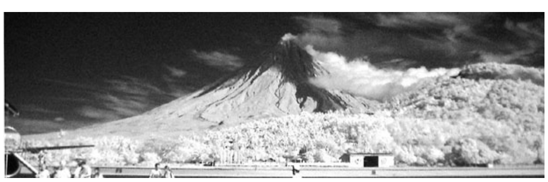


Fig. 3. NIR image of Mayon volcano observed from Legaspi airport 11.5 km south from the summit.

3-1. Interval recordings with visible-spectrum cameras

Automatic interval recording at Mt. Mayon began on 22 June 2003 as joint work of the Philippine Institute of Volcanology and Seismology(PHIVOLCS) and the Kagoshima group. Digital and video cameras were set in an observatory on Lignon Hill situated at 11 km SSE of the summit crater. Fig. 4 exhibits a few video scenes of the plume flow, which depends on the wind around the summit height. From the records for eight months, it was found that cloud-free scenes are generally limited to morning and evening, as clouds develop to cover the summit during sunny days, following the tropical diurnal mesoscale convection cycle. This indicates the difficulty of satellite monitoring of volcanic eruptions in the moist tropical areas.

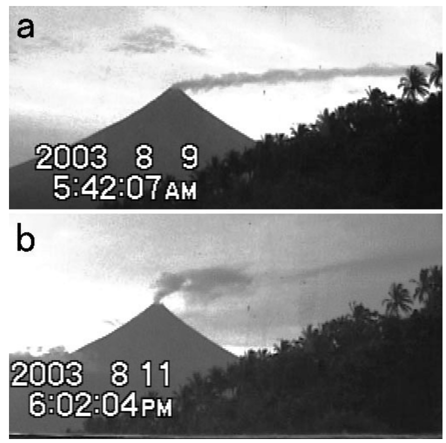


Fig. 4. Typical scenes of the plumes at Mayon volcano.
(a) Horizontal flow for fresh wind,
(b) Rise and flow under mild wind.

3-2. Network camera system to take NIR and visible images

On 24 February 2004, we installed a network camera system that has NIR and visible cameras in parallel, as shown in Fig. 5, except for the Internet connection.

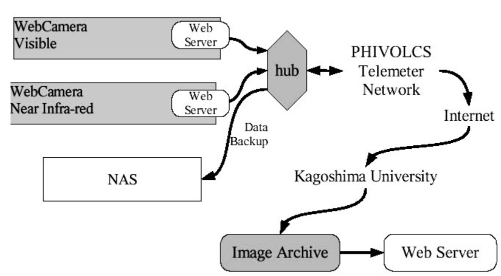


Fig. 5. Network camera system.

The system started to operate as a local network, to store visible images every ten minutes during 5:30 and 18:30, and near-infrared images every one-hour continuously in a network-attached storage (NAS).

Since April 2004, the network camera system is connected with the Internet, and real time access is possible from Quezon and Kagoshima. It should be noted, however, that the Internet is often disconnected by the shutdown of a server in the route whenever there are thunderstorms to avoid power surges and spikes. We are planning to construct a semi-real time homepage for worldwide access. A preliminary report of volcanic cloud observation at Mt. Mayon is given in [3].

4. Island volcanoes in southwest Japan

There is a chain of island volcanoes in the Nansei Islands in southwest Japan (Fig. 6). Among them, Suwanosejima volcano is the most eruptive in Japan in these years, while Satsuma-Iojima volcano is continuously ejecting plumes for many years.

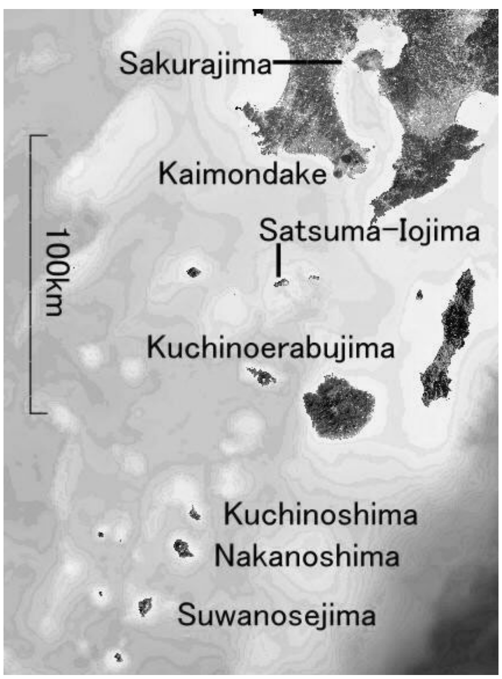


Fig. 6. Location of Suwanosejima and Satsuma-Iojima. Three small islands in between them are also volcanic islands.

4-1. Suwanosejima

There were many eruptions of Strombolian and Vulcanian types from the summit crater (799 m) at Suwanosejima in the last century. The volcano was rather dormant for five years since 1995, and resumed eruptions since the end of 2000. Eruption clouds at Suwanosejima are hazardous for low level (4-5 km) aviation, and the emitted ash frequently affects other populated islands in the vicinity. As it was difficult to have a good observation station on the island, we set a network camera at Nakanoshima, 25 km to the northeast, and connected it with the Internet on 6 August 2002.

Suwanosejima was especially active in 2002, erupting many times almost every day in August, and with 72 eruptions on 5 December. Some of them were detected by NOAA/AVHRR, EOS/MODIS and GMS/VISSR images, and reported by pilots to Tokyo-VAAC. Most of them since August were seen in the monitoring records such as shown in Fig. 7, though many of them were somewhat obscured by sea-haze. A summary of ground and satellite observations in 2002 is described in [4].

Fig. 7. Suwanosejima eruption on 14 Aug. 2002

Fig. 8. NIR monitoring camera image of Suwanosejima plume on 29 April, 2004 at 12:00 JST.

On 18 February 2004, the monitoring camera at Nakanoshima was changed from a conventional visible type to NIR type in order to minimize the sea-haze obscuration and to detect hot anomalies. Improved results have been obtained in spite of the long distance over the sea, such as shown in Fig. 8.

At the points where AC power supply is not available in Suwanosejima, we tested the interval recording by using digital camera package with rechargeable battery pack in a sealed transparent box. Such a package may be useful in long-time field observation, as it is small, lightweight and relatively expendable.

4-2. Satsuma-Iojima

Satsuma-Iojima (or Kikaijima) is a volcanic island at the NW rim of the Kikai caldera, most of which lies below the sea level formed about 7000 years ago. It has continued active ejection of gas mainly from the summit crater at Io-dake (703 m) for more than several hundred years.

Long-time automatic recording of the volcanic cloud started in July 1998 at a station about 3 km WSW of the crater, under the support of Nittetsu Mining Co. Ltd. A digital camera for hourly interval such as shown in Fig. 9, and a video camera with 0.2 sec. recording with 3 min. interval were installed. The video recording has been changed into 0.5 sec. with 10 min. interval since September 1999. In these modes, the automatic recordings are possible without changing media for about three months.

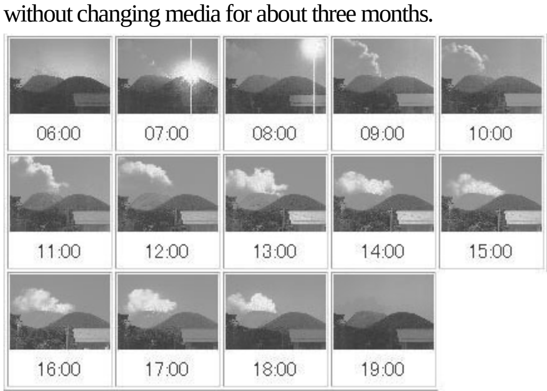


Fig. 9. Digital camera records at Satsuma-Iojima on 22 Aug. 2002.

Explosive eruptions affecting aviation have been rare at Io-dake in recent years. The ejection of volcanic plume was rather constant most of the time, with the height about 100-800 m above the summit depending on the winds. The highest heights in 2000-2002 were about1300-1500 m. Further discussions are given in [5].

For real time monitoring and archiving, a web camera system was installed in February 2003, and the camera head has been turned into NIR type since December 2003. The video camera has been turned into NIR mode since July 2003. It was found that analog connection of the telephone line was troublesome for the web-camera system. The Japan Meteorological Agency (JMA), which is responsible for volcanic disaster prevention, installed a high sensitivity camera with satellite communication line in November 2002. JMA also installed similar system at Nakanoshima for Suwanosejima monitoring in March 2003. It is desirable that different systems and modes are running in remote island volcanoes to observe various aspects of volcanic clouds and backup each other.

5. Sakurajima

Since 1972, Sakurajima volcano has been continuously active, ejecting ash plumes almost daily from the summit crater Minamidake (1040 m), mixed with Vulcanian and Strombolian eruptions occasionally. There had been many ash encounters of commercial aircrafts until 1991. The encounters have been quite reduced since then, by routing aircraft away from ash.

The Kagoshima group started interval recording of Sakurajima clouds in September 1987 at B in Fig. 10, 9.8 km WSW from the crater, and has published highlighted results on the Internet since 1997. Previous works of ground observations and satellite imagery of volcanic clouds are summarized in [6]. All of the archived records are now being converted into digital movies. Real time monitoring and archiving of the cloud images, accessible via the Internet, commenced at A in Fig. 10 in December 2000, and also at Ta and C in February and March 2003.

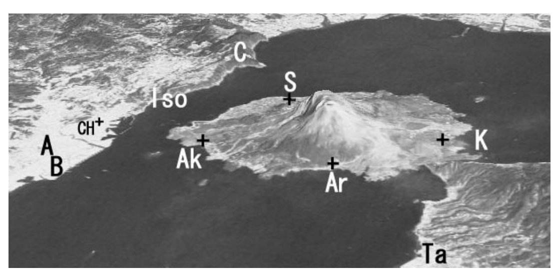


Fig. 10. The topography of Sakurajima and the surrounding Kagoshima Bay observed from southern sky (SiPSE 3D graphics). The gas monitoring stations (+), and camera monitoring points (A, B, C, Ta) are indicated.

At the foot of the volcano around the crater, there are four stations monitoring surface concentration of SO_2 and suspended particulate matter (SPM), as shown in Fig. 10, providing continuous measurement data with one-hour resolution since the 1980s. By comparing these data with the record of volcanic clouds and upper wind data, it was found that SO_2 concentrations at the foot of the volcano are high only when the winds around the summit are strong enough to create a lee wave and blow the volcanic plumes and gases down to a measuring station [7].

6. Miyakejima

Since July 8, 2000, Miyakejima volcano, about 160 km south of Tokyo (Fig. 11), has been very active, with a few big eruptions to disturb aviation in August 2000, and continuous ejection of enormous amount of poisonous gases since mid-August 2000, which compelled all of the inhabitants to evacuate from September 2000. The SO_2 flux in the ejected gas monitored by airborne Correlation Spectrometer was a few 10000s of ton/day in late-2000, and decreased gradually: it is still 4000-10000 ton/day in 2004. SO_2 was detected 100-400 km leeward in the mainland of Japan.

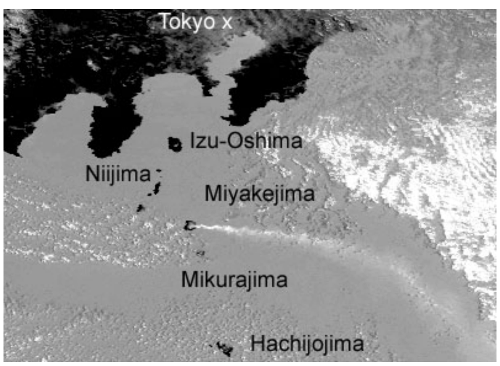


Fig. 11. Miyakejima and other Izu islands (NOAA/AVHRR image on 11 Dec. 2000, 13:25 JST).

The number of SO_2 monitoring stations at the foot of the volcano increased from three in December 2000 to fourteen in April 2004. The Kagoshima group analyzed the data, comparing with upper winds at Hachijojima, NOAA/AVHRR images and ground observation data from Mikurajima [8]. It was confirmed that, as in Sakurajima, fresh winds around the summit are responsible for the high concentration events at downstream stations [9]. The ground monitoring of the clouds is now performed by JMA at various points inside and outside the island.

7. Concluding remarks

Long-time automatic observation by the cameras from the ground, combined with satellite images, is useful for the studies of volcanic clouds and gas.

The use of NIR band has opened a new era of the ground observation.

Real time monitoring from the ground is important for aviation safety, disaster prevention of inhabitants and avoidance of ash and gas damages far away. It is especially important in order to speculate the flow of poisonous gas from the crater.

References

[1] Kagoshima Univ. Group, Volcanic Eruption Clouds in the Western Pacific - Ground and satellite based observations and analyses -, 2004.

[2] K. Kinoshita et al., Ground and Satellite Monitoring of Volcanic Aerosols in Visible and Infrared Bands, The CEReS Int. Symp. Remote Sensing, Chiba, Japan, Dec. 2003, 187-196 (Paper I in [1]).

[3] K. Kinoshita et al., Ground and satellite-based monitoring of Mayon Volcano, Philippines, paper III in [1]. http://arist.edu.kagoshima-u.ac.jp/volc/mayon/

[4] C. Kanagaki et al., Ground and Satellite Observation of Eruptions and Plumes at Suwanosejima, IUGG 2003 Scientific Program, and Paper XI in [1].

[5] T. Matsui et al., Automatic long-time observation of the volcanic clouds at Satsuma-Iojima, paper X in [1].

[6] K. Kinoshita, Observation of Flow and Dispersion of Volcanic Clouds from Mt. Sakurajima, Atmos. Env. **30**, 2831-2837; 1996, K. Kinoshita (ed.), Flow and Dispersion of Volcanic Clouds, Kagoshima Univ., 2001. http://arist.edu.kagoshima-u.ac.jp/volc/index-e.html

[7] K. Kinoshita et al., Ground observation of volcanic plumes and high SO_2 concentrations at Sakurajima volcano, paper IX in [1].

[8] A. Terada, Y. Ida and T. Ohminato, Automatic Image Recording System Using the Windows PCs:Application to the Eruption Columns of Miyakejima Volcano, Japan, Kazan, **48**, 445-459, 2003.

[9] Papers V-VIII in [1].

ACOUSTIC SURVEILLANCE FOR HAZARDOUS ERUPTIONS (ASHE): A PROPOSAL FOR A PROOF-OF-CONCEPT EXPERIMENT

McCormack[1], D, P. Chen[2], M. Jean[2], H. Bass[3], M. Garces[4]

[1]Geological Survey of Canada, 1 Observatory Crescent, Ottawa K1A 0Y3 Ontario, Canada. cormack@seismo.nrcan.gc.ca
[2]Canadian Meteorological Centre, 2121 North Service Road, Trans Canada Highway, Dorval, Quebec, H9P 1J3, Canada, Peter.Chen@ec.gc.ca, Michel.Jean@ec.gc.ca
[3]National Center for Physical Acoustics, University of Mississippi, University, MS 38677, pabass@olemiss.edu
[4]Infrasound Laboratory, University of Hawaii, Manoa, 73-4460 Queen Kaahumanu Hwy., #119, Kailua-Kona, HI 96740-2638, milton@isla.hawaii.edu

SUMMARY

Ash injected into the atmosphere from volcanic eruptions poses a significant hazard to aircraft operations. In principle, infrasound monitoring will complement both seismic observation and satellite remote sensing to improve continuous monitoring of wide regions of potential eruption hazard at modest cost. This paper proposes an experiment to test both the practical utility of infrasound as a regional-scale volcanic eruption detection tool, and the feasibility of using such an infrasound system to contribute to the aviation industry timely operational alerts through Volcanic Ash Advisory Centres (VAACs). We propose a field deployment of several small prototype infrasound arrays in a suitably selected region, sending data in real time to a central data centre where algorithms for eruption detection may be prototyped. The results will be sent on a test basis to participating VAACs for comparison with the performance of existing warning systems.

Introduction

More than 80 separate incidents of interaction between aircraft and ash have been reported over the last twenty years. Incidents on international flight paths over remote areas have resulted in engine failures and significant damage and expense to commercial airlines. In order to protect aviation from volcanic ash, pilots need rapid and reliable notification of ash-generating events. Systems need to produce a minimum of false alarms to reduce additional fuel costs and delays from re-routings.

Whilst many volcanoes, particularly near population centres or in developed countries, are instrumented directly with cameras, microphones, strain and deformation meters, seismometers, etc.[1], there remain large portions of the earth's surface, particularly in remote areas or less-developed countries, where local ground-based surveillance systems are sparse or non-existent. Despite their remoteness, some of these areas lie under major intercontinental air routes. To instrument all known volcanoes with on-site sensors would be extremely expensive, both in terms of hardware and ongoing operational costs, and consequently attention is focused on using remote-sensing systems of various types to monitor broad areas in a cost-effective fashion.

Existing Broad-Area Monitoring Systems

Much research has gone into use of Earth observation satellites both for eruption detection and tracking of ash once injected into the atmosphere. Although multispectral techniques have had some impressive successes, timeliness is limited by the sampling interval of appropriate satellite images, and weaknesses remain in the ability to robustly identify ash in the presence of intervening cloud or when there is ice entrained in the ash.[2]

Since many volcanoes are in tectonically active regions where earthquakes are frequent, there are often regional seismic networks already in place. However, volcano-associated seismic signals are often of low magnitude and are difficult to detect reliably at distances of hundreds of kilometres, requiring a high density of seismometers near the volcanoes. Additionally, there is no exact correspondence between seismic and eruptive activity, resulting in possible high false alarm rates from regional seismic monitoring. Acoustic surveillance can reduce the ambiguity between eruptive and purely seismic activity in an active volcano and provide additional (and possibly more precise) estimates for the onset time of an eruption.

Use of Infrasound

The potential of using low frequency sound, or infrasound, to rapidly identify explosive volcanic eruptions has been discussed in the environmental acoustics and aviation safety communities for some time[3,4]. A direct link between the excitation of acoustic signals and the pressurized injection of ash into the atmosphere during an eruption has been demonstrated by over a century of observation[5]. The ability of sounds in the frequency range from 0.01-10 Hz to propagate for long distances in the atmosphere with little attenuation would suggest broad-area regional monitoring with a modest number of observing sites should be possible. However, progress on a demonstration of the concept has been slow, hampered by uncertainty as to the operational feasibility of the technique, lack of experience running infrasound systems for prolonged periods in remote areas, difficulties with data access, and a general lack of support for infrasound science.

Largely driven by the infrasound requirements of the Comprehensive Nuclear Test Ban Treaty (CTBT) International Monitoring System (IMS), significant practical experience has now been gained in the operation of autonomous infrasound systems in a wide range of environments from tropical jungles to polar ice sheets. In addition, low powered satellite communications systems are now available which make it feasible to install real-time communications links between data centres and remote operating locations far from civil infrastructure. Consequently, it seems an appropriate time to revisit the idea of using infrasound for remote volcano monitoring.

Although there is progress in resolving existing policies that restrict access to IMS data for civil applications[6], in practical terms the IMS network is not optimized for a volcanic monitoring role. The requirement that a 60 station infrasound network cover the globe yields stations thousands of kilometres apart with few close to areas of concern to the aviation community. Consequently, and for operational reasons, we propose deploying new infrasound arrays for the experiment, tailored for the task and free of any restrictions on data distribution.

Experimental Design

The first objective of the experiment is to test that infrasound is a practical tool for detection of ash-generating eruptions. We propose to identify a region with a number of active, well-monitored volcanoes, and deploy at least two infrasound arrays. The arrays would telemeter data in real-time to an appropriate central location where we could test various detection and identification schemes. We would seek to record and identify acoustic signals from an azimuth corresponding to a known candidate source, and ideally determine signal characteristics that would suggest a volcanic origin. Initial calculations suggest that arrays with four sensors and an aperture of 200-300 metres provide adequate azimuthal resolution over distances of several hundred kilometres. Comparison of results with on-site volcano monitoring technologies would provide ground-truth validation of results.

Although demonstrating reliable infrasound detection of an eruption is critical, an operational alert system also requires that the information be relayed rapidly to aircraft in the vicinity. Clearly, the closer one can install instruments to a source, the larger the signal[7], and the sooner it arrives. However, this must be balanced against the need to cover large areas from a reasonable number of discrete observing locations. Initial discussions with the FAA noted that while users have stated a requirement to receive notification of an eruption within 5 minutes of an eruption for an alert of airborne ash, it was felt that an alert issued within approximately 15 minutes of the time of eruption would be of significant benefit, particularly in remote and unmonitored regions of the world.[8] The International Civil Aviation Organization (ICAO) has designated a number of meteorological centres as regional Volcanic Ash Advisory Centres (VAACs) which are charged with the responsibility of issuing so-called Volcanic Ash Advisories to the aviation community, based on a synthesis of available information from pilots' reports, satellite observations, local observatories, etc. We propose to use one or more VAACs as recipients of the output of the prototype infrasound system. Feedback on comparisons of the system performance versus existing surveillance systems will provide additional feedback on system feasibility.

Conclusion and Next Steps

Recent developments in infrasound technology and expertise, automatic data processing, and satellite communications technology suggest that this is an opportune moment to revisit the concept of acoustic surveillance for detections and alerting of hazardous eruptions. A projected increase in the confidence and timeliness of an alert would help protect aircraft from the effects of ash. The next step is to identify a suitable partner organization in a country with active volcanoes that can provide technical and logistical assistance for a deployment of sufficient duration to evaluate the concepts presented in this paper.

---

[1] See http://www.cenapred.unam.mx/mvolcan.html for an interesting example.

[2] Tupper, A., S. Carn, J. Davey, Y. Kamada, R. Potts, F. Prata, and M. Tokuno, 2004: An evaluation of volcanic cloud detection techniques during recent significant eruptions in the western 'Ring of Fire'. Remote Sensing of Environment, in press.

[3] Chen, P. and D.R. Christie, 1995: Infrasound Detection of Volcanic Explosions by the CTBT International Monitoring System: Implications for Aviation Safety. Information paper, 2nd Meeting of the ICAO Volcanic Ash Warning Study Group, 2 November 1995, Montreal Canada, 5pp.

[4] Kamo, Kosuke, K. Ishihara, and M. Tahira, 1994, Infrasonic and Seismic detection of explosive eruptions at Sakurajima Volcano, Japan, and the PEGASAS-VE early-warning system. Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety, USGS Bulletin 2047, 357-365.

[5] Strachey, R., 1888. On the air waves and sounds caused by the eruption of Krakotoa in August, 1883, in The Eruption of Krakatoa and Subsequent Phenomenoa, pp. 57-88, Trubner, London.

[6] See http://www.wmo.ch/web/www/DPS/DPFS-ERA-US/ ERA-COG-Doc8(2)-F.pdf for additional information.

[7] We are neglecting here complexities introduced by atmospheric structure. Precise locations for the experiment will be chosen after detailed modelling of signal propagation.

[8] This timeframe defines a scale for the distances of the infrasound arrays from the source, considering the acoustic propagation velocity.

RECURRENCE OF EXPLOSIVE ERUPTIONS AT ETNA VOLCANO THAT PRODUCE HAZARD FOR AVIATION

Paola Del Carlo, INGV, Catania, Italy
Mauro Coltelli, INGV, Catania, Italy

The recent activity of Etna is characterised by the occurrence of a large number of explosive eruptions, many of which have produced eruptive plume and copious ash fallout on its flanks. Since 1989 Etna summit craters have produced more than 150 fire fountain episodes, characterized by: i) eruptive columns from 2 to 12 km high above the vent, ii) tephra volumes ranging from 10^4 to 10^7 m^3 and iii) magnitude from violent strombolian to subplinian. Furthermore, in 2001 and 2002 flank eruptions, a prolonged explosive activity, forming a 1-4 km high ash column, caused continuous tephra fallout for several weeks. Lapilli and ash blanketed the volcano slopes and fine particles reached hundreds of km of distance. The effects have been very serious on both economy and health, particularly for the disruption of the operations of Catania and Reggio Calabria airports. Widening the temporal interval to the last 3 centuries, the historical record documents other five flank eruptions, comparable to the 2001 and 2002, that produced copious tephra fallout up to Malta Island and Calabria region. Furthermore, from the 18th century onwards, summit activity was characterised by several episodes of fire fountain and some short-lived sub-plinian episodes (on average two per century) that caused ash fallout on the eastern Sicily. Therefore, the eruptive behaviour of Etna observed in the last fifteen years does not represent any anomaly in the activity over the past three centuries. Nonetheless, the historical record analysis indicates an increase of the frequency of ash-plume forming eruptions from 1880 and again from 1961, highlighting Etna as certain source of risk for aviation in central Mediterranean region.

A PROPOSED ALERT-LEVEL NOTIFICATION SCHEME FOR AVIATION AND GROUND-BASED HAZARDS AT U.S. VOLCANOES

C.A. Gardner, USGS Cascades Volcano Observatory, Vancouver, WA 98683 USA, cgardner@usgs.gov
Marianne Guffanti, USGS National Center, Reston, VA 20192 USA
C.C. Helicker, USGS Hawaiian Volcano Observatory, Hawai'i Volcanoes National Park, HI 96718 USA
D.P. Hill, USGS Long Valley Observatory, Menlo Park CA 94025 USA
J.B. Lowenstern, USGS Yellowstone Volcano Observatories, Menlo Park CA 94025 USA
T.L. Murray, USGS Alaska Volcano Observatory, Anchorage, AK 99508 USA

Introduction

The function of hazard notification schemes is to give public officials and the public warning about the proximity of a hazardous event (Scott, this volume). How precise these warnings can be depends upon the nature of the hazardous event. Prior to eruptions, volcanoes exhibit precursory behavior over a period of days to years, such that notices of impending eruptions can usually be made far enough in advance for affected groups to take mitigative action. But, volcanoes do not erupt with consistent precursors or in a uniform style; nor do all episodes of unrest end in eruption. Thus there is considerable uncertainty in assessing future volcanic behavior at restless volcanoes. These uncertainties affect the precision of volcano notification schemes and provide a challenge in developing them.

In this paper, we discuss a proposed alert-level notification scheme for activity at U.S. volcanoes monitored by the U.S. Geological Survey's Volcano Hazards Program (USGS-VHP). We discuss the motivation and goals of the scheme, the rationale for the different levels, and how it is incorporated into the USGS-VHP's overall mitigation strategy to inform the public about potential volcanic eruptions.

Proposed Notification Scheme

The U.S. and its territories have approximately 170 volcanoes that have erupted over the past 10,000 years, 80 of which have had one or more eruptions in historical time (past 250 years). Of the 80 historically active volcanoes, about 50 are monitored at varying levels of thoroughness. Some of these volcanoes are near major cities, whereas others are in remote areas hundreds to thousands of kilometers away from ground-based populations.

Under Federal law, the USGS has the responsibility to monitor U.S. volcanoes and provide timely warnings to public officials and affected communities. The USGS-VHP currently has five volcano observatories and provides assistance to the Commonwealth of the Northern Mariana Islands. Three of the five observatories have developed alert-level notification schemes in order to meet the needs of nearby populations and the aviation community. Although there are similarities among the three schemes, they are not identical. To minimize confusion from multiple schemes in the future, especially if there are simultaneous eruptions being handled by different observatories, and to avoid re-inventing schemes by observatories currently without one, a single system is explored.

The goal is to design a single system that (1) can accommodate a range of styles, sizes, and durations of volcanic activity (both precursory and eruptive); (2) will work during escalating and de-escalating activity; (3) is useful to both ground-based communities and the aviation sector; (4) does not disrupt currently effective communication between the observatories and their partners; and (5) is scientifically defensible.

These are not trivial requirements. Typical volcanic eruptions can vary in style from relatively passive events to extremely explosive ones and in size (volume of erupted material) from 0.001 km^3 to, rarely, >100 km^3. Generally, an eruption involves episodes of eruptive activity separated by non-eruptive intervals of hours to months. The duration of a single eruptive episode usually ranges from a few minutes to tens of hours, whereas the entire eruption can last for a day to many decades (Simpkin and Siebert, 1994; Wunderman et al., this volume). As a result, an observatory may need to change alert levels numerous times over the course of a volcanic eruption. Similarly, during unrest, volcanoes exhibit a wide range in precursory styles and durations. There may be several cycles of increasing and decreasing unrest, before or after an eruptive episode, or before it is clear no eruption will occur. Again, it is important that notification systems can accommodate the up-and-down pattern of many volcanic crises. Some eruptions affect only ground-based communities and others only the aviation sector, but explosive eruptions at volcanoes that are near major communities, or that are large enough that the ash falls on populated areas, will affect both. Lastly, although there are many challenges in eruption forecasting (see Newhall, this volume), an alert system must be scientifically defensible to be consistently applied.

The scheme proposed here (Fig. 1) has four levels, each assigned a color (Green, Yellow, Orange, Red), based on a modified stop-light configuration and the aviation color-code system developed by the Alaska Volcano Observatory (AVO) and recommended by the International Civil Aviation Organization (ICAO). The scheme also includes hazard terms that are used by the National Weather Service (NWS) and familiar to most ground-based emergency management personnel. The dual system of colors and terms allows the aviation and emergency management communities to use the terminology that best suits them, but only a single alert-level would be issued (e.g., Yellow/Advisory) at any time. The descriptions reflect activity **at the volcano** and can be used during escalation and de-escalation. The descriptions are general to allow for the variety of volcanic unrest and eruption and to give observatories the flexibility to expand the definitions or, if necessary, to subdivide alert levels in order to meet the needs of user groups. Any modifications, however, should reflect the overall intention of the levels as discussed in the following paragraphs.

GREEN/NORMAL is the typical non-eruptive state of a volcano. This level allows for periods of increased steaming, seismic events, deformation, thermal anomalies, or degassing, as long as the activity is within the range seen at the volcano during its monitoring history, or at similar types of volcanoes. One difficulty is how to interpret data from new monitoring techniques, such as InSAR, because there may be no comparable data to use as a baseline. Another nuance of this level is that unrest initially seen as "anomalous" -- such as the increased steam and thermal output at Mount Baker volcano in 1975, or some of the periods of elevated unrest at Long Valley caldera through the 1980s and 1990s -- may, after some time, become considered normal background or regional activity.

Figure 1. Proposed unified alert-level notification scheme for volcanic activity

Color	**Term**	**Description**
GREEN	NORMAL	Normal non-eruptive state; typical background activity
YELLOW	ADVISORY	Elevated unrest above known background activity
ORANGE	WATCH	Escalating or sustained unrest indicates eruption likely, timeframe variable. OR, eruption underway that poses a localized hazard
RED	WARNING	Hazardous eruption is underway OR expected within hours

YELLOW/ADVISORY signifies that one or more monitoring parameters are outside the "normal" range of activity. This level implies that what drives the unrest may be magmatic in origin and could be precursory to an eruption, but that we expect to see much higher levels of unrest before an eruption begins. At this level, there is a strong possibility that no eruption will occur. Stating precisely when unrest is above "normal" is often difficult, especially when unrest begins gradually. During de-escalation, the definition is the same as during escalation and implies that monitoring parameters have not yet returned to baseline levels.

ORANGE/WATCH means either that (1) sustained high levels of unrest of one or more monitoring parameters are well outside the "normal" range or, (2) an eruption is in progress but poses only a localized hazard (i.e., no communities, major airports, or overflight paths). The rationale for this dual nature primarily is the need to distinguish between hazardous eruptions and those that do not pose a significant hazard to life or property. For example, lava flows from Kilauea Volcano, Hawai'i are currently flowing through Hawai'i Volcanoes

National Park, but they are not a threat to homes or important Park structures. Using our proposed scheme, we would consider the alert level as Orange/Watch. If the lava were to start flowing through communities and threatening homes and businesses (as it has done in the past), then the alert level would be raised to Red/Warning.

Another example of a non-threatening eruption is dome growth at a remote volcano (e.g., Bezymianny, Kamchatka). In this situation, however, dome collapse could quickly change the situation from being non-threatening to potentially hazardous for air traffic. In situations like dome growth/collapse and when escalating to or de-escalating (sustained unrest) from hazardous eruptions, Orange/Watch is a warning that the situation is dynamic and could (not will) change quickly. There is no specific time frame associated with this level, but during escalation it usually implies that an eruption is more likely and more imminent (but still not guaranteed) than when in Yellow/Advisory.

We decided against using a fifth color to handle non-threatening eruptions because (1) there is no equivalent in the NWS terminology so there would be no familiar term for the ground-based communities, (2) it would be non-linear as one wouldn't necessarily escalate or de-escalate through this color, (3) it would be non-intuitive (is color A more or less of a concern than color B?), and (4) we wanted to avoid confusion with the U.S. Department of Homeland Security's five-tiered color code system.

The proposed Orange/Watch definition is similar in intent to the AVO and ICAO color code ORANGE. Like those schemes, the proposed level has a dual nature of either high unrest or a largely non-hazardous eruption. It differs primarily in that it does not define an ash plume threshold. The ash plume altitude of 25,000' was conceived as a useful threshold of concern for the North Pacific Region where many volcanoes are remote but where ash plumes above 25,000' can affect a large volume of air traffic at cruise altitudes. A concern with the 25,000' threshold for all observatories is that in places where airports are close to volcanoes, ash plumes of less than 25,000' can be very hazardous to the aviation industry. Thus we have tried to adhere to the intent and duality of the original ORANGE definition, but have deleted the specific altitude threshold so that it could be more widely applied. In some instances, observatories may want to assign an altitude or some other threshold to an alert level in order to highlight specific aviation or ground-based concerns. For example, at remote locations where there are no nearby populations or airports, an observatory may want to use an altitude, similar to that currently in use at AVO to define Orange/Watch. **Even if no ash plume threshold is assigned, any available information regarding ash plume height should be part of all alert-level notices when in Orange/Watch or Red/Warning.**

RED/WARNING means that monitoring data are at levels that suggest a potentially hazardous eruption is underway or is expected in the near future (hours). This level does not indicate whether the eruption is small, moderate, or large, or who is at risk—aviation, ground -based communities, or both. Rather it indicates that the eruption either is, or potentially is, life threatening to one or both groups, and that action to mitigate the threat is needed or should have been completed already by those groups. An observatory may choose to have sublevels within Red/Warning for explosive volcanoes that have a large range in eruption size.

Because volcanologists cannot reliably forecast eruption size, most observatories would likely raise the alert level to Red/Warning as soon as an eruption began for those volcanoes that have a history of at least some moderate explosive events (VEI $\geq$ 3; Newhall and Self 1992; Newhall this volume). Although some eruptions raised to Red/Warning may be better classified as Orange/Watch in hindsight, it may be better to be cautious than to mistake a hazardous event for a non-hazardous one.

Volcanic events are unique enough that it is impossible to predetermine a detailed set of criteria for each level that would be applicable in all situations. The above definitions are guidelines for scientists to use to categorize the level of unrest, and for public officials and the public to consider when deciding what actions they need to take. Our scheme as portrayed in Figure 1 is a way to communicate quickly our scientific judgment about the level of unrest. For more detailed information, the USGS-VHP usually issues daily, or more often if needed, updates on the status of the volcano. These communications typically give the volcano's location in latitude and longitude, height of the volcano's summit, the alert level, a short synopsis of the monitoring data, interpretation of that data, and both a short- and long-term forecast of likely activity. These daily updates are essentially the scientific rationale for the alert level assigned. If the volcano erupts, information about when the eruption began, the presence or absence of a plume, plume height and volcanic phenomena that affect ground-based activities would be conveyed along with the change in alert level.

In order for alert-notification systems to succeed, users must be aware the system exists, understand its strengths and weaknesses, and provide feedback when it works and when it fails. Communication is a critical element to mitigating any crisis. Effective communication includes two-way exchanges of information as events unfold and clear protocols for disseminating warnings when needed.

Because volcanologists do not directly measure the rise of magma during volcanic unrest, and because not all volcanoes are monitored, visual observations are an important monitoring tool. Volcanologists are located in only a few places compared to the geographical distribution of volcanoes, so observations from pilots and individuals on the ground can be vital in detecting unrest and eruptive activity. For example, a pilot was the first to note the second eruption of Crater Peak, Alaska, on 18 August 1992 and immediately informed the AVO of the event. At that time there was only a weak signal on the seismic records which would not have been interpreted as the beginning of an eruption (Eichelberger et al. 1995). It is critical that outside observers know how to contact observatories and that those observatories are receptive to outside observations in order for two-way exchanges of information to occur.

Although two-way exchanges of information are important for monitoring unrest and activity, protocols are needed to ensure that essential information is communicated efficiently and that the source of the information can be quickly verified. Every year there are many false reports of eruptions and one can only imagine the disruptions they would cause if they were all acted upon. Protocols work best if they are already in place before a crisis begins and if they are practiced regularly. The USGS-VHP is working with emergency managers and aviation personnel to set up protocols in the event of volcanic unrest and eruption. Face-to-face interactions are one of the biggest benefits of such discussions, as it is often easier to communicate openly with someone you know than with a stranger. It is not always possible to develop protocols in advance, but when they are already in place they often help diffuse many of the problems that arise during a crisis.

We digress here briefly to discuss our justification for combining the aviation and ground-based communities into one system. Perhaps the best reason for combining them is to ensure that there is a consistent message regarding the status of the volcano. One can imagine the possible confusion that could arise in populated areas if a volcano is at Red/Warning for aviation hazards but at Orange/Watch for ground hazards. All it would take would be one media or observatory report to confuse the two for a potential disaster to happen. Moreover, as restless volcanoes near populations escalate towards or de-escalate from an eruption, the information conveyed by alert levels and in daily updates is of equal importance to both communities. Many explosive eruptions may not affect both communities equally, but the differences may be slight. As long as regional airport operations are affected by ash fall, lava flows or lahars, airport-supported response and recovery efforts will be difficult or impossible to deploy. The only cases in which one community will be effected in the other not, are when volcanoes are very remote or when eruptive activity is non-explosive and far from airports. Overall we feel that there is more to be gained by combining these two groups within one system than by having two separate ones. The challenge for observatory scientists is to write eruption communications well enough so that each group can quickly identify and locate the volcanic phenomena of concern.

Closing

There are many ways to develop a volcano alert-level notification system and ours is but one of many (Scott, this volume). As stated in the title, this is a proposed system and we are in the process of testing it and evaluating it internally. Even now, we are trying to determine whether Red/Warning should only mean "hazardous eruption in progress" or stay with the current dual definition of "hazardous eruption in progress or hazardous eruption imminent." Another area of discussion is whether we should set protocols as to how long we stay in Red/Warning—only for the duration of the eruption (which may be minutes to many hours) or for a set time period, perhaps 12 hours after the eruption has ended? The latter would cover the time period when ground-based catastrophic events would have occurred and most of the tephra would have moved substantially downwind of the volcano. As we move forward with this process, we would greatly appreciate comments as to potential problems and benefits of this proposed scheme from the aviation, ground-based, and volcanological communities.

References Cited

ICAO (International Civil Aviation Organization), 2004, Handbook on the International Airways Volcano Watch, ICAO Document 9766-AN/968, http://www.icao.int/icaonet/dcs/9766_2_en.pdf

Eichelberger, JC, Keith, TEC, Miller, TP, Nye, CJ, 1995, The 1992 eruptions of Crater Peak vent, Mount Spurr Volcano, Alaska: Chronology and Summary, *in* Keith, TEC, editor, The 1992 eruptions of Crater Peak vent, Mount Spurr Volcano, Alaska: U.S. Geological Survey Bulletin 2139, p. 1-18.

Newhall CG, *this volume*, Promise and pitfalls in eruption forecasting.

Newhall CG, Self S, 1982, The Volcanic Explosivity Index (VEI): an estimate of explosive magnitude for historical volcanism. J Geophys Res, v. 87, p. 1231-1238.

Scott B, *this volume*, Volcanic alert systems: an overview of their form and function.

Simkin T, Siebert L, 1994, Volcanoes of the World, 2nd ed., Geoscience Press, Tucson, 349 p.

Wunderman R, Siebert L, Luhr J, Simkin T, Venzke E, *this volume*, A global perspective on volcanoes and eruptions.

MONITORING AND REPORTING OF KAMCHATKAN VOLCANIC ERUPTIONS

Evgenii Gordeev[1] (+7-415-22-59531; gord@emsd.iks.ru)
Sergei Senjukov[2] (+7-415-22-59523; ssl@emsd.iks.ru)
Olga Girina[1] (+7-415-22-58627; girina@kcs.iks.ru)

Institute of Volcanology and Seismology, Russian Academy of Sciences, Petropavlovsk-Kamchatsky, Russia
Kamchatkian Department, Geophysical Service, Russian Academy of Sciences, Petropavlovsk-Kamchatsky, Russia

Kamchatka is a part of Pacific volcanic ring with 29 active volcanoes. Every year 2- 3 of these volcanoes produce explosive ash clouds that spread across heavily traveled international air routes between Asia and North America. The Kamchatka Volcanic Eruption Response Team (KVERT) has since 1993 provided reports and notices of volcanic activity. In collaboration with the Institute of Volcanology and Seismology (IVS) and Kamchatkan Experimental and Methodical Seismological Department (KEMSD) of the Russian Academy of Sciences, the KVERT staff monitors active volcanoes of Kamchatka seismically, by video and visual observations, and using satellite images for ash cloud tracking and detection of thermal anomalies. As of 2003, 28 remote seismic stations are operating at 11 of the most active volcanoes in Kamchatka and North Kurile Islands. Three volcanoes, Kyuchevskoy, Sheveluch and Bezymyanny are under control by video-camera system, which makes real-time images of volcanoes available on the Internet (http://emsd.iks.ru). Seismic observations are a universal tool used to reveal the beginning of volcano unrest and to recognize volcanic blasts of frequently weather obscured volcanoes. KVERT scientists have developed methods of estimating eruption plume height from the intensity of the seismic signals. In cooperation with the Alaska Volcano Observatory, KVERT examines data from Japanese and U.S. meteorological satellites. Several times a day, images from GMS (Geostationary Meteorological Satellite), GOES (Geostationary Operational Enviromental Satellites) and polar-orbiting satellites carrying AVHRR (Advanced Very High Resolution Radiometer) are examined for volcanic activity. Since 2002, KVERT has used daily images from NOAA16 and NOAA17 satellites received by the Kamchatkan Center Communication and Monitoring (KCCM). In the future, KVERT will expand its monitoring and warning capacity by adding more seismic networks and video systems and by enhancing satellite analysis of Kamchatka and the adjacent Kurile Islands.

VOLCANO-RELATED INFORMATION AVAILABLE ON THE INTERNET: FROM CURRENT ACTIVITY TO THE PAST 10,000 YEARS

Gari Mayberry, US Geological Survey, Washington DC, USA
Edward Venzke, Smithsonian Institution, Washington DC, USA
James Luhr, Smithsonian Institution, Washington DC, USA
Richard Wunderman, Smithsonian Institution, Washington DC, USA
Lee Siebert, Smithsonian Institution, Washington DC, USA
Marianne Guffanti, US Geological Survey, Reston, VA, USA

Introduction

A wealth of information is available on the Internet about volcanoes and the ash clouds they emit, but it can be a daunting task for pilots and aviation officials to find the most pertinent information. Scientists with the US Geological Survey's (USGS) Volcano Hazards Program and the Smithsonian Institution's Global Volcanism Program (GVP) recognize that information concerning volcanic activity should be readily available to the aviation community. To that end, they provide two pages of particular relevance on their websites: the GVP/USGS Weekly Volcanic Activity Report, and the USGS Current Updates for US and Russian Volcanoes.

Worldwide Volcanic Information

Up-to-date information about significant worldwide volcanic activity is available on a weekly basis via the online GVP/USGS Weekly Volcanic Activity Report at http://www.volcano.si.edu/reports/usgs/. The report is a joint project between the Volcano Hazards Program and GVP that became available to the public on November 1, 2000.

The most significant section of the website is the brief description of the activity that occurred at the volcano during the report week. These accounts include information about (1) volcano-related activity that either did not result in an eruption or preceded and accompanied an eruption – i.e., increased seismicity, gas emissions, deformation, surficial changes, (2) eruptions, with emissions including lava flows, ash, and other fragmental volcanic material, (3) secondary activity such as mudflows/lahars and re-suspended ash, and (4) eruption impacts, including health impacts, airport closures, flights affected, and property damage. In each volcano report, volcanological terms that the general public may not be familiar with are linked to a photo glossary on the USGS Volcano Hazards Program website. In addition, acronyms and abbreviations are commonly used in the reports, so there is a link to a list with their meanings.

Background information from the GVP website is included with each volcano report that briefly summarizes the geological history of the volcano and noteworthy past eruptions. Each report also has links to maps showing the location of the report volcano in relation to nearby volcanoes and large cities, the source of the reported information when available on the Internet, and a link to more information, images, and data on the GVP website.

All volcano reports are archived on the Internet by volcano and report date, so that they are easily accessible. In the 4 years that the GVP/USGS Weekly Volcanic Activity Report has been available to the public (November 1, 2000 to November 2, 2004), there have been reports written about 146 volcanoes in 33 different countries and island nations (note that all reports document the minimum amount of activity in any given week due to under-reporting). A majority of reports (53) discuss small eruptions at volcanoes that had not erupted for at least 3 months (Table 1). Small eruptions include ash emissions that did not rise higher than approximately 5 km above the volcano. Most of the remaining reports cover non-eruptive volcanic activity (48) and ongoing activity (25) not considered anomalous.

Table 1. Types of activity reported in the GVP/USGS Weekly Volcanic Activity Report during November 1, 2000 to November 2, 2004.

Type of Activity	**Number of Volcanoes**
Non-eruptive, Precursory Activity	48
Ongoing Activity	25
Small New Eruptions	53
Large Eruptions	13
Evacuations	20
Deaths	2
Injuries	2
Aviation Impacted	12

Reports were written about 13 large eruptions – i.e., produced ash clouds that rose higher than 5 km above the volcano and had significant impacts on populations or aviation (Table 2). Eight of these eruptions led to evacuations of residents near the volcanoes; eruptions at 12 other volcanoes led to evacuations when large eruptions did not occur (20 evacuations total since November 1, 2000.) Eruption-related deaths were reportedly caused by two eruptions. Injuries were reported from two eruptions, and numerous incidents occurred where people's health was adversely affected by ash and gas

Table 2: List of the 13 large eruptions reported in the GVP/USGS Weekly Volcanic Activity Report during November 1, 2000 to November 2, 2004.

Volcano, Country	**Eruption Date**
Popocatépetl, México	Dec. 2000
Cleveland, USA	Feb. 2001
Merapi, Indonesia	Feb. 2001
Etna, Italy	May-Aug. 2001 Oct. 2002
Mayon, Philippines	June, July 2001
Nyiragongo, D. R. Congo	Jan. 2002
Pago, Papua New Guinea	Aug. 2002
Tungurahua, Ecuador	Oct. 2002
Reventador, Ecuador	Nov. 2002
Bezymianny, Russia	July 2003 Jan. 2004
Anatahan, Mariana Islands	May 2003
Manam, Papua New Guinea	Oct. 2004
Grímsvötn, Iceland	Nov. 2004

Ash from eruptions at 12 different volcanoes disrupted activities at airports and/or affected aircraft in flight (See Guffanti et al., this volume). The GVP/USGS Weekly Volcanic Activity Report provides valuable information about ash and aircraft/airport incidents by consistently documenting them in a timely manner

Timely reporting of volcanic activity does not always allow time for in-depth verification of information by scientists in the field or by GVP/USGS Weekly Volcanic Activity Report editors. Therefore, false reports can sometimes be included. Six false reports of eruptions have been included in the GVP/USGS Weekly Volcanic Activity Report, and were corrected once new information was received.

The GVP/USGS Weekly Volcanic Activity Report utilizes the wealth of volcano-related information available on the GVP website at http://www.volcano.si.edu/ by providing links to data about the report volcano on the website. While the GVP/USGS Weekly Volcanic Activity Report has provided brief updates on significant volcanism around the world for the past four years, the Smithsonian GVP has provided information since 1968 about Earth's current eruptions and those that occurred in the past 10,000 years. Monthly newsletters discussing current activity have been produced since 1975, and have been posted on the Internet since 1994.

For more than three decades, GVP has compiled descriptions, data, maps, and images of volcanoes and their eruptions in order to better understand the full range of Earth's eruptive activity and to make these resources available to the ever-broadening community interested in volcanism (Siebert and Simkin, 2002). Two previous hardcopy versions of the GVP volcano and eruption data (Simkin et al., 1981 and Simkin and Siebert, 1994) have been published, but in 2002 the data became accessible on the GVP website (Venzke, et al., 2002). The development of the world wide web has made possible much wider and faster dissemination of these data, which are frequently updated.

U.S. Volcanic Information

For users specifically interested in current activity at volcanoes in the United States and Russia, the USGS Volcano Hazards Program website compiles daily-to-monthly volcano

updates from all five volcano observatories in the United States and an observatory in Kamchatka. The USGS Current Updates for US and Russian Volcanoes page is available at http://volcanoes.usgs.gov/update.html.
The page also has links to each individual observatory website where detailed information about the volcanoes within the observatory's region of responsibility can be found.

Summary

The GVP/USGS Weekly Volcanic Activity Report, with links to the GVP website, and the USGS Current Updates for US and Russian Volcanoes page place air traffic controllers, pilots, and airport authorities abundant information regarding volcanic activity around the world literally at their fingertips to help them quickly make informed decisions when planning flight routes.

References Cited

Guffanti, M., Casadevall, T.J., and Mayberry, G.C., *this volume*, Effects of volcanic activity on airports.

Siebert, L., and Simkin, T., (2002-). Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and their Eruptions. Smithsonian Institution, Global Volcanism Program, Digital Information Series,GVP-3, (http://www.volcano.si.edu/world/).

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newhall, C., and Latter, J.H., (1981). Volcanoes of the World. Hutchinson-Ross, Stroudsburg, Pennsylvania, 232 p.

Simkin, T., and Siebert, L., (1994). Volcanoes of the World, 2nd edition. Geoscience Press, Tucson, 349 p.

Venzke, E., Wunderman, R.W., McClelland, L., Simkin, T., Luhr, J.F., Siebert, L., and Mayberry, G., (eds.) (2002-). Global Volcanism, 1968 to the Present. Smithsonian Institution, Global Volcanism Program Digital Information Series, GVP-4 (http://www.volcano.si.edu/reports/).

VOLCANIC TREMOR AND ITS USE IN ESTIMATING ERUPTION PARAMETERS

Stephen R. McNutt
Alaska Volcano Observatory, Geophysical Institute UAF, Fairbanks, AK 99775 USA

Volcanic tremor, a continuous seismic signal, accompanies virtually all eruptions. Several published studies have examined relations between tremor reduced displacement (DR, a normalized amplitude measure; Aki and Koyanagi, 1981; Fehler, 1983) and the Volcanic Explosivity Index (VEI; Newhall and Self, 1982) or ash plume height. The goals of these studies are to determine the physical relationships between tremor and eruptions and to use DR values to provide real-time estimates of eruption parameters.

This study examines tremor for 50 eruptions from 31 volcanoes. This is a significant expansion of the data set from an earlier study of 21 eruptions from 14 volcanoes (McNutt, 1994). Several new trends are observed when DR is plotted versus VEI (Figure 1): 1) large eruptions produce stronger tremor than small ones; 2) fissure eruptions produce stronger tremor than circular vents for the same fountain height (F in Figure 1); 3) eruptions with higher gas content (H in Figure 1) produce stronger tremor than those with low gas content (L in Figure 1); and 4) phreatic eruptions produce stronger tremor than magmatic eruptions for the same VEI (P in Figure 1).

The three volcanoes with varying gas content are Redoubt 1989-1990, based on eruption type (vertically oriented pumice eruption versus dome collapse; Miller, 1994); Mount Spurr in 1992 based on SO_2 measurements (Bluth et al., 1995); and Shishaldin volcano in 1999 based on presence or absence of large explosions on a pressure sensor (Caplan-Auerbach and McNutt, 2003).

Using tremor DR to estimate eruption parameters is a statistical problem with several factors contributing to uncertainties. First, tremor occurs when volcanoes do not erupt as well as when they do. Based on a worldwide sample, 60-80 percent of tremor episodes accompany eruptions, while 20-40 percent of episodes do not. Thus, there is a significant chance that no eruption is occurring. Second, for each VEI, there is a range of DR, so it is possible to overestimate or underestimate the VEI. Hence there will always be a false alarm rate (~10 percent). Improvements can be made in the estimates if the types of eruptions, shapes of vents, and gas contents are known in advance. These can be estimated from previous eruptions or measured near-real-time from independent data. However, adding additional information takes time, delaying forecasts. A primary benefit of seismic data is that they are real-time, are not affected by darkness, and are usable during poor weather, although the signal-to-noise ratio can be worsened. Monitoring tremor DR is therefore an effective way to characterize eruptions in progress.

References:

Aki, K., and Koyanagi, R.Y. (1981). Deep volcanic tremor and magma ascent mechanism under Kilauea, Hawaii. *Jour. Geophys. Res*. **86**, 7095-7110.

Bluth, G.J.S., C.J. Scott, I.E. Sprod, C.C. Schnetzler, A.J. Krueger, and L.S. Walter (1995). Explosive emissions of sulfur dioxide from the 1992 Crater Peak eruptions, Mount Spurr Volcano, Alaska. In: T.E.C. Keith (Ed.) The 1992 Eruptions of Crater Peak Vent, Mount Spurr Volcano, Alaska. . U.S. Geol. Survey Bull. 2139, 37-45.

Caplan-Auerbach J., McNutt S.R. (2003). New Insights into the 1999 Eruptions of Shishaldin Volcano Based on Acoustic Data. *Bull. Volcanol*. **65**: 405-17, 10.1007/s00445-002-0267-5

Fehler, M. (1983). Observations of volcanic tremor at Mount St. Helens volcano. *Jour. Geophys. Res*. **88**, 3476-3484.

McNutt, S.R. (1994). Volcanic tremor amplitude correlated with volcano explosivity and its potential use in determining ash hazards to aviation. U.S. Geol. Survey Bull. 2047, 377-385.

Miller, T.P. (1994). Dome growth and destruction during the 1989-1990 eruption of Redoubt Volcano, Alaska. In: T.P. Miller and B.A. Chouet (Eds.), The 1989-1990 Eruptions of Redoubt Volcano, Alaska. *J. Volcanol. Geotherm. Res.*, **62**, 197-212.

Newhall, C.G., and S. Self (1982). The Volcanic Explosivity Index (VEI): An estimate of explosive magnitude for historical volcanism. *J. Geophys. Res*. **87**, 1231-1238.

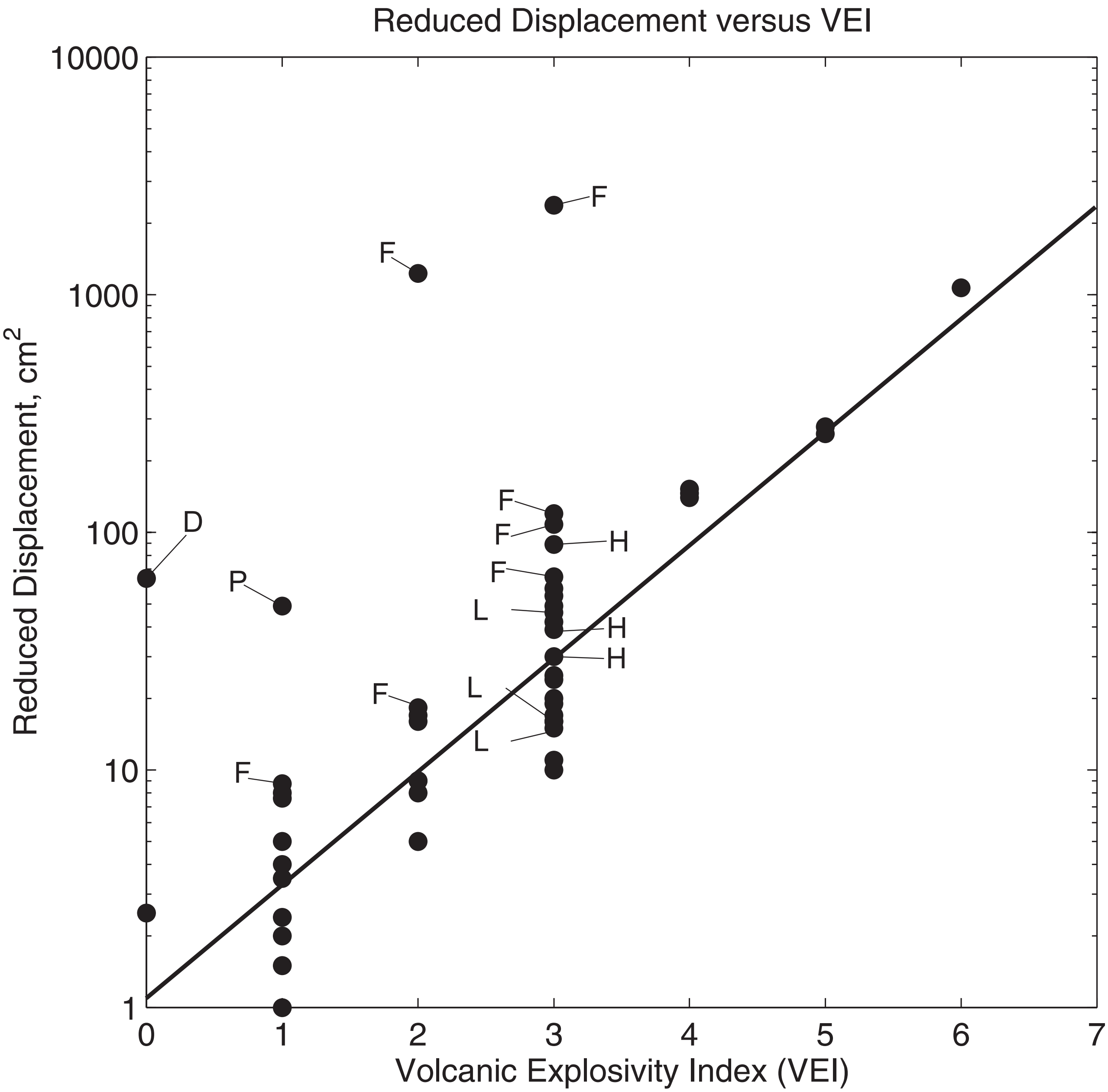


Figure 1. Reduced displacement, a normalized measure of amplitude, versus the Volcanic Explosivity Index for 50 eruptions at 31 volcanoes. The regression line is from McNutt (1994) based on a smaller data set and is shown for comparison. Fissure eruptions are labeled F; a phreatic eruption is labeled P; deep (40 km) tremor from Kilauea is labeled D (no eruption for this one); and three pairs of values from VEI=3 eruptions with high and low gas content are labeled H and L, respectively.

SURPRISE/SUDDEN ONSET ERUPTIONS: THE CASE OF REVENTADOR VOLCANO-ECUADOR, 03-NOVEMBER, 2002

Patricia Mothes, Minard L. Hall, Patricia Ramón and Hugo Yepes
Instituto Geofísico, Escuela Politécnica Nacional, Quito-Ecuador

Not all volcanoes show a progressive build up over weeks and months of precursory activity prior to a major eruption. Several of these include Redoubt (1989) and most recently Reventador in eastern Ecuador. Prior to Reventador's VEI 4 subplinian eruption on 03 November, 2002, 10 seismic events were registered on 06 October, 2002 by the two telemetered seismic stations closest to the active cone. Superficial manifestations observed from a nearby construction camp were minor. On the day of the eruption only seven hours of tremor and >100 local earthquakes preceded the paroxysmal eruption at 09H12 (LT) that resulted in a 17 km high ash-rich column and 5 andesitic pyroclastic flows which descended 9 km down valley. Ash clouds entered the populated InterAndean Valley and ash began falling between 12H00 and 16H00 depositing a 5-15 mm thick layer. Quito's International Airport, 100 km west of the volcano, was closed officially at 12H45, hence most aircraft remained at the airport and were completely covered by the ash. Reventador has had at least 7 eruptive periods since 1900. In this most recent episode, the rapid ascent of volatile-rich magma was mainly aseismic. Only telemetered seismic stations operating directly on the cone may have provided a clearer warning of the impending eruption. Reventador is similar to several other active volcanoes in Ecuador which have minimal or no monitoring because of the "low" direct risk they present to important population centers. Airlines and local Civil Aviation could opt to contribute to establish more intense monitoring of these volcanoes to maximize eruption predictive capacity and at the same time have plans in place to deal with unexpected-surprise eruptions.

ASHFALL SCENARIOS AND AVIATION IMPACTS OF FUTURE ERUPTIONS OF COTOPAXI VOLCANO-ECUADOR

Patricia Mothes, Minard L. Hall, Pablo Samaniego and Hugo Yepes
Instituto Geofísico, Escuela Politécnica Nacional, Quito-Ecuador

Cotopaxi is a 5900 meter high stratocone on the eastern edge of the densely populated InterAndean Valley. In November, 2001 Cotopaxi's monitoring network began to display frequent and intense anomalous seismic events. Although this activity has mostly subsided, it may be a long-term warning that a slow awakening is occurring. The volcano's last important eruption was in June, 1877. Covered by ~14 km^2 of ice and snow, Cotopaxi is well known for its destructive lahars that have traveled down all 3 main drainages. Ashfalls also had important consequences for the agriculturally-based communities during the 13 notable VEI 3-4 magnitude eruptions of the 18^{th} and 19^{th} centuries. Extensive field mapping of 10 main ash fall units of the Holocene shows that the bulk of the coarser tephra has been deposited to the W-NW of the cone and that in only two cases have important ash/pumice layers been deposited to the east. As seen during recent eruptions of other Ecuadorian volcanoes, windshearing is common after the column enters the stratosphere, directing the fines-component of ash clouds eastward. Historic accounts following Cotopaxi eruptions report fine ash falls as far north as Pasto- Colombia, to Piura- Perú, to the south, and westward upon coastal Ecuador where ash falls often persisted 4 to 5 days. Future eruptions are likely to be of similar VEI 3-4.5 magnitude, producing plinian columns and pyroclastic flows, which have the effect of injecting ash-rich clouds high into the stratosphere, potentially affecting national and international airline traffic for many days in all of Ecuador, and perhaps on a regional scale. In all probability, the three main international airports- Quito, Latacunga and Guayaquil will suffer some consequences of ashfalls.

AIRBORNE ASH HAZARD MITIGATION IN THE NORTH PACIFIC: A MULTI-AGENCY, INTERNATIONAL COLLABORATION

Christina Neal and Alaska Volcano Observatory staff, U.S. Geological Survey, Anchorage, AK, USA
Olga Girina, Kamchatkan Volcanic Eruption Response Team, Petropavlovsk, Russia
Gail Ferguson, Federal Aviation Administration, Anchorage, AK, USA
Jeffrey Osiensky, NOAA, National Weather Service, Anchorage, AK, USA

More than 100 active volcanoes bordering the Pacific Ocean from southern Alaska, along the Aleutians, Kamchatka and through the Kuriles, pose a significant risk to aviation. To address this problem, scientific institutes, federal and state/regional governmental agencies, international organizations, and private industry work together to ensure effective volcanic hazard warnings. The principal earth science agencies responsible for detecting and issuing warnings of volcanic unrest in Alaska and Russia are the Alaska Volcano Observatory (AVO) and the Kamchatka Volcanic Eruption Response Team (KVERT). AVO and KVERT utilize real-time seismic networks, satellite remote sensing of ash and thermal anomalies, and visual observations to detect and characterize volcanic activity. Warnings are issued as quickly as possible by phone, fax, and the Internet to an established recipient list. Information is also rapidly posted on the Internet. AVO works closely with the National Weather Service, the Federal Aviation Administration, and others to ensure that formal operational guidance to the aviation community contains all critical volcanic hazard information. KVERT has a similar relationship with the regional aviation and meteorological authorities in Kamchatka. AVO and KVERT also issue weekly status reports on all seismically monitored volcanoes and conduct scientific studies in support of hazard assessments. Both groups utilize a 4-level, color-coded alert scheme to summarize the severity of volcanic unrest and hazard. Agency responsibilities, relationships, and operational protocols for eruptions in Alaska are formalized in the "Alaska Interagency Operating Plan for Volcanic Ash Episodes". Frequent review of response protocols is necessary to maintain proficiency and to meet demands for increasingly rapid communication of volcanic hazards.

GROUND-BASED DETECTION OF VOLCANIC ASH AND SULPHUR DIOXIDE

Fred Prata, CSIRO Atmospheric Research, Aspendale, Australia
Cirilo Bernardo, CSIRO Atmospheric Research, Aspendale, Australia

We present the first thermal infrared image data showing detection and discrimination of volcanic ash and sulphur dioxide gas emitted from erupting volcanoes. The images are acquired from a new multichannel uncooled thermal imaging camera suitable for deployment within ~10 km of an active volcano. Algorithms for ash and SO_2 detection are described. Images from the system, named G-bIRD (Ground-based InfraRed Detector) are acquired rapidly (within a few seconds), analysed and transmitted via satellite or landline to a computer with access to the Internet and utilising a standard web browser. Tests of the system have been undertaken at Etna and Stromboli, Italy, at Anatahan, NMI and at Tavurvur, Rabaul and results will be presented. G-bIRD offers a new means for monitoring hazardous volcanic substances from the ground and could provide complementary information for providing volcanic ash and SO2 warnings to the aviation industry.

THE NEW ZEALAND VOLCANO ALERT LEVEL SYSTEM – ITS PERFORMANCE IN RECENT ERUPTIVE ACTIVITY

Bradley Scott, Institute of Geological and Nuclear Sciences,
Wairakei, New Zealand

In November 1994, the New Zealand Ministry of Civil Defence introduced a new annex entitled ‘Volcanic Impacts’ into the National Civil Defence Plan. This was based on a five level volcanic alert system that encompassed all volcanoes in New Zealand. The newly introduced volcano alert system received its first significant test with eruptions at Ruapehu volcano from December 1994-April 1995; we learnt some important lessons that highlighted several operational problems with the system. A revised system was introduced in August 1995 by the Ministry. On 18 September 1995, a major episode of eruptive activity commenced from Crater Lake, Mt Ruapehu with large explosions expelling the crater lake, producing lahars through ski fields and an eruption plume over 10 km high; activity continued for weeks, testing the revised system. The revised volcano alert system is based on six levels and has two separate schemes that clearly differentiate between frequently active volcanoes and reawakening activity at a dormant volcanic centre. The system provides an indication of eruptive status and is not intended to be predictive. This revised system has been effectively used during the 1995 and 1996 eruption episodes at Ruapehu and during recent eruptions at White Island (1998-2001). The introduction of a volcano alert level system has produced a uniform platform for responding agencies like central and local government, critical industries/services, aviation and the public to focus their response on. Based on experiences with the Ruapehu eruptions, volcano contingency planning now uses the alert levels as the basic building block for that process. This presentation will outline aspects of the recent eruptions, the interaction with the alert levels and comment on our experiences.

STATUS OF MONITORING ACTIVE VOLCANOES OF THE KURILE ISLANDS: PRESENT AND FUTURE

Alexander V. Rybin[1], Y.V. Karagusov[2], Pavel Izbekov[3], Nikolay S. Terentyev[2], Vyacheslav B. Guryanov[1], Christina Neal[4], and Ken Dean[3]

[1] Institute of Marine Geology and Geophysics, Yuzhno-Sakhalinsk, Russia
[2] DalInformGeoCenter, Yuzhno-Sakhalinsk, Russia
[3] Alaska Volcano Observatory, Fairbanks, Alaska, USA
[4] Alaska Volcano Observatory, USGS, Anchorage, Alaska, USA

Abstract

Important international air routes from Asia to North America are located immediately above and to east of the Kurile Islands. There are thirty six volcanoes within the Kurile Island chain which are considered to be active, explosive, and capable of sending volcanic ash to altitudes used by commercial airliners. The remoteness and the lack of communication links hinder the development of the ground-based monitoring of the active volcanoes of the Kuriles. Therefore, the efficient use of satellite imagery and coordinated multi agency efforts in response to volcanic events are required to reduce the risk for aviation.

Part of the "Pacific Rim of Fire", the 1250-km-long chain of Kurile Islands extends from Kamchatka Peninsula, Russia to Hokkaido Island, Japan. It consists of 68 volcanic centers, among which 36 are considered to be active, i.e. have records of historic eruptive activities (Figure 1). On average, large eruptions (VEI 4) have occurred in the Kuriles every 33 years; moderate-large (VEI 3) eruptions every 22 years; moderate eruptions (VEI 2) every 11 years; and small eruptions (VEI 1) every 1-5 years. Sixty eruptions were recorded in the Kuriles during the 20th century, among which the most significant were the eruptions of Tiatia, Grozny, Sarychev, Severgin, Raikoke, Ebeko, and Alaid (Gorshkov, 1967; Simkin & Siebert, 1994). The most recent examples include the eruption of Chikurachki volcano in April-June 2003 and the eruption of Chirinkotan volcano in July 2004. Eruptions are typically explosive and capable of sending volcanic ash to an altitude of 11 km (36,000 ft) and higher, thus posing a potential danger to aviation.

Although the population of the Kuriles is quite sparse, there are several permanent settlements on the southern islands of Kunashir, Iturup and Shikotan, as well as on the northern islands of Paramushir and Shumshu. With the exception of the settlement on the Shikotan Island, all others are located in the vicinity of active volcanoes, and eruptions may also cause a significant impact on a population and infrastructure of the settlements.

The most reliable method of volcano monitoring includes the use of ground-based seismic networks providing real-time data on the seismicity beneath active volcanoes. An increase in seismicity may be used as an early warning of an eruption. Unfortunately, there are no permanent seismic networks in the Kuriles. At present, there are only four single component seismic stations in the entire Kurile arc (on the flank of the Alaid volcano, in Kurilsk, Yuzhno-Kurilsk, and Severo-Kurilsk settlements). These stations provide rudimentary seismic data for a few volcanoes, whereas the majority of the active volcanoes are tens to hundreds of kilometers from the nearest station. Installation of the permanent local seismic networks is expensive and feasible only for a few volcanoes which pose a threat to local communities (i.e. Tiatia, Mendeleev, Grozny, Baransky, Chirip, Ebeko, Chikurachki, and Alaid). Remoteness and the lack of communication links will likely preclude the establishment of the regular seismic monitoring (and/or ground observations) for most of the Kuriles for the next few decades.

It appears that remote sensing is the most convenient and cost-effective approach to regular volcano monitoring of the Kuriles. At present, two major sources of the satellite data are used by our group in daily observations: (1) AVHRR data from the NOAA series of polar orbiters and (2) MODIS data from Terra and Aqua satellites.

From 1995 to 2000, AVHRR data from NOAA-12 and NOAA-14 satellites have been acquired locally by the Institute of Marine Geology and Geophysics (IMGG) using the "ScanEx" receiving station made by the Research & Development Center ScanEx, Moscow (http://www.scanex.ru). Although there were a few confirmed small eruptive events during this period of observation the low spatial resolution of AVHRR imagery did not allow their detection. For instance, according to visual observations by on site observers a phreatic eruption of Kudriavy volcano on October 7, 1999 produced a small volcanic ash cloud, which reached an elevation of 1000 meters above sea level. The temperature of a small, hydrothermally heated area at the volcano reached 30°C with the temperatures of emissions from individual fumaroles exceeding 900°C. This activity was not detectable in either the visual, or infrared bands of AVHRR imagery. Meanwhile, the larger scale ash producing eruptive events in the neighboring Kamchatka have been reliably detected and reported to our Kamchatkan colleagues, e.g. 1995 eruption of Bezymianny (Abdurakhmanov et al. (2001).

Since 2001 MODIS data have been acquired by the DalInformGeoCenter of the Ministry of Natural Resources of Russia in Yuzhno-Sakhalinsk using the "UniScan" ground receiving station made by the aforementioned R&DC ScanEx. Compared to AVHRR, MODIS data has significantly improved spectral and spatial resolutions, i.e. 36 channels in visual, NIR and IR spectrums with 250, 500 and 1000 meter resolutions, respectively. Since the launch of Aqua satellite in 2002, we have been able to acquire two swaths daily for the Kuriles. The entire station mask covers the area from the Arctic regions to Taiwan Island and from the Anadyr Bay to the Western Siberia (Figure 2). In 2003, the DalInformGeoCenter resumed the acquisition of NOAA AVHRR data. At present, more than twenty two swaths are received daily for the Kuriles from NOAA-12, 14, 15, 16, and 17 satellites. Our monitoring capabilities will improve following the anticipated upgrade of the receiving station by summer 2004, which will allow acquisition of MSU-E and MSU-SK data from the Meteor-3M satellite with 35-m and 250-m ground resolutions respectively.

Beginning in January 2003, our Sakhalin-based group of scientists from IMGG and DalInformGeoCenter has performed satellite observations of the Kurile Islands on a regular basis. The high spatial resolution of MODIS imagery complemented by the high temporal resolution of AVHRR data allowed us to observe the 2003 Chikurachki eruption (Figure 3) as well as the manifestations of moderate volcanic activity, i.e. steam plumes at Sinarka and Severgin volcanoes, mud flows from Tiatia volcano (Figure 4), and most recently the gas and ash plume at Chirinkotan volcano. Because of a high volume of the original data, it is first processed at the receiving stations of DalInformGeoCenter, which includes (1) acquisition of the raw data from satellites, pre-processing and calibrating, (2) georeferencing the data, (3) extracting the sub sectors covering the Kuriles (Figure 2), and (4) converting data to BMP and JPEG formats. This allows us to reduce the MODIS data to three files totaling 5 Mb in size (Table 1). As soon as processing is completed, these images are sent via email to the Volcanological Laboratory of the IMGG, where they can be interpreted by volcanologists.

Over the course of the next year, we hope to streamline this process to improve the timeliness of observation and reporting. We also intend to incorporate any information from Kurile seismic stations and ground observers and eventually distribute Kurile Volcano Information Statements to aviation and meteorological authorities for wider distribution in support of aviation safety. At present, we are still gathering financial and organizational support and working with colleagues at the Alaska Volcano Observatory and KVERT to develop reliable communication protocols.

References

Abdurakhmanov A.I., Bulgakov R.F. & Guryanov V.B (2001) An analysis of a thermal anomaly due to eruption products of Bezymianny volcano discharged October 6-8 1996 based on NOAA satellite spectrozonal information. Volcanology and Seismology, v.5, pp. 63-72 (in Russian).

Gorshkov, G.S. (1967) Volcanism of the Kurile island arc, Academy Nauk USSR, Moscow, 286 pages (in Russian).

Dean, K. G., Dehn, Jon, Engle, Kevin, Izbekov, Pavel, Papp, Ken, and Patrick, Mathew (2002) Operational satellite monitoring of volcanoes at the Alaska Volcano Observatory. in Harris, A. J. H., Wooster, M. J., and Rothery, D. A., eds., Monitoring Volcanic Hotspots Using Thermal Remote Sensing: Advances in Environmental Monitoring and Modelling, v. 1, n. 3, p. 70-97, available at http://www.kcl.ac.uk/advances

Simkin, T.S. & Siebert, Lee (1994) Volcanoes of the world: a regional directory, gazetteer, and chronology of volcanism during the last 10,000 years. 2 ed. 1994: Geoscience Press, Tucson, AZ, 349 pages.

Table 1. MODIS bands used to produce the color-composite images used in our daily monitoring

MODIS file name (example)	Spatial resolution (meters)	Bands	Wavelength range	Image size (Mb)	Application
MOD02QKM.A0403040013r	250	1 2	620-670 nm R,B 811-876 nm G	3	Volcanic clouds
MOD02HKM.A0403040013r	500	3 5 7	469-479 nm B 1230-1250 nm G 2105-2155 nm R	1,5	Volcanic clouds and thermal anomalies
MOD021KM.A0403040013r	1000	20 22 23	3,66-3,84 um B 3,929-3,989 um G 4,020-4,080 um R	0,6	Thermal anomalies

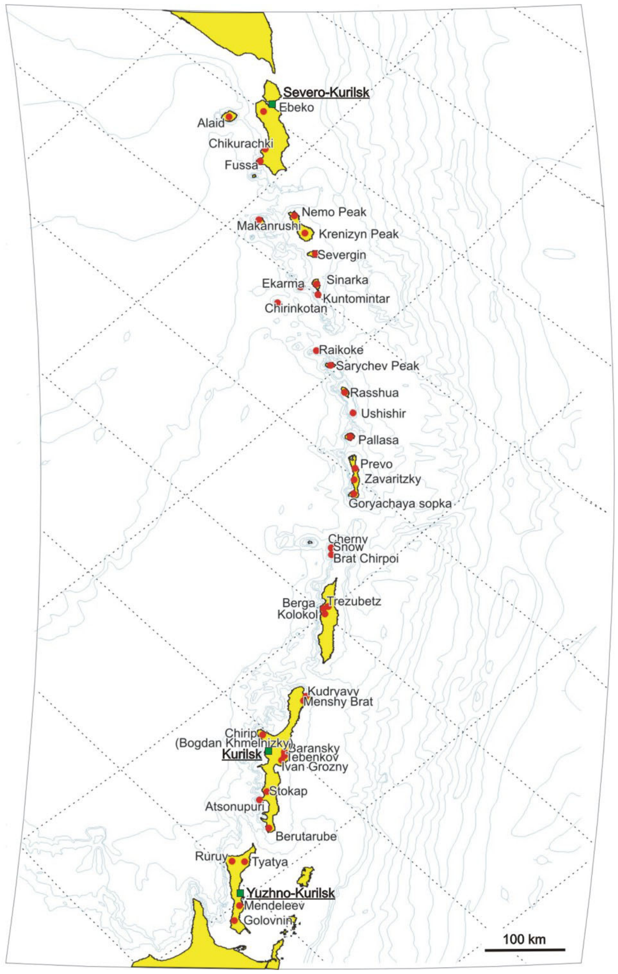


Figure 1 Map of Kurile Islands. The locations of active volcanoes are indicated by solid dots, main settlements are indicated by solid boxes with their names underlined.

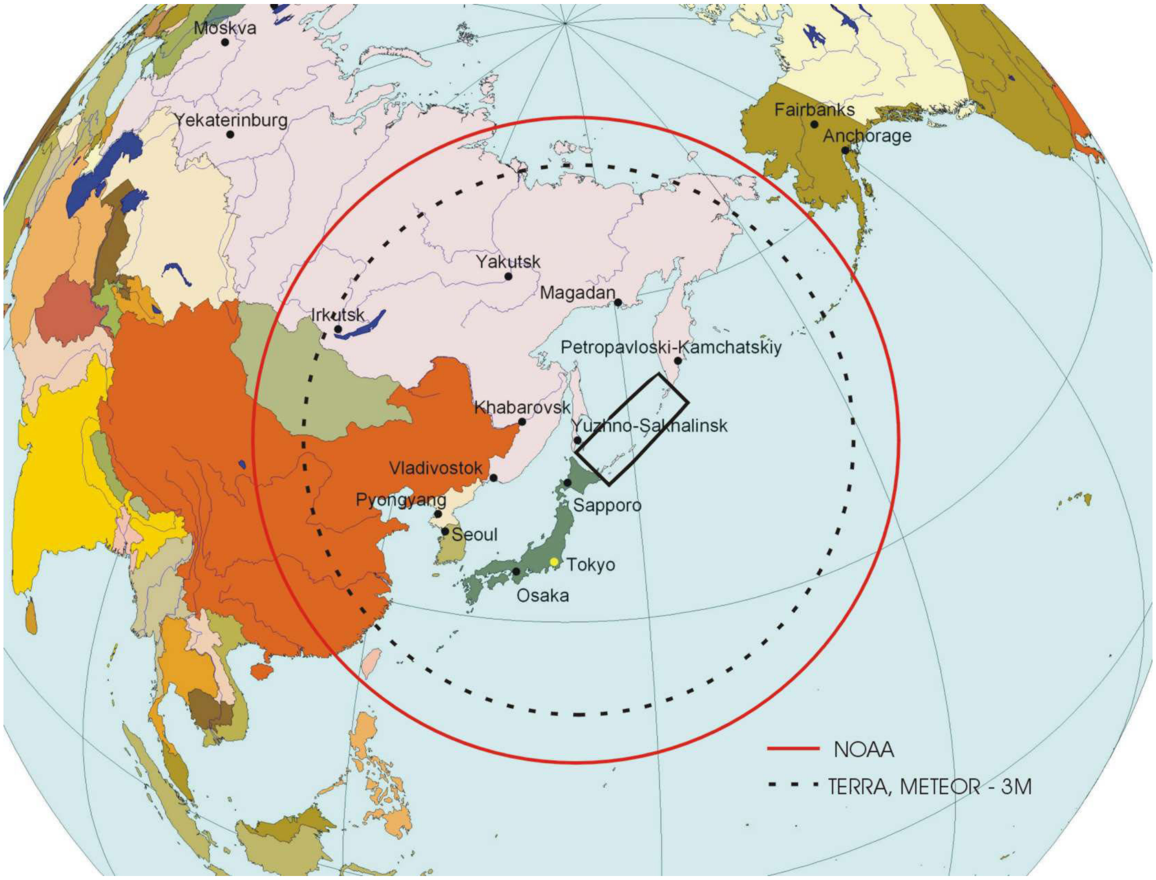


Figure 2 The DalInformGeoCenter's station mask for NOAA series polar orbiters (red circle) and for Terra, Aqua, and Meteor-3m satellites (black dotted circle). The Kuriles sub sector is shown by a black open rectangle.

Figure 3 Color-composit MODIS image of the erupting Chikurachki volcano acquired on April 22, 2003.

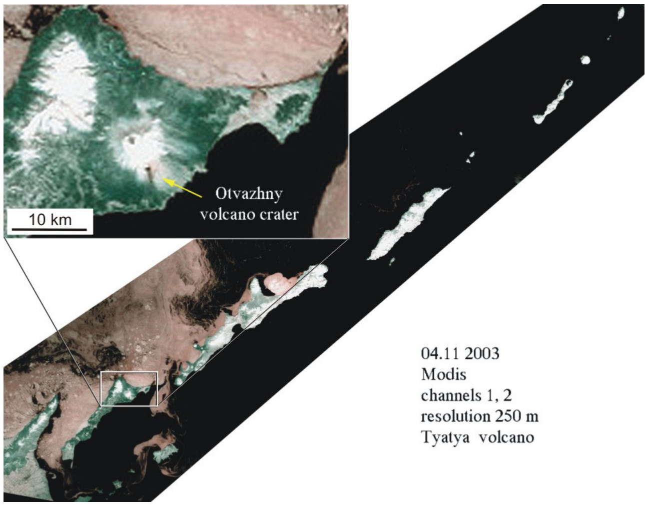


Figure 4 Color-composit MODIS image acquired on April 11, 2003 showing the mud flow from the Otvazhny crater of Tyatya volcano.

TOTAL WATER CONTENTS IN VOLCANIC ERUPTION CLOUDS AND IMPLICATIONS FOR ELECTRIFICATION AND LIGHTNING*

Earle R. Williams[1], Stephen R. McNutt[2]
[1]MIT Lincoln Laboratory, Lexington, Massachusetts
[2]UAF Geophysical Institute, Fairbanks, Alaska

1. INTRODUCTION

The fundamental role of ice particle collisions in the separation of electric charge and generation of lightning in thunderclouds is now reasonably well established (Latham, 1981; Williams, 1985; Saunders, 1995). Charge separation and lightning are also prevalent in volcanic eruptions. A recent literature survey by McNutt and Davis (2000), and its recent extension, has shown more than 150 incidents of volcanic lightning. The efficacy of the ice-based process in thunderclouds has raised the interest in the possible applicability of the same process to a class of explosive volcanic eruptions. This study is concerned with an evaluation of volcanic eruptions as atmospheric ice factories.

The behavior of water in magma within the Earth is reasonably well understood in volcanology, and the behavior of water in the atmosphere is adequately understood in meteorology. The perceived gap in understanding lies in the transition from Earth to atmosphere. This study is aimed at bridging this gap.

2. WATER CONTENT IN EXPLOSIVE MAGMA

Volatiles in magma have been well studied (Johnson et al, 1993; Wallace and Anderson, 2000; Wallace, 2004). The volatiles of greatest scientific interest have been H_2O, CO_2, and SO_2, but water is dominant in total mass by more than an order of magnitude. The solubility of water in magma is known to increase with pressure, and this physics is basic to explosive volcanism (Wilson et al, 1980). The water contents of magmas are traditionally estimated as a percent by weight of the magma. Numbers in the literature in a wide variety of studies, sampled in Table 1, are remarkably consistent.

Volcano	Water Content (Wt %)	Investigator
Bezymianni (1955)	4	Markinen (1962)
Cerro Negro	3 – 6	Roggensack et al (1997)
Fuego	1 – 6	Sisson and Layne (1993)
Mt. St. Helens	4.6 – 6.1	Carey et al (1995) Gardner et al (1995)
Pinatubo (1991)	5	Wallace and Gerlach (2004)
Vesuvius (79 AD)	3.5 – 4.7	Cornell (1987)

Table 1: Water Content of Explosive Magma

The water contents in Table 1 are large from a meteorological perspective. For example, a cubic meter of magma at depth with mean magma density 2.5 gm/m^3 and with 4% water by weight contains 100 kilograms of water. In condensed form, this is 100 liters of liquid. Following the Clausius-Clapeyron relation, this amount in vapor form is sufficient to saturate 4000 m^3 of tropical atmosphere at a temperature T=30^{o}C. At a temperature T= -50^{o}C typical of conditions at the tops of Plinian eruption clouds, the same mass of water vapor is sufficient to ice-saturate more than 10^7 m^3 of atmosphere.

3. EXPLOSIVE ERUPTIONS AND THE RELAXATION VOLUME

Water is widely recognized as the working substance of explosive volcanic eruptions. Water dissolved in magma at depth, and with typical weight % values given in Table 1, is exsolved to vapor in bubbles as the magma ascends and the pressure declines (Wilson et al, 1980). If the vapor phase remains disconnected in the magma, typical of isolated bubble inclusions in the magma matrix and typical of explosive eruptions over subduction zones, large confined gas pressures can develop. When the highly viscous magma fractures at a

* This work was sponsored by the National Aeronautics and Space Administration (NASA) Contract No. F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Government.

Corresponding author address: Dr. Earle R. Williams, Massachusetts Institute of Technology Lincoln Laboratory, 244 Wood St., Lexington, MA 02421-0000, earlew@ll.mit.edu

Corresponding author address: Dr. Stephen R. McNutt, Alaska Volcano Observatory, UAFGI, P.O. Box 757320, Fairbanks, AK 99775-7320, steve@giseis.alaska.edu

critical porosity (Gardner et al, 1996), the stored energy is released explosively, with an ultimate relaxation of the elevated pressure to ambient atmospheric pressure P_o.

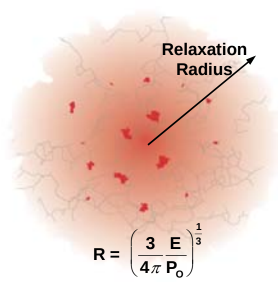
Conservation of energy for a simple spherical explosion equates the available energy E and the pressure-volume work performed against the ambient atmospheric pressure P_o:

$$E = P_o (4\pi R^3/3) \qquad (1)$$

A rough estimate for the explosion radius R, the so-called 'relaxation radius' (Few, 1980), is then given by:

$$R = (3E/4\pi P_o)^{1/3} \qquad (2)$$

This process is illustrated in Figure 1. Though ignored in this simple calculation, the relaxation volume will invariably be highly turbulent and involve a homogenization of the exploding material with the ambient atmosphere. Figure 1 also provides numerical estimates for different kinds of explosions. Detonations of small Chinese firecrackers have relaxation radii of centimeters, whereas energetic Fourth of July 'bombs' show relaxation smoke clouds of order meters. For a Krakatoa-level explosive eruption with estimated total energy 10^{17} joules, the relaxation radius is more than 4000 m. These scales are commensurate with the updraft widths of thunderstorm supercells (Williams, 2001), the largest and most violent form of convection known to terrestrial meteorology.



Source	E (joules)	R (m)
Chinese Firecracker	30 joules	2×10^{-2} m
Stick of Dynamite	2×10^{6} joules	0.6 m
1 kT Explosive	4.2×10^{12} joules	220 m
Krakatoa Eruption	10^{17} joules	4300 m

Energy E of explosion invested in expansion against ambient pressure P_O

$$P_O\left(\frac{4}{3}\pi R^3\right) = E$$

Figure 1: The eruption bomb based on water substance: illustration of the physical process of the relaxation radius, and some calculated values.

The relaxation radius concept was developed initially to treat the cylindrical explosions around lightning channels (Few, 1980), with the aim of estimating the dominant acoustic frequency of thunder. The dominant acoustic wavelength is of the order of the relaxation radius. For this reason, Chinese firecrackers emit in the acoustic range for human hearing and exhibit a sharp 'crack', whereas much longer wavelengths are dominant for explosions in the category of volcanic eruptions, inaudible at distance. Hence there is current interest in detecting volcanic eruptions worldwide with infrasonic methods (Bass et al, 2004).

4. THE WATER CONTENT AND TEMPERATURE IN ERUPTION CLOUDS

The relaxation volume together with estimates of magma water content and temperature enable estimates of both the average water content and temperature of eruption clouds. In both cases, it is assumed that the magma property is distributed homogeneously within the ultimate relaxation volume.

The water content is considered first. A lower bound on cloud water content is considered by assuming the ambient atmosphere to be completely dry. The favorable assumption is also made that all of the water dissolved at depth is released to the atmosphere in the explosion. This assumption is supported by the observations that the porous (water vapor) phase is connected (Gardner et al, 1996) in post-explosive tephra. Under this assumption, the mean cloud water content (MWC) is simply:

$$MWC = \frac{\text{total water in magma}}{\text{relaxation volume}} \qquad (3)$$

$$= \frac{(\text{wt\%})(\text{total tephra mass})}{(E/P_o)} \qquad (4)$$

$$= \frac{(\text{wt\%}) M P_o}{E} \qquad (5)$$

A useful reference point for total energy E is the design threshold for the Comprehensive Test Ban Treaty (CTBT) network (Sullivan, 1998): a bomb yield of 1 kiloton (1 kT = 4.2×10^{12} joules). The total energy on the scale of Volcanic Explosivity Index (VEI) (Simkin and Siebert, 1994) is not specified, but if the gravitational potential energy of the lofted tephra is 1% of the total energy, then a 1 kT event is at the low end of the VEI scale (VEI~0) where the tephra volume M ~10^4 m^3. Following Figure 1, the relaxation radius for a 1 kT total energy is ~220 meters.

If M is proportional to energy, the general assumption in considerations of VEI (Simkin and Siebert, 1994), and wt% is independent of eruption magnitude (broadly supported by the results in Table 1), then it follows that:

$$MWC = (wt\%)\,(620) \quad gm/m^3 \quad (6)$$

And for a representative value of wt% = 5 (based on Table 1):

$$MWC \sim 30 \ gm/m^3 \quad (7)$$

From a meteorological perspective, this number is again large. It exceeds by 50% the value needed to saturate air at 30°C. It exceeds by more than two orders of magnitude the value needed to saturate the upper troposphere at typical ambient temperatures. These comparisons suggest that the assumption of a dry entrained atmosphere is not a bad one, because the entrainment of a realistic moist atmosphere would not change the estimates appreciably. The magma water dominates the water budget.

Here it has been assumed that the eruption cloud will have the same temperature as the atmospheric environment in which it is mixed. Such is not strictly the case, but the cloud temperature can be estimated from similar considerations of the relaxation volume.

If the pre-explosive hot porous magma causing a volcanic explosion has temperature T_M and volume V_M, then the average temperature of the eruption cloud can be estimated from the volume mixing law:

$$V_M T_M + V_A T_A = (V_M + V_A)\, T_C \quad (8)$$

$$T_C = \frac{V_M T_M + V_A T_A}{(V_M + V_A)} \quad (9)$$

V_M is directly related to the VEI (Simkin and Siebert, 1994) and V_A is essentially the relaxation volume. Taking values for the nominal 1 kiloton explosion, VEI = 0 case, we have $V_M = 10^4$ m^3, $V_A = 4.2 \times 10^7$ m^3, $T_M = 1000°C$, $T_A = 30°C$, we obtain a mean cloud temperature from equation (1):

$$T_C \sim 30.2°C \quad (10)$$

which is only 0.2 °C warmer than the atmospheric environment. This modest temperature perturbation is expected in general because $V_M \ll V_A$, despite the large temperature contrast between magma and atmosphere.

This result suggests that the rapidly rising cumuliform towers in explosive eruptions are caused primarily by the kinetic energy of the explosions (on the way to the relaxation radius), rather than by cloud buoyancy forces set up by cloud-atmosphere temperature contrasts. This conclusion must be considered tentative however, as it is based on a thorough mixing of the explosion emission over the entire relaxation volume. In the case of the 1980 Mt St Helens eruption, the lateral blast that initiated the eruption was clearly NOT well mixed with environmental air (Kieffer, 1981), and substantial enhancements of temperature (>100 °C) were documented. Modelling studies of eruptions (e.g., Woods and Self, 1992) show 20-30 ° C temperature contrasts between plume and environment. Furthermore, Pack et al (2000) have documented thermal anomalies from space indicative of strong temperature perturbations in Plinean eruptions, but more interpretation of these anomalies is needed. For the calculations here, we are not concerned with the short time scales of the initial blast, however, but rather the disposition of temperature and water substance at the time of 'relaxation'.

5. SUPPORTING OBSERVATIONS OF WATER SUBSTANCE IN VOLCANIC ERUPTION CLOUDS

The foregoing calculations suggest that condensation of water vapor to the liquid and solid phase should be a common occurrence in explosive volcanic eruptions. How do these simple predictions square with available observations?

Regarding the evidence for liquid water in volcanic eruptions, Clarke (1821) describes observations of the May 31, 1806 eruption of Vesuvius in Italy: "two places were deluged with a thick black rain, consisting of a species of mud filled with sulphureous particles". In the case of the more recent Mt St Helens eruption in 1980, Waitt (1981) reports, "…dark gray pisolitic mud fell from the second high-level cloud", and Thompson (2000) notes "…mud balls the size of a half-dollar fell like rain for several minutes". In tropical eruptions, wet conditions have also been documented, though in these cases the interpretation is less clear-cut, owing to the abundance of moisture and the prevalence of natural precipitating convection that may be processing atmospheric water vapor rather than magma water. Nevertheless, the reports form the tropics are worth noting in light of the predictions. In the case of the Rabaul volcano, Rose et al (1995) reported, "some of the ash fallout was very wet, and a 'rain of mud' occurred in some areas around Rabaul". For the Pinatubo (Philippines) eruptions in 1991, Oswalt et al (1996) reported: "Tephra fall continued throughout the day…varying from completely dry ash through a cement-like mud, to muddy water". Paladio-Melosantos et al (1996) document Pinatubo conditions as follows: "An area of about 2000 square kilometers was blanketed by 10 to 25 centimeters of rain-soaked tephra." Note that a typhoon accompanied the Pinatubo eruption so some of the water came from the typhoon.

In addition to this evidence for liquid water, ice has been reported in volcanic eruptions in a few instances. Owing to the lower saturation thresholds and the prevalence of subfreezing conditions in the upper troposphere, ice is expected to be the most prevalent fate of magmatic water. In the case of the Surtsey volcano in Iceland, Thorarinsson (1966) reported, "…fallout of icy pyroclasts onto local ships was described as hail showers with a grain of ash within each hailstone". Using remote sensing methods on the Rabaul volcano, Rose et al (1995) "…report the detection, using a satellite-borne infrared sensor, of >million tons of ice in the cloud". For the 1980 eruption of Mount St. Helens, Hoblitt (2000) states, "upon the arrival of the yellow cloud, ice and ice-cold mudballs began to fall…". Of the same eruption, Thompson (2000) notes: "ice-cube sized chunks of glacier ice began pelting the ground…". In the latter case, the interpretation is again fuzzy, as the ice particles could have originated from glacial ice on the volcano slope, rather than from magmatic water. Note the small number of cases cited here. Ironically, these observations, which are key for lightning studies, are not made systematically for volcanoes.

6. IMPLICATIONS FOR MICROPHYSICS IN VOLCANIC CLOUDS

The evidence for an abundance of water in all three phases in eruption clouds has important implications for the cloud microphysics occurring therein. Textor et al (2003) have already treated some of these processes in numerical simulations of volcanic clouds.

Firstly, the fine volcanic ash particles will serve as nuclei for condensation—cloud condensation nuclei for the liquid phase of water and ice nuclei for the solid phase (Mason, 1971; Hobbs, 1975). The high concentrations of such nuclei in volcanic clouds in comparison to the concentration of natural aerosol in thunderclouds will likely serve to keep the nucleated cloud droplets and ice crystals small, thereby suppressing the precipitation process (by either coalescence or by riming).

Secondly, the classical Bergeron process involving the liquid and solid phases of water is expected to be active in the mixed phase region of volcanic eruptions where the in situ temperature lies between 0^oC and -40^oC. This process will stimulate the growth of ice crystals at the expense of the liquid droplets.

Thirdly, given the presence of supercooled water droplets and ice particles, the riming process should occur for the larger, faster-falling tephra particles, with consequent accretion of ice on the surfaces of these particles, so long as the supercooled droplets are not too small. In eruptions clouds with extreme updrafts, substantially larger than those in thunderclouds, the available time for riming is expected to be shorter. Nevertheless, the collection action of nucleation and riming are expected to coat the volcanic particles with water substance in ether liquid or solid form, with considerable efficiency. This widespread coating of the volcanic debris would seem to preclude mechanisms for charge separation based on tribo-electrification of silicate mineral surfaces. At least within the mixed phase region, often half the depth of the troposphere, ice particle collisions need to be considered in the electrification process.

7. GROSS ELECTRICAL DIPOLE STRUCTURE OF VOLCANIC ERUPTIONS

A characteristic feature of ordinary thunderstorms is their gross positive dipolar structure—positive charge in upper levels and negative charge at lower levels of the ice region. A weak test of whether ice is responsible for the charge separation in volcanic eruptions is the inquiry into the gross charge structure of eruptions. The available observations summarized in Table 2, show gross positive dipole structure and so pass this weak test. The test is 'weak' because one has a 50-50 chance of being correct.

Anderson et al (1965), Surtsey volcano
"…downwind, there is a region of negative charge beneath the region of positive charge."

Cobb (1980) Mt. St. Helens volcano
"the measurements always indicated a positively charged plume"

Hobbs and Lyons (1983), Mt. St. Helens volcano
"negatively charged particles at lower altitudes, and positively charged particles higher up"

Hoblitt (1994), Redoubt volcano
"the flash polarity tended to change through time from negative to positive"

Lane and Gilbert (1992), Sakurajima volcano
"positive charges develop in the gas-rich top and negative charges in the ash-rich part of plume"

Gilbert and Lane (1994), Sakurajima volcano
"positive charges dominate at the top of the plume and negative charges dominate at the base"

McNutt and Davis (2000), Mt Spurr volcano
"thunderstorms…and eruptions…both show the same sequence of first negative, then positive…"

Table 2: Gross Dipole Polarity of Eruption Clouds

Eruptions such as Mt St. Helens in May 1980 (Cobb, 1980) grow to heights greater than the tallest thunderclouds, and given the foregoing calculations, are expected to be rich in ice in upper levels. Some of the eruption clouds documented in Table 2, however, have insufficient depth to penetrate the cold part of the troposphere, and in this case, their inclusion in the table may not be appropriate. It is however useful to consider in this context a meteorological entity composed of dry silicate minerals—the small vigorous vortices developing in desert environments called 'dust devils'. The desert conditions typically involve dry air (20% relative humidity or less), and deep boundary layers in which condensation and cloud do not occur. There can be little doubt that dust devils involve collisions between dry silicate minerals only—no liquid water and no ice is available. Electrical measurements show that the gross dipole polarity of dust devils is negative—i.e., negative charge in upper levels and positive charge at lower levels (Freier, 1960; Crozier, 1964; Ette et al, 1971). Freier (1960) refers to the dust devil dipole as an 'inverted thunderstorm'. This dust devil polarity is not consistent with any of the results in Table 2, even for the smaller eruptions (i.e., Sakurajima volcano) that are most likely NOT to contain ice.

The polarity behavior noted for cloud-to-ground lightning discharges from volcanic eruptions also bears a similarity with thunderstorms, as noted also in Table 2. Both Hoblitt (1994) and McNutt and Davis (2000) have noted a sequence of activity involving ground flashes of negative polarity followed by ground flashes with positive polarity. This behavior is characteristic of thunderclouds as they transition from their mature phase to their dissipating stage (Moore and Vonnegut, 1977; Williams and Boccippio, 1993).

8. IMPLICATIONS OF PREDICTIONS FOR THE SATELLITE-DETECTION OF ERUPTION CLOUDS

Satellite remote sensing of volcanic ash clouds has focused on the split window technique (Prata, 1989), based on the differential infrared response of dry volcanic ash. Ice is well known to show the opposite response (Prata, 1989). Ice-coated ash particles are expected to respond as ice. Given the calculations in the present study, one can expect difficulties with the split window technique in distinguishing thunderclouds from explosive volcanic eruptions. This expectation is borne out by the observations (Simpson et al, 2000; Tupper et al, 2004), and in many instances the dry ash signature will not appear strongly until the ice near the tops of eruptions clouds has sublimated to expose the dry ash.

'Dry' eruptions are referred to in the literature (Ellrod et al, 2002), but this is a relative term only. Given the water-based physics believed responsible for explosive eruptions, it is difficult to see how any eruption can be dry. Further observations of volcanic eruptions with fine time resolution from the earliest stages are needed to throw more light on this issue.

9. CONCLUSIONS

Calculations have been presented which treat the transferal of magma water in the Earth to eruptions clouds in the atmosphere. Volcanic lightning appears to be widespread, and the high water contents of magmas may be key to electrification processes. Under favorable assumptions, water in both its condensed phases is expected to be abundant in large Plinean eruptions. Further evidence involving gross electrical structure and lightning behavior is identified for a fundamental role for ice and lightning production in large eruptions. However, basic information on water and ice contents in volcanic plumes is poorly known. Instrumental electrical data and direct sampling of the water contents of ash columns and adjacent atmosphere are needed for at least a few case studies.

REFERENCES

The page limitation for this submission did not allow inclusion of references. These will be supplied on request from earlew@ll.mit.edu or steve@giseis.alaska.edu.

ACKNOWLEDGEMENTS

We appreciate discussions and correspondence on these issues with Marcia Baker, Gary Ellrod, Gerald Ernst, John Ewert, Fred Frey, Jennie Gilbert, Tim Grove, Marianne Guffanti, Paul Herzegh, Peter Hobbs, Rick Hoblitt, Patricia Mothes, Chris Newhall, Scott Oswalt, Dee Pack, Alex Proussevitch, Carl Rice, Bill Rose, Danny Rosenfeld, Tom Shaw, Lee Siebert, Tom Simkin, Inna Sofonova, Edna Sugihara, Christiane Textor, Andrew Tupper, Paul Wallace, Richard Waitt, Mark Weber and Rick Wunderman.

This research was supported by FAA's Oceanic Weather Program and by the NASA program on Advanced Satellite Aviation Products. We acknowledge Gloria Kulesa, Pete Kirchoffer, and John Murray for their support.

We thank Cynthia Woods and Nancy Bonanno for their kind assistance in the processing of the manuscript.

MODELING VOLCANIC ASH TRANSPORT AND DISPERSION: EXPECTATIONS AND REALITY

René Servranckx and Peter Chen
Montréal Volcanic Ash Advisory Centre, Canadian Meteorological Centre,
Meteorological Service of Canada

FINAGLE's LAWS OF INFORMATION:
The information you have is not what you want
The information you want is not what you need
The information you need is not what you can obtain
The information you can obtain costs more than you want to pay

1. INTRODUCTION

1.1 Finagle's aphorisms capture the essence of the volcanic ash transport and dispersion modeling problem. Forecasting accurately the transport of airborne volcanic ash is a complex challenge. Yet, improvements in model formulation, a rapid increase in computing power combined with 24-hr real time monitoring meteorological operations have lead to significant improvements in the prediction of airborne volcanic ash. It would be unthinkable to operate today without the use of volcanic ash transport and dispersion models (VATDM).

1.2 The aviation community operates in a very precise and high accuracy environment. Aircraft flying at high speed are separated vertically by only a thousand feet. The time of landing thousand of kilometers away can be predicted to within a few minutes. This naturally leads users to have high expectations for VATDM, given their usefulness and recent successes.

1.3 Users expect VATDM to produce accurate information on where ash is or isn't present both in time and space. As importantly, they expect this information to be delivered in a timely matter.

1.4 What do these expectations mean from a modeling perspective and, more importantly, can VATDM meet them? The objective of this paper is to discuss these points (''reality check''), to present some of the limiting factors and to suggest some areas for improvement.

2. BASIC COMPONENTS OF THE PROBLEM

2.1 In its simplest form, the problem of accurately forecasting ash with VATDM can be expressed as having 3 distinct components:

- VOLCANIC ASH SOURCE
- METEOROLOGY
- TRANSPORT AND DISPERSION

2.2 The **VOLCANIC ASH SOURCE** component comprises all non-meteorological parameters that characterize a specific eruption or a volcanic ash cloud. For example, the volume / mass of ash released in the atmosphere, the duration of the eruption, the vertical and horizontal distributions of the ash around the volcano or in a detached volcanic ash cloud, the base and top of the ash cloud, particle size distribution, etc.

2.3 The **METEOROLOGY** component includes all meteorological parameters (wind fields, moisture, stability, etc.) that are predicted by NWP (numerical weather prediction) models.

2.4 The **TRANSPORT AND DISPERSION** component essentially combines inputs from the previous 2 components, though the use of VATDM, to displace and disperse the volcanic ash in the atmosphere as well as depositing it at the surface using various removal and deposition mechanisms.

3. TIMELINESS AND ACCURACY

3.1 Timeliness is the ability to quickly deliver the information. Its exact definition varies from one user to another according to specific needs. Accuracy is also a relative term for the same reasons. Its definition also depends on whether the approach is qualitative or quantitative.

3.2 In the context of aircraft operating at 700 knots, timeliness translates to having VATDM guidance delivered in a matter of minutes after notification of the eruption. At the same time, accuracy means that VATDM are expected to give precise and exact information on where ash is or isn't present in time and space.

3.3 In the context of the operational, real time application of VATDM, timeliness and accuracy are equally important for aircraft operations. Unfortunately, they are also somewhat counter posing. Timeliness implies that the guidance is made available quickly. A prerequisite for accuracy is that accurate data and information must first be collected and checked before being fed to the VATDM. This however takes time.

3.4 Attaining a balance between timeliness and accuracy is not easy. It can however be helped by quickly issuing a first run based on whatever information is available initially and default source term parameters for the rest. Subsequent runs and updates are then done as new information becomes available.

3.5 Putting aside the timeliness issue, it is clear that the accuracy of the guidance produced by the transport and dispersion component, through the use of VATDM, is highly dependent on the quantitative accuracy of the volcanic ash source and meteorology components that feed it. In short, an accurate quantitative time / space forecast of airborne volcanic ash can not be achieved without accurate quantitative information from the volcanic ash source and meteorology components.

3.6 The expectations for VATDM to produce accurate information on where ash is located in time and space can be expressed quantitatively in the modeling context in the form ''the volcanic ash concentration at latitude / longitude X in Y hours after the start of the eruption will be Z micrograms of ash per cubic meters at an altitude of W feet''.

3.7 What are the factors that limit or restrict attaining accurate quantitative forecasts of airborne volcanic ash? They are discussed in the next section.

4. LIMITING FACTORS

4.1 Some of the limiting factors for the **VOLCANIC ASH SOURCE** component include:

4.1.1 Eruption parameters are largely unknown and / or poorly quantified. This is especially true for the real time response but also, in many cases, long after the eruption has ended. Large uncertainties exist in the estimate of the total amount of ash released, the time and duration of the eruption, the vertical and horizontal distribution of the ash. Even the height to which the plume rises is at times hard to determine, for example when ice or water clouds are present.

4.1.2 Because many of the world's active volcanoes are located in uninhabited regions, the rapid detection and location of volcanic eruptions are often problematic. In this regard, and aside from limited monitoring instruments such as seismological and infrasound, satellite remote sensing techniques (hot spot identification, ash signature, etc.) are used. However there are practical problems limiting their reliability and coverage (e.g. cloud cover, satellite coverage, signal contamination, detection schemes, day versus night application, etc). Simply put, the remote sensing instruments and tools currently available are not capable of producing an accurate quantitative measurement of the 3D space and time structure of airborne volcanic ash. Even when data are available (for example, estimates of the total volcanic ash mass loading estimated from satellite imagery), there is little or no information on the vertical distribution.

4.1.3 Objective measurements (wind tunnel experiments) of the threshold concentration at which volcanic ash becomes a ''significant" threat to engines or other components of aircraft have not been done. It is likely that the threshold value would vary with type of engine and aircraft. From a scientific point of view, it would be important to conduct such studies but is not clear, from an operational perspective, how this information might be used to improve the VATDM, given the numerous other remaining uncertainties.

4.1.4 A report on the brief and inadvertent encounter of a NASA DC-8 research airplane with a diffuse volcanic cloud 35 hours Mt. Hekla, Iceland erupted in February 2000 provides a fascinating insight on how very low concentrations of volcanic ash can apparently still be damaging (Grindle and Burcham, 2003). The flight crew noted no change in cockpit readings, but the sensitive research instruments onboard the plane detected the diffuse cloud of ash and sulfur dioxide. During the next 3 days, seven other research flights were done in the same region of the Arctic. The sensitive research instruments again recorded traces of the volcanic ash / SO2 cloud but much more diffuse than in the first encounter. Subsequent inspections to the plane lead to the removal and overhaul of the engines at a cost of $3.2 million. Apparently, damage can occur with very little ash.

4.1.5 Because of uncertainties of the source term, the VAACs' guidance charts err on the side of safety and depict hazardous zones relative to low threshold values. This may at times overestimate the actual extent of the volcanic ash cloud. While this approach is prudent from a VAAC perspective, it may be problematic for the Meteorological Watch Offices issuing SIGMETs, and equally for the primary users: air traffic controllers and the airline companies. Decisions based on SIGMETs, while primarily for safety arguments, can also have major economic and other operational implications.

4.1.6 The criterion for displaying volcanic ash on the guidance charts is based on a "visual ash cloud" (ICAO, 1998). Yet, there is no quantitative or scientifically-based definition of what constitutes a visual ash cloud. This problem has been raised on a number of occasions, including international meetings, but there is no simple way of defining it. A visual ash cloud as sighted by a pilot may be different from that detected by a satellite or predicted by a model. Even with an objective definition of ''visual ash cloud'', it is very likely that a single value for all situations would not exist. For a specific situation, the value is likely to change also in time and space. This is especially true for a long lived event where the atmospheric transport would disperse the ash over a large domain. Forecasters can play with contouring of the predicted ash plume or use "ash reduction" schemes for the model source term eruption parameters. The VAAC meteorologist can also adjust the threshold value defining the model output ash plume and the corresponding contouring on the charts based on real time data. Unfortunately, these modifications may at times introduce additional uncertainties and complications for non-specialist users trying to interpret the ash charts.

4.1.7 Eruption heights are often reported in flight levels given its general use by the aviation community. Flight levels are based on what is know as the ''standard atmosphere'' and rely on a number of assumptions. Because of this, there can be significant differences between the flight level reported by an aircraft and the true height with respect to the ground or sea level.

4.2 For the **METEOROLOGY** component, some of the limiting factors are:

4.2.1 The horizontal resolution of Numerical Weather Prediction (NWP) models typically range from a few kilometers for a limited domain / high resolution model to 100 kilometers for global models.

4.2.2 NWP models use a certain number of discrete levels (typically in the range 25 to 60) to represent the vertical component of the atmosphere. This means that meteorological parameters at a level other than the model levels have to be deduced in one way or another (interpolation, averaging of 2 model levels, etc). Also, there are more levels in the lower portion of the atmosphere. Typically, half of the levels or so are found below 600 hPa.

4.2.3 The fundamental vertical coordinate of most NWP models is pressure (SIGMA and ETA coordinates). The conversion of the wind and temperature fields to flight levels or heights is based on a number of assumptions that have limitations.

4.2.4 The earth's surface features (topography) in NWP models are adjusted to a scale that is consistent with the horizontal and vertical resolution of the models. A very high, steep mountain will therefore be represented as a smoothed, rounder and flatter surface in the NWP model topography. This of course depends on the specific resolution of a model but, as a general rule, there are always differences between reality and what the model sees. A concrete, but somewhat extreme example of this: the topography of the Regional GEM model of the Meteorological Service of Canada for one of its recent operational configurations (24 kilometers horizontal resolution; 28 vertical levels) had its highest surface point in Alaska at 2640 meters. Yet in reality the highest peak, Mount McKinley, reaches 6194 meters!

4.2.5 Accuracy of the predicted fields: Our knowledge of the initial conditions in the atmosphere is incomplete due to a number of factors (limited observational data, errors in measurements, data cut-off deadlines, etc). We are faced with the problem of creating a sufficiently accurate picture of the state of the atmosphere at the outset of the forecast process. Errors introduced at the beginning of the forecast will propagate and amplify at each forecast interval, gradually eroding its accuracy and usefulness. In some situations, a small difference in the initial atmospheric conditions can produced significant differences in the forecasts. While NWP models are generally quite good in their predictions for the initial 24 to 48 hours, some atmospheric flows and patterns are much harder to predict accurately than others.

4.2.6 Another area of errors in NWP models results from a type of approximation called ‘’parameterization’’. It can be defined as the representation, in a dynamic model, of physical effects in terms of admittedly oversimplified parameters, rather than realistically requiring such effects to be consequences of the dynamics of the system. It is done to take into account the large-scale effects of phenomena that are too small to be picked-up at the model's resolution or too complex to be represented exactly. For instance, individual thunderstorms are too small to be forecasted by the model; yet in order to be useful the model must still produce a good approximation of the effects of thunderstorms on large-scale precipitation and temperature patterns. To be successful, the model must integrate an understanding of many different phenomena and their interactions: wind fields; how energy received from the sun is absorbed and transformed by oceans, the ground, the air, and the clouds; how water vapor condensates into clouds and how droplets of water turn to rain, ice and snow; etc. Thus, errors in handling one type of phenomenon can propagate to other parts of the model, or amplify errors in other model sub-systems.

4.3 Limiting factors for the **<u>TRANSPORT AND DISPERSION</u>** component:

4.3.1 The limiting factors presented in sections 4.1 and 4.2 have a clear, direct and important influence on the accuracy of the transport and dispersion component. Many of the factors previously covered also apply to the transport and dispersion component. They will not be repeated here.

4.3.2 At the same time, VATDM also have limiting factors that can be considered as quasi-independent from the source term and meteorology components. For one, VATDM must formulate the source term in one way or another. Even if the source term parameters were perfectly known, the VATDM formulation of the source term would have to be parameterized.

4.3.3 Another limiting factor is that the VATDM, for a number of reasons, often operate on space / time grids that are different from the ones used by the NWP models. This involves a number of interpolations.

4.3.4 Wind fields contribute largely to the horizontal transport airborne volcanic ash but parameterization must be used to account for the dispersal, removal and deposition of ash in time and space.

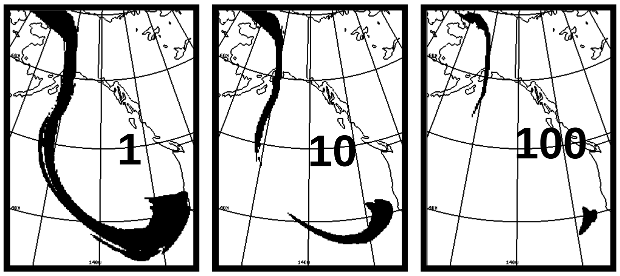
4.3.5 Real time assimilation of airborne ash plume data is not done by models. This would improve the tracking of ash movement and spreading over longer time spans. The data assimilation techniques are routinely used for other meteorological variables such as wind, temperature and pressure. However, the problem of volcanic ash is more complex and quite similar to total ozone data assimilation. The problem is also compounded by the absence of quantitative data on the vertical and horizontal space and time structure of the ash cloud. Given the important differences in wind speed as a function of altitude, this vertical distribution is, in fact, critical to operational decisions.

4.3.6 The ability of VATDM to predict accurately is also dependent on actual atmospheric circulation and flow into which the volcanic ash is injected. Some flows will be conducive to maintaining an integral ash cloud for many days and hence at great distances from the eruption. These are likely to be easier to forecast.

4.3.7 Another factor to consider is how information is presented to the users. Many operational constraints restrict the type and amount of information that can realistically be provided, especially in real time. This is important because how one interprets information is highly dependant on a number of factors, including the tools and technology available to display the information, how the information is presented and how one looks at the information.

4.3.8 To illustrate this, we present two examples. First look at the image on the right and note how your perception of what it shows is changed once you start looking for faces

(www.banane.be/images.php). As another example, we look at some Canadian Emergency Response Model images showing the ‘’visual ash cloud’’ 45 hours after the start of the Mt Cleveland Alaska eruption in February 2001. The 3 images are based on identical conditions for the volcanic ash source, the meteorology and the dispersion / transport (Simpson et al, 2001). The only difference is the threshold value to display the ‘’visual’’ ash cloud boundary. The units are indicated on each image, in micrograms per cubic meter average volcanic ash concentration for the layer 20 to 35 thousand feet. Note how the perception of where ash is or is not present changes wit the display threshold.



5. DISCUSSION / AREAS FOR IMPROVEMENT

5.1 The large number of uncertainties and limitations described in Section 4 may lead one to have doubts about the usefulness of the VATDM guidance. These are not founded. The qualitative verification of VATDM guidance based on satellite data and other tools has shown it to be of great value.

5.2 It would be unthinkable to operate today without VATDM. This is particularly true in an operational, real-time response context where timeliness in the delivery of the guidance is of key importance. Also, at times, the only guidance available is the one provided by VATDM. For example, we may not be able to detect volcanic ash with satellites when meteorological clouds are present. Also, satellite data may not be available in the area in interest.

5.3 The limitations also point out the importance of not using the guidance blindly. A careful interpretation of the guidance must be done by the user and this can not be done without a good knowledge of the limitations.

5.4 VATDM guidance and remote sensing techniques must be used together. Each can benefit from information provided by the other. But in addition, their simultaneous use is synergetic and sometimes even synergistic. For example, satellite data can help to better define what concentrations should be displayed on VATDM guidance while VATDM can help remote sensing detection by pointing out where ash is likely to be found. This synergy has been demonstrated on a number of occasions.

5.5 Clearly, any improvement that might reduce the uncertainties and limitations listed in section 4 would be beneficial. Listed below are some of the key elements that should be considered in order to maximize the improvements in VAFTD guidance:

5.5.1 Source term – eruption parameters: The reports of the Second and Third International Workshop on Volcanic Ash (Toulouse, May 1998 and September 2003) indicated that substantial improvements could be made in VATDM guidance if the source term estimates were improved. The basic question remains: is it possible to produce quantitative estimates of the source parameters for a specific eruption based on historical events, types of volcanoes, etc? What about the amount of ash released, the vertical and horizontal distributions, the particle size distribution, etc.? We seek the expertise of volcanologists to help answer these questions. If quantitative estimates can not realistically be produced, VATDM will simply continue to use some default parameters. A clear answer to these questions would help bring some closure to the subject.

5.5.2 Source term and Transport / Dispersion: The NASA DC-8 plane encounter with a diffuse volcanic cloud points to the fact that very small ash concentrations can produce damage and highlights he importance of a better definition of the source term. The encounter provides another example of a long-lived volcanic cloud. From a modeling perspective, it raises the question of how far out into the future can VATDM predictions be still considered reliable - even if the meteorological inputs have been updated along the way. For the purpose of immediate alerting, perhaps this is irrelevant. But if unconditional ash-avoidance is the rule, predictions beyond 72-hours would still be relevant - i.e. as long as there is ash, there should be an interest. Obviously, the predictions could be made over longer time periods and with more reliably / credibly if we could assimilate airborne ash information.

5.5.3 Source term - Remote sensing and detection of ash: Any technological advancement that might lead to a better quantitative estimate of airborne volcanic in the horizontal and vertical would have great benefits for VAFTD.

5.5.4 Source term – Assimilation of volcanic ash data: Some exploratory work on volcanic ash assimilation has already been done. For example, Siebert et al. 2002 used the basic idea that the vertical wind shear in the atmosphere (e.g. change of wind speed and / or direction with height) leads to different transport paths of the cloud (or parts of it) at different initial heights. The movement of the ash cloud diagnosed from satellite data and images could then possibility be used to infer its vertical displacement and hopefully even a vertical distribution. Exploratory work is also being done elsewhere, for example at the NOAA Air Resources Laboratory. How much can be achieved in this area is highly dependant on improvements in the area of remote sensing (section 5.5.3). The reality is that real-time assimilation of volcanic ash data in a meteorological analysis using an objective numerical procedure remains a complex problem that will not be solved quickly.

5.5.5 Meteorology – NWP models: The improvement of NWP models is an ongoing process. Major NWP Centers regularly implement operational modifications to their analyses and forecast systems as a result of advancements in the areas of remote sensing, data assimilation, parameterization, computing power, etc. The vertical, horizontal and temporal resolutions of NWP models are also increased on a regular basis.

5.5.6 Meteorology and Transport / Dispersion – Ensemble forecasting: We already discussed the fact that the guidance skill diminishes with forecast time because of the growth of inevitable uncertainties in the initial conditions, and because numerical models describe in only an approximate way the exact laws of physics. Ensemble Forecasting provides a practical tool for estimating how these errors could affect the guidance. The basic principle is to produce many runs with NWP models and / or VATDM, using slightly different initial conditions to simulate errors in measurements, different parameterization schemes, etc. The results of the ensemble members are then averaged. It has been shown that this way of proceeding produces better guidance than what is obtained by looking at the results of a single model run. Furthermore, a measure of confidence in the average can be obtained from what is called the ''spread'' of the ensemble. It is a measure of how similar or different the various members (i.e. runs) are. A small spread indicates that the runs are similar while a large spread signals large differences. This is important because we know that the accuracy of the guidance is greater when the ensemble spread is small. Ensemble forecasting is already done operationally by major National Weather Centers in the area of NWP models but has not been yet attempted for VATDM. This might be an interesting avenue to explore. At the same time, the timeliness question would also need to be evaluated if ensemble forecasts were done, given that many runs need to be executed.

6. CONCLUSION

This paper presented the main factors that influence and sometimes limit VATDM. Despite the limitations and uncertainties, VATDM have proven to be of great value, to the point where it would be unthinkable today to operate today without them. At the same time, users must be aware of the limitations when using VATDM outputs. Another important point is that VATDM can not be used blindly. In fact, there is a synergistic benefit in using VATDM in conjunction with other sources of information.

REFERENCES

ICAO, 1998: International Civil Aviation Organization International Standards and Recommended Practices - Meteorological Service for International Air Navigation - Annex 3 to the Convention on International Civil Aviation (July 1998), 92 pp.

Grindle, T.J. and F. W. Burcham, 2003: Engine Damage to a NASA DC8-72 Airplane from a High-Altitude Encounter with a Diffuse Volcanic Ash Cloud. NASA/TM-2003-212030, August 2003, 27 pages. (www.dfrc.nasa.gov/DTRS/2003/PDF/H-2511.pdf)

Siebert, P., A. Frank and R. Servranckx, 2002: Satellite Data Assimilation for Volcanic Ash Forecasts. Poster presented at the European Geophysical Society General Assembly, Nice, France, April 2002. (A PDF version is available on request).

Simpson, James J., Hufford, Gary L., Pieri, David, Servranckx, René, Berg, Jared S., Bauer, Craig: The February 2001 Eruption of Mount Cleveland, Alaska: Case Study of an Aviation Hazard, Weather and Forecasting 2002 17: 691-704.

DISCREPANCIES BETWEEN SATELLITE DETECTION AND FORECAST MODEL RESULTS OF ASH CLOUD TRANSPORT: CASE STUDY OF THE 2001 ERUPTION OF MT. CLEVELAND VOLCANO, ALASKA

David J. Schneider, USGS-Alaska Volcano Observatory, Anchorage, AK, USA
Rene Servranckx, Environment Canada, Montreal VAAC, Montreal, Canada
Jeff Osiensky, National Weather Service, Anchorage VAAC, Anchorage, AK, USA

Volcanic ash transport and dispersion models are used in conjunction with satellite image data to forecast the movement of potentially hazardous volcanic ash clouds. Although these sources of information typically agree, discrepancies do occur. These discrepancies cause difficulty in accurately forecasting ash movement, especially in cases wherein model results indicate the presence of ash but none is detected in satellite data. A case study of the February 19, 2001 eruption of Mt. Cleveland volcano, Alaska is presented utilizing results from the CANERM dispersion model and GOES satellite images. For this eruption, the extent of volcanic ash predicted from ash transport and dispersion models was much larger than the extent detected in satellite image data. A discussion of the operational forecast decisions and information releases that were made during this eruption will illustrate the challenge faced in these instances: Whether to issue warnings based solely on model results or solely on satellite data.

ASSESSING VOLCANIC ASH HAZARD BY USING THE CALPUFF SYSTEM

Sara Barsotti[1], Augusto Neri[1], and Joe Scire[2]
[1] Centro di Modellistica Fisica e Pericolosità dei Processi Vulcanici, Istituto Nazionale di Geofisica e Vulcanologia, via Della Faggiola 32, 56126 Pisa, Italy
[2] Earth Tech Inc., Concorde, MA USA

1. Introduction

Nowadays the presence of volcanic ash in the atmosphere represents a serious risk for the aviation. A large number of volcanoes is indeed situated near main commercial and civil air routes; for examples the regions of North-West America, Alaska, and the Kamchatka Peninsula. In Europe, the problem is probably less relevant than in other parts of the world. However, just in the last few years, the explosive activity of Mt.Etna, Sicily (Italy), has focused the attention of volcanologists and air traffic operators to the problem of an active volcano located very close to two international airports (Catania and Sigonella) as well as to the city of Catania and many other towns.

Although this problem has drawn the attention of the scientific community for many years, a reliable instrument for forecasting ash cloud movements and, therefore, for avoiding plane encounters does not exist yet (Williamson, this issue). To this aim a number of computer codes able to describe the temporal and spatial evolution of the ash plume have been developed worldwide in the last 15 years. Some of them are actually in use at the Volcanic Ash Advisory Centers (VAACs), such as CANERM (which is operative at the Canadian Meteorological Centre), MEDIA (operative at Toulouse Meteo France), NAME (operative at London Met Office) and VAFTAD (developed by NOAA ARL and in use at the Washington and Anchorage VAACs). CANERM (Simpson et al., 2002) is a 3D Eulerian model used for medium- and long-range transport which assumes a virtual source described by a distribution of mass in the vertical direction. Similarly, MEDIA (Piedelievre et al., 1990) is an Eulerian atmospheric transport/diffusion model focused on the long-range dispersal of particles ejected from a source at a given altitude. Vice versa, NAME (Watkin et al., this issue) is a Lagrangian particle model that can work on either regional or global scales and is able to consider areal as well as point-like sources. Finally, VAFTAD (Heffter and Stunder, 1993) is a 3D time-dependent Eulerian model which needs the maximum height reached by the volcanic column to model the source, as input. In addition to those used at the VAACs a few more models have been developed for or applied to the problem of volcanic ash. For instance, the well-known model PUFF, (Searcy et al., 1998), currently used at the University of Tsukuba (Japan) in collaboration with the Japan Meteorological Agency and at the U.S. National Weather Service, Alaska, describes the movements of a collection of discrete ash particles representing a sample of the eruption cloud by using a Lagrangian scheme and treating the source as a virtual pre-assigned vertical distribution of mass. Similarly, HYSPLIT (Draxler and Taylor, 1982, Draxler and Hess, 1998), developed at the NOAA Air Resources Laboratory describes, by a Lagrangian approach, the evolution of puffs (containing material particles with diameters up to 30µm) without taking account of buoyancy effects. Finally, FALL3D (Costa and Macedonio, this issue), is an Eulerian advection/diffusion code, developed at Osservatorio Vesuviano-INGV, that uses a virtual point-like or vertical source of mass on air, and that was specifically designed for the estimation of in-air ash concentration and ground deposition at medium and long distances from the source.

From such a brief summary it is clear how most of the dispersal models in use are relevant only to medium- and long-distance dispersal areas and do not account for the influence of volcano orography on the wind flow field. In addition, none of the above models describes the dynamics of the buoyant volcanic plume thus making the definition of the virtual source quite subjective.

The aim of this work is to present a new modelling system, called CALPUFF, able to describe the movements of the ash cloud, as well as the in-air ash concentration and ground deposition, generated by a given source (Scire et al., 2000). As several other codes used in volcanological applications, CALPUFF has been originally developed as an air quality modelling code for transport of pollutants and then applied to several other environmental problems. The CALPUFF System is composed of three main parts; the geophysical pre-processor, the meteorological processor (named CALMET) and the Lagrangian dispersal model (named CALPUFF). The dispersal model treats the ash cloud as a discrete series of packets of particles, or *puffs*, which are advected by the prevailing winds and, at the same time, diffuse in

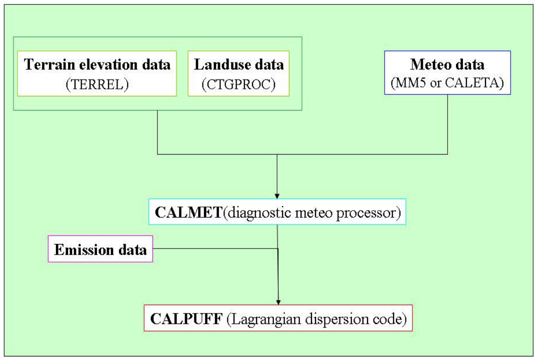


Figure 1. The flowchart of the CALPUFF System as used in our simulations.

the atmosphere. In addition, CALPUFF is able to describe the dynamics of the rising buoyant plume, and therefore the altitude of the virtual source, through the solution of a full non-Boussinesq form of the transport equations. Finally, CALPUFF can describe the ash dispersal dynamics using very refined computational grids (with a final resolution up to 1 km or less), while keeping the execution time very short (of the order of minutes). In the following sections the main features of the system and a first application to a real eruption will be presented.

2. The CALPUFF System

With the terms "CALPUFF System" here we mean the whole numerical procedure that from meteorological and geophysical input data computes the concentration of the ejected material in the atmosphere and at the ground. The CALPUFF system was developed by the Earth Tech Inc. in the '90 and it is available on line at the website http://www.src.com/calpuff/calpuff1.htm. CALPUFF is a quite complex model composed of a great number of sub-processors. Figure 1 shows the basic configuration of the modelling system as we have used it in our study. The procedure starts with the elaboration of the geophysical information, as terrain elevation and land-use data. This procedure is run only once after the choice of the computational domain is made. The geophysical data are then processed by two different programs in order to make them readable to another pre-processor (named MAKEGEO) that merges all the data and produces a single geophysical file for the meteorological processor CALMET.

In parallel with the elaboration of the geophysical data, the processing of the meteorological data occurs in order to provide CALMET of the necessary input data every three hours. The meteorological processor CALMET is a diagnostic code; this means that it computes the values of the meteorological variables on a finer grid without solving the time-dependent equation of motion. CALMET, in particular, works on two steps that refine and correct an initial guess field typically provided by a prognostic code. In the first step the initial data are interpolated on a grid usually much finer than the one used in the mesoscale models and the effects of the local orography are accounted for. In the second step, data collected at the ground or at upper air stations, when available, are considered in order to correct the computed wind field through an objective analysis that assigns appropriate weight to each data. The output provided by CALMET contains the wind field and the other micro-meteorological variables hourly and on a grid in a terrain-following coordinate system with a vertical and horizontal user-defined resolution. This file, together with the one containing the data related to the source, is fed as input to the core of the system: the CALPUFF dispersal model.

This is a Lagrangian dispersion code that treats the emitted material as a sequence of *puffs* each containing a discrete quantity of particles. Each hour a finite number of puffs are emitted and subjected to wind advection, vertical and horizontal diffusion and removal of material due to gravity as well as wet deposition. The user is then free to define a grid of receptors or choose discrete receptors at which concentration and ground deposition will be calculated. Before illustrating the way in which the code computes the ash concentration at a given receptor the treatment of the buoyant plume leaving the crater is briefly described.

CALPUFF is indeed able to handle an areal source which emits in the atmosphere hot material under the action of inertia and buoyancy. To this aim the code solves, each hour of simulation, the three equations of conservation of mass (eq.(a)), momentum (eq.(b)) and energy (eq.(c)) here expressed as (refer to the original work of Hoult and Weil (1972) for a detailed description of them):

$$\frac{d}{ds}(\rho U_{sc} r^2) = 2r\alpha\rho_a |U_{sc} - U_a \cos\varphi| + 2r\beta\rho_a |U_a \sin\varphi| \qquad \text{(a)}$$

$$\frac{d}{ds}(\rho U_{sc} r^2 (u - U_a)) = -r^2 \rho w \frac{dU_a}{dz} \qquad \text{(b)}$$

$$\frac{d}{ds}(\rho U_{sc} r^2 w) = g r^2 (\rho_a - \rho)$$

$$\frac{d}{ds}(\rho U_{sc} r^2 (T - T_a)) = \rho \frac{d\eta_a}{dz} w r^2 + \frac{Q}{c_p} r^2 \qquad \text{(c)}$$

At this stage, only the hot gas of the plume has been considered in the above equations; this assumption will be removed in the future when the presence of particles will be explicitly considered. The code can also treat the case of non-steady emission of ash from the crater once an input file containing all the temporal variations of the source variables is provided.

Once the plume has reached its maximum height the puff description begins. At the emission point, localized at a given downwind distance from the vent and at an effective height above the ground as computed by the above described source model, the pyroclastic material is released as a series of puffs whose dynamics are described in a Lagrangian way.

During one sampling time step (the time interval at which the ash concentration is computed) the puff diffuses and its contribution to the concentration at each receptor defined is calculated. The mathematical expression of this contribution is the following Gaussian function corrected to account for vertical and horizontal diffusion as well as for gravitational settling (Scire et al., 2000):

$$C = \frac{Q}{2\pi\sigma_x\sigma_y} g \exp[-d_a^2/(2\sigma_x^2)]\exp[-d_c^2/(2\sigma_y^2)] \quad \text{(d)}$$

The quantity of mass in the puff is represented by the variable Q and it varies with time because of the removal of material due to gravity. CALPUFF permits to describe the behaviour of different granulometric classes characterized by different diameters, densities, and, of course, settling velocities. However, the present version of CALPUFF is limited to the consideration of particles up to a few tens of microns. In eq. (d), d_a and d_c are the downwind and crosswind distances between the puff centre and the receptor, g is the so-called *vertical term* that takes into account the vertical diffusion due to the mixing lid, and the two sigmas represent the horizontal diffusion due to turbulent atmospheric motions, buoyancy and lateral dimension of the areal source.

Finally, it is worth noting that the CALPUFF System has been validated through extensive comparison of model predictions to experimental data such as the Cross-Appalachian Tracer Experiment (CAPTEX). Due to the very good performance of the model, the U.S. Environmental Protection Agency (Scire et al., 2000) has proposed the CALPUFF modelling system as a guideline model for regulatory application involving long-range transport and in-near field applications where non–steady-state effects may be important.

3. A first CALPUFF application to Mt.Etna, Sicily, Italy

A first application of the CALPUFF System, as it stands at this time, to a recent eruption of Mt. Etna has been carried out in order to a preliminary assessment of the capabilities and limits of the code. As a consequence this application has to be interpreted just as a first step of the research work we have planned in order to develop an appropriate version of CALPUFF System to be used for volcanic purposes.

The eruption of Mt. Etna we refer to started on 18th July 2001 and produced a quite intense explosive activity for about one week. This activity was characterized by an almost continuous injection of ash and lapilli in the atmosphere with the formation of ash columns up to about 5 km (Coltelli et al., 2001; Coltelli, this issue). As mentioned above, the ash and lapilli blanketed the city of Catania, producing major problems to the city airport, whereas the finer particles reached the coasts of Africa. The evolution of the ash cloud was closely observed and many satellite images are available for a first comparison with the model predictions.

3.1. Input data and computational parameters

Geophysical, meteorological, and source data were defined in order to carry out the dispersal predictions. Geophysical data were adopted from USGS. In detail, GTOPO global data and global land-use data with a resolution of about 900 m were implemented. SRTM data for terrain elevation were also implemented producing very similar results. As far as the meteorological data, two different datasets were used: one provided by NOAA and the other one by ECMWF. Both datasets had a spatial resolution of 2.5*2.5 degrees and a temporal resolution of 6 hours (both of them were produced by reanalysis studies). This double choice was actually due to our interest in investigating the sensitivity of CALPUFF results on meteorological data. Finally, in Table 1 are reported the vent data used as input data and boundary conditions for the solution of eqs. (a)-(c) as well as the main puff parameters.

The computational domain is composed by 100*100 cells with a grid spacing of 2km and twelve vertical levels not uniformly spaced. It should also be noted that, so far, we have used CALMET in a no-observational mode, i.e. skipping the objective analysis described above.

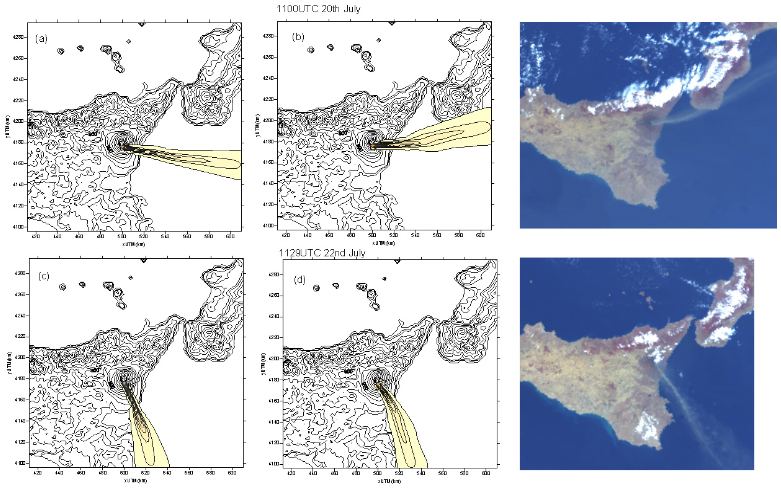


Figure 2. Comparison between CALPUFF modelling results and satellite images on July 20 (top) and July 22 (bottom).The first column refers to the NOAA meteo data, the second column to the ECMWF meteo data.
The minimum value chosen for the graphic is equal to 10^-7 kg/m^3

Table1. Vent input data and puff parameters as used in the simulations (Coltelli et al., 2001, IAVCEI 2004).

Vent velocity	25-75 m/s
Vent temperature	100-300 °C
Vent radius	25-75 m
Ground elevation	2550 m
Vent height a.g.	100 m
Emission rate	10^5 kg/s
Particle diameter	3-64 µm
Particle density	2500 kg/m^3

3.2. Main results

The following aspects of the dispersal process have been investigated by simulating the eruption over five days (starting at 00UTC 20th till 24UTC 24th of July): 1) the main large-scale features of the dispersal, 2) the sensitivity of results on the meteorological datasets used and 3) the model capability of describing the rising phase of the plume. Model results, shown in form of animations, clearly describe the temporal evolution of the ash cloud that results to be mostly affected by the wind direction at the level of puff emission. The predicted dispersal direction is for long period consistent with observations. With full particular, observations indicate that, for all the 20th of July, the plume is directed in the N-E direction whereas it moves in the S-E direction for the remaining days interesting repeatedly the city of Catania and the Fontanarossa Airport. In addition, in the early morning of July 22 a plume bifurcation, which disappeared within few hours, was observed in satellite images.

Figure 2 shows an example of comparison between model predictions and observations with satellite images. Plots (a) and (b) refer to 11UTC of July 20, whereas plots (c) and (d) refer to 1130UTC of July 22. All plots show the cumulative concentration (kg/m^3), integrated over the vertical levels, as calculated by CALPUFF. In particular, plots (a) and (c) were generated using NOAA data, whereas plots (b) and (d) were generated using the ECMWF data. From the figure it is evident that the comparison is quite good for both datasets even though, for July 20, the data provided by ECMWF seem to produce results which agree more with the observations. In this case, a deeper analysis of the meteorological conditions showed that, even though at that time the heights of puff emission were very similar, some hours before, the difference in wind direction in correspondence with the emission heights was about 30 degrees.
The dynamics of the rising plume was also analysed due to its importance in the determination of the puff emission point. In particular, the temporal evolution of the effective height and the downwind distance of the emission point from the vent was investigated. Results showed that these two variables are strictly related - when one increases the other decreases - and strongly depend on meteorological conditions such as the mixing layer depth (that in turn depends on the hour of the day).
Finally, by using an appropriate set of receptors it was possible to investigate the spatial and temporal distributions of ash concentration in the atmosphere. In particular, the horizontal and vertical distribution along the dispersal axis was analysed. It was found that, even at constant emission rate, the observed variability, in time and distance from the vent, of the maximum ash concentration is strongly affected by

the temporal movements of the emission point as well as by the meteorological conditions and the turbulent processes that control the ash diffusion.

4. Conclusive remarks

In the light of the above described modelling capabilities and results obtained from its first volcanological application, the CALPUFF modelling system appears to be a very promising tool for the real-time monitoring and forecasting of ash dispersal dynamics produced by a weak plume. The possibility to describe the dynamics of the rising plume, to account for the volcano topography and direct measurements of meteorological conditions, to work with a user-defined spatial resolution, to obtain results in near real-time, are some of its more attractive features. In addition, the ability of reproducing correctly the large-scale evolution of the ash cloud movements underlies the efficiency of the meteorological processor CALMET in generating a reliable wind field even using a low resolution meteorological input data. However, the sensitivity analysis on the meteorological dataset highlights the importance of using high-resolution meteo data, as well as an accurate description of plume rise, in order to get a correct prediction of ash dispersal. Future works should also focus on the extension of the code to the modelling of coarse ash and lapilli in order to describe the more proximal fallout.
Finally, it is worth mentioning that an effective progress in the modelling and forecasting of ash dispersal appears strictly tied to the definition of accurate volcanological datasets to be used in model validation studies as well as to the carrying out of real-time measurements of the plume.

Acknowledgements
This work has been partially supported by Dipartimento di Protezione Civile, Gruppo Nazionale per la Vulcanologia, Italy, Framework Programme 2000-2003, project no. 9, and by Ministero dell'Istruzione dell'Università e della Ricerca, Italy, FIRB project no. RBAU01M72W.

References

Coltelli M., 2004: Recent Etna's explosive eruptions threaten seriously aviation in central Mediterranean region, Proc. *2nd International Conference on Volcanic Ash and Aviation Safety*.

Coltelli M., Del Carlo P. and Macedonio G., 2001: The plume of the 2001 eruption of Etna: observation, modelling and impact on Catania airport operations, Proc. *Assemblea Generale del Gruppo Nazionale per la Vulcanologia.*

Costa A. and Macedonio G., 2004: FALL3D: A numerical model for volcanic ash dispersion in the atmosphere. Proc. *2nd International Conference on Volcanic Ash and Aviation Safety*.

Draxler R.R. and Taylor A.D., 1982: Horizontal dispersion parameters for long-range transport modelling, J. Appl. Met., 21, 367-372.

Draxler R.R and Hess G.D., 1998: An overview of the HYSPLIT_4 modelling system for trajectories, dispersion and deposition, Austral. Meteorol. Mag., 47, 295-308.

Heffter J.L and Stunder B.J.B., 1993: Volcanic ash forecast transport and dispersion (VAFTAD) model, Weath. Forecast., 8, 533-541.

Hoult D.P. and Weil J.C., 1972: A turbulent plume in a laminar crossflow, Atmos.Environ., 6, 513-531.

IAVCEI Tephra Group webpage 2004: www.soest.edu/IAVCEI-tephra-group/.

Piedelievre J.P., Musson-Genon L. and Bompay F., 1990: MEDIA- An Eulerian model of atmospheric dispersion: a first validation on the Chernobyl release, J. Appl. Meteor., 29, 12, 1205-1220.

Scire J., Strimaitis D.G. and Yamartino R.J., 2000: CALPUFF user's guide.

Searcy C., Dean K. and Stringer W., 1998: PUFF: a Lagrangian trajectory volcanic ash tracking model, J. Volcanol. Geotherm. Res., 80, 1-16.

Simpson J.J., Hufford G.L., Servranckx R., Berg J.S. and Bauer C., 2002: The February 2001 eruption of Mt. Cleveland, Alaska: Case study of an aviation hazard, American Meteorol. Soc., 17, 691-704.

Watkin S., Ryall D., Watkin H., Champion H., Wortley S. and Gait N., Volcanic ash monitoring and forecasting at the London VAAC, Proc. *2nd International Conference on Volcanic Ash and Aviation Safety.*

POTENTIAL OF THE ATHAM MODEL FOR USE IN AIR TRAFFIC SAFETY

[1]Christiane Textor, [2]Gerald GJ Ernst, [3]Michael Herzog, [4]Andrew Tupper

[1] Lab. Sciences du Climat et de l'Environnement, CEA-CNRS, Paris, France
[2] Geological Institute, University of Ghent, Krijgslaan 281/S8, B-9000 Gent, Belgium
[3] Dept. of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, USA
[4] Bureau of Meteorology, Darwin, Northern Territory, Australia, and School of Mathematical Sciences, Monash University, Victoria, Australia

Abstract

Numerical models used by the VAAC centers often fail to accurately predict volcanic ash dispersal, because they do not include sufficient information on the initial ash distribution in the proximity of the volcano. In addition, ash dispersal is assumed to be determined by the atmospheric background conditions only, and effects of the eruption on the ambient motions are neglected.

In this paper we present the eruption column model ATHAM (**A**ctive **T**racer **H**igh resolution **A**tmospheric **M**odel). This model simulates the processes within the eruption column, and the dispersal of the ash cloud on spatial scales of some hundreds of kilometers during some hours. We show the development of the ash cloud and of hydrometeors during a plinian eruption simulated with the ATHAM model.

ATHAM can be used to improve understanding of in-column processes, and of the initial ash distribution. Better initialization of the usual VAAC models will lead to more accurate forecasts of ash dispersal.

1. Introduction

Various numerical models are used by VAAC centers to forecast volcanic ash dispersal for air traffic safety (e.g., VAFTAD, NAME, CANERM, HYSPLIT, PUFF, etc.). These emphasize the role of background atmospheric motions and ignore the role of the eruption dynamics itself upon dispersal. The initial ash distribution close to the volcano is often not well known and has thus to be prescribed in a simplified, sometimes unrealistic way. These models tend to have a physically unsound source term description. Their forecasts often fail to accurately predict the extent of the volcanic ash cloud, even for small explosive eruptions (e.g., Hekla 2000 eruption, Iceland [*Grindle and Burcham*, 2002; *Grindle and Burcham*, 2003]), especially in the first six hours of spreading, with source errors propagated for the 12h+ forecasts. For full-blown plinian eruptions or any moderately explosive eruptions in weak winds, the models often fail to predict ash dispersal with satisfactory accuracy, because of imprecise observations of the initial plume height. On the other hand, the ATHAM model is a numerical eruption column model that predicts the rise of volcanic gases, ash and hydrometeors from the lithosphere to the height neutral buoyancy column, and the atmospheric dispersal of the plume during the eruption and some hours afterwards. The model is based on first physical principles and includes eruption dynamics, cloud meteorology and chemical aspects. ATHAM can be run quickly on a fast PC, has a flexible modular structure ideal for 1) testing against observations and 2) comparisons with simple numerical simulations and laboratory experiments. In the following, we will introduce the ATHAM model, and then show some results form numerical simulations.

2. Dynamics

ATHAM has been designed to simulate the dispersal of a volcanic eruption [*Graf et al.*, 1999; *Herzog et al.*, 1998; *Herzog et al.*, 2003; *Oberhuber et al.*, 1998]. The simulation time is some hours covering spatial scales of some hundreds of kilometers. ATHAM is a non-steady state, non-hydrostatic model. It solves the full set of Navier-Stokes equations for the multiphase system. Sound waves are included, because the flow can be supersonic in the high-density lower parts of the eruption column. Tracers (liquid and solid particles and gases) can occur in very high concentrations in the erupted gas-particle mixture. They act on the dynamics of the system by altering the mixture's density and heat capacity. The description of this system requires a large set of dynamic and thermodynamic equations for each component and the interactions between them. However, the gas-particle mixture can be assumed to be in thermal and dynamical equilibrium[1], on the condition that all particles are smaller than about a millimeter. Based on these assumptions, the

[1] Thermal equilibrium: All tracers have the same in-situ temperature. Dynamical equilibrium: The model does not resolve accelerations between tracers and gas. Tracers move with their terminal fall velocity, however, the mixture can be accelerated as a whole.

equations have only to be solved for volume mean quantities. For each active tracer one additional transport equation is needed that takes into account the tracer's fall velocity. Active tracers and dynamical variables are coupled through the bulk density and the heat capacity of the mixture.

To avoid conflicts with the model assumptions processes in the high pressure, hot temperature regime within and close to the crater cannot be resolved, and the topography of the volcanic vent has to be neglected. The simulations start just after pressure adjustment to atmospheric values, hence we do not prescribe any overpressure. Typically, decompression takes place within a vertical distance of some jet radii above the vent. Hence, we can neglect the topography of the volcanic crater and simply use a flat surface. Due to the low gas content of the erupting gas-particle-mixture, the temperature does not change significantly during decompression [*Woods and Bower*, 1995]. In an explosive eruption, the vertical velocity after decompression at the base of the eruption column is about twice the speed of sound for a freely decompressing jet. If the apex angle of the crater is small, the flow behaves like a high-speed supersonic flow in a divergent nozzle and the velocity can be even higher.

3. Turbulence

A turbulence closure scheme describes sub-scale turbulent processes in the eruption column [*Herzog et al.*, 2003]. Turbulent exchange coefficients are predicted for each prognostic quantity. The strong influence of buoyancy forces and vertical transports in the eruption column is represented by differentiating between horizontal and vertical turbulent exchange. Turbulent disequilibria are possible, and anisotropic effects are included in the formulation of turbulent kinetic energy. High tracer concentrations as well as supersonic effects at low Mach numbers are taken into account. The turbulent exchange coefficients are derived from a set of three coupled differential equations for the horizontal and vertical turbulent energy, and the turbulent length scale.

4. Cloud microphysics

The development of liquid and frozen meteorological clouds and precipitation is simulated. The effect of latent heat release on the dynamics is taken into account [*Graf et al.*, 1999; *Herzog et al.*, 1998; *Textor et al.*, 2004]. Two types of schemes can be alternatively used in ATHAM. The bulk scheme [*Herzog et al.*, 1998] predicts the mass mixing ratio of liquid and frozen hydrometeors, and is for suitable for the investigation of latent heat effects on the eruption column dynamics. The more complex two-ment-scheme [*Textor et al.*, 2004] predicts both the mass mixing ratio and the number concentration, and offers the possibility to simulate interactions between volcanic particles and hydrometeors. This scheme can be used to examine the microphysical properties of volcanic eruption clouds under different volcanic and environmental conditions.

5. Ash aggregation

In the current version of ATHAM, volcanic particles are assumed to aggregate as soon as they are coated with water or ice, with the hydrometeors acting as adhesive, thus forming larger hydrometeor-ash aggregates [*Textor et al.*, 2004]. The aggregation coefficients (describing the ratio of successful particle growth resulting from a theoretical particle collision) are approximated with the parameterizations commonly used in cloud microphysics. These values are modified with a simple function depending on the amount of hydrometeor available at the particle. The inclusion of this wet or icy aggregation process leads to more realistic sedimentation features.

6. Gas scavenging

The scavenging module calculates the dissolution of volcanic gases (SO_2, HCl, H_2S, and HBr) by liquid droplets and their incorporation into ice particles. The kinetics of the phase transfer and the subsequent dissociation in the liquid phase is considered as a function of the drop acidity. In addition, incorporation into ice particles is taken into account. Gaseous compounds enter the ice phase via co-condensation of water vapor and gases at growing ice. The concentration of volcanic gases in ice is then rather ruled by phase transfer kinetics than by the low equilibrium solubility. The redistribution of species contained in hydrometeors due to microphysical processes is included [*Textor et al.*, 2003a; *Textor et al.*, 2003b].

7. Model concept

The solution of the complete Navier-Stokes equation is computed on a Cartesian Arakawa C grid [*Mesinger and Arakawa*, 1976] using a Eulerian method. An implicit time stepping scheme is used (Cranck-Nicholson, 25% forward, 75% backward). A parallel iteration of the dynamic quantities accounts for the temporal coupling of the equations with updated density. The conservation of mass and momentum is explicitly guaranteed by applying the flux form for the equations of motion and continuity of the tracers. The time step is automatically adapted to satisfy the Courant-Friedrichs-Lewy criterion (with CFL<= 0.8) and typically varies between 0.1 and 10 sec. A grid stretching allows using a higher spatial resolution in the model center than at the boundaries. The grid distances increase from some hundreds of meters to some kilometers. The Neumann boundary condition (fixed derivatives, open for sound waves) is applied at the lateral boundaries. We use a fixed bottom, including tracer deposition as lower boundary condition. Pressure and temperature anomalies are damped in the upper model levels.

The ATHAM model can be run in fast, two-dimensional versions for sensitivity studies. The first version in Cartesian coordinates represents a vertical slice of the three-dimensional model. The use of second two-dimensional version in cylindrical coordinates allows for a more realistic dilution of the eruption column in an atmosphere at rest, but cross-wind effects cannot be studied. The most realistic three-dimensional version has been parallelized for efficient use on multi-processor computers [*Herzog et al.*, 2000].

The ATHAM model is written in a modular structure. It is easy to add additional modules of different levels of complexity for specific investigations.

8. Simulations with the ATHAM model

For the simulation we present here, the ATHAM model was initialized with horizontally homogeneous profiles of temperature, relative humidity and wind representative for a tropical atmosphere, as shown in Figure 1.

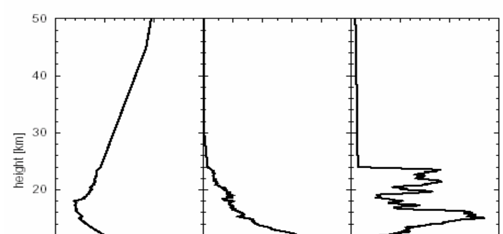


Figure 1: Atmospheric background conditions taken from [*McClatchey et al.*, 1972].

A plinian eruption of 60 min was simulated [*Herzog et al.*, 2003]. The model domain was 250x200x50 km3, with 127x107x127 grid points. Typical plinian conditions prescribed at the eruption column base are given below.

- Mountain height: 2500m,
- Width of eruption column base: 300m,
- Temperature: 1073 K,
- Gas fraction: 6 % by mass,
- Water vapor fraction of tot. gas: 50% by mass,
- Bulk density of the gas particle mixture: 3.1 kg/m3,
- Vertical velocity at eruption column base: 250 m/s,
- Mass eruption rate: ~5.55 107 kg/s,
- Particle density: 2000 kg/m3,
- Three particle classes, 1/3 by mass each,
- Particle diameter: 10, 200, and 4000 μm.

Figure 2 shows results from a three dimensional simulation (see also [*Herzog et al.*, 2003]) at three different times for volcanic ash and for hydrometeors. The ash plume is observed from 10-km altitude, that of the hydrometeors from somewhat lower. The background wind blows from the left side along the lines shown on the ground. The eruption column penetrates the tropopause at about 17 km after about 5 min of eruption. The average vertical velocity in the central rising zone is larger than 100 m/s. An orographic cloud, which is partly entrained into the plume, can be seen on the right of the eruption column between 5 and 10 km in figure 2b. An ice cloud forms in the umbrella region (figures 2b, 2d, and 2f). After 30 min of eruption, the three particle size classes occur at different heights, the umbrella region consists mainly of fine ash particles (figure 2c). Larger particles leave the umbrella region more quickly due to sedimentation, or do not even reach the height of neutral buoyancy. At 70 min of simulation, this separation of large particles from the fine ash and gases is even more evident (figure 2e). A large ice cloud has developed in the stratosphere. Most of the hydrometeors in the eruption column are in the frozen state (figure 2f).

9. Conclusions

In this paper, we have presented the concept of ATHAM model and the modules available for cloud microphysics, ash aggregation and scavenging of volcanic gases. In addition, codes for gas phase chemistry and for radiative transfer calculations exist [*Trentmann et al.*, 2003a; *Trentmann et al.*, 2003b]. We have shown results from a three-dimensional simulation of a plinian eruption in a tropical environment. These three-dimensional simulations remain to be carefully tested against volcanological observations. We plan to simulate a well-observed eruption and the first hours of ash dispersal under realistic ambient conditions. An earlier evaluation of results from the simpler two-dimensional, axis-symmetric version confirmed that the results are relatively robust, and three-dimensional fire-simulations have been successfully tested against data [*Trentmann et al.*, 2002].

The ATHAM model has been used for the examination of specific processes and of the parameters controlling them within the rising eruption column, and during plume dispersal in the atmosphere. Applications included investigations on the influence of the ambient conditions on the plume development [*Graf et al.*, 1999], on cloud microphysics [*Herzog et al.*, 1998], gas scavenging [*Textor et al.*, 2003a; *Textor et al.*, 2003b] and on ash aggregation [*Textor et al.*, 2004].

Results from sensitivity studies using ATHAM provide insights into cloud and aggregation processes, and of ash removal within the eruption column (see extended abstract of A. Tupper et al. in this volume). These help to improve the source term matrix of the VAAC ash forecasting models and thus to more accurately forecast ash for air traffic safety.

10. References

Graf, H.-F., M. Herzog, J.M. Oberhuber, and C. Textor, The effect of environmental conditions on volcanic plume rise, *JGR*, *104*, 24309--24320, 1999.

Grindle, T., and F.W.J. Burcham, Even Minor Volcanic Ash Encounters Can Cause Major Damage to Aircraft, *ICAO journal*, *57* (2), 12-14, 2002.

Grindle, T., and F.W.J. Burcham, Engine Damage to a NASA DC8-72 Airplane From a High-Altitude Encounter With a Diffuse Volcanic Ash Cloud, *NASA/TM*, *2003-212030*, 27, 2003.

Herzog, M., H.-F. Graf, C. Textor, and J.M. Oberhuber, The Effect of Phase Changes of Water on the Development of Volcanic Plumes, *JVGR*, *87*, 55--74, 1998.

Herzog, M., J.M. Oberhuber, and H.F. Graf, A prognostic turbulence scheme for the non-hydrostatic plume model, *JAS*, *60*, 2783--2796, 2003.

Herzog, M., C. Textor, and M. Antonelli, Modelling Volcanic Eruption Plumes, *HPC News*, *13*, 2000.

McClatchey, R.A., R.W. Fenn, J.E.A. Selby, F.E. Volz, and J.S. Garing, Optical properties of the atmosphere, 3rd ed., 1972.

Mesinger, F., and A. Arakawa, Numerical methods used in atmospheric models, *GARP*, *17*, 1976.

Oberhuber, J.M., M. Herzog, H.-F. Graf, and K. Schwanke, Volcanic Plume Simulation on Large Scales, *J. Volcanol. Geotherm. Res.*, *87*, 29--53, 1998.

Textor, C., H.-F. Graf, M. Herzog, and J.M. Oberhuber, Injection of Gases into the Stratosphere by Explosive Volcanic Eruptions, *JGR*, *108* (D19), 10.1029/2002JD002987, 2003a.

Textor, C., H.-F. Graf, M. Herzog, J.M. Oberhuber, W.I. Rose, and G.G.J. Ernst, Volcanic Particle Aggregation in Explosive Eruption Columns Part I: Hydrometeor-Ash Particle Growth in Volcanic Eruption Column Part II: Numerical Experiments, *submitted to Journal of Volcanological and Geothermal Research*, 2004.

Textor, C., P.M. Sachs, H.-F.Graf, and T.H. Hansteen, The 12,900 yr BP Laacher See eruption: estimation of volatile yields and simulation of their fate in the plume, in *Volcanic Degassing*, edited by C. Oppenheimer, D. Pyle, and J. Barclay, Geological Society, London, Special Publications, 2003b.

Trentmann, J., M.O. Andreae, and H.-F. Graf, Chemical processes in a young biomass-burning plume, *JGR*, *108* (D22), 10.1029/2003JD003732, 2003a.

Trentmann, J., M.O. Andreae, H.-F. Graf, P.V. Hobbs, R.D. Ottmar, and T. Trautmann, Simulation of a biomass-burning plume: Comparison of model results with observations, in *JGR*, pp. 10.1029/2001JD000410, 2002.

Trentmann, J., B. Früh, O. Boucher, T. Trautmann, and M.O. Andreae, Three-dimensional solar radiation effects on the actinic flux field in a biomass burning plume, *Journal of Geophysical Research*, *108*, 4558, 2003b.

Woods, A.W., and S. Bower, The decompression of volcanic jets in craters, *EPL*, *131*, 189--205, 1995.

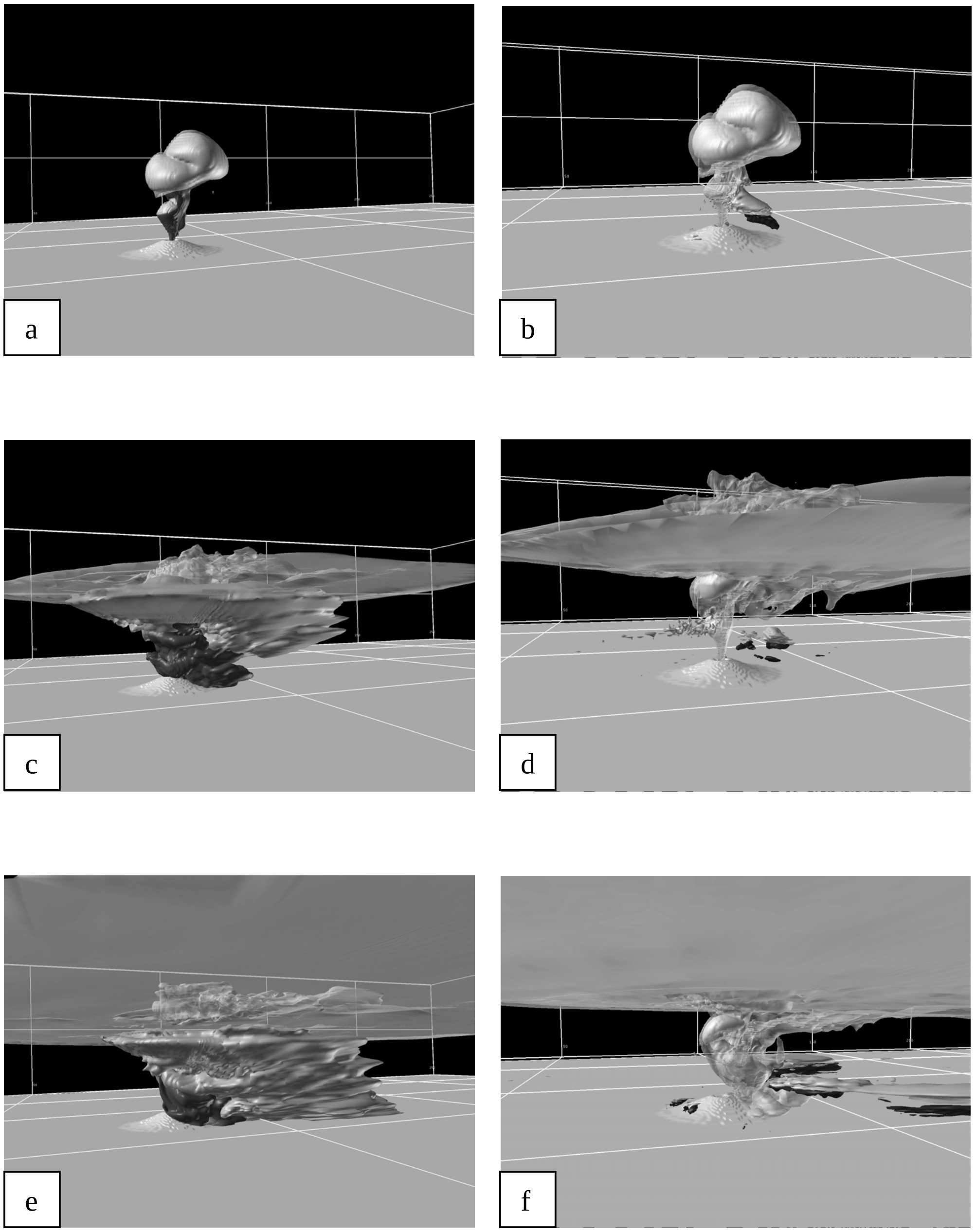


Figure 2: Simulation of a volcanic eruption with the three dimensional version of ATHAM LIT. The plots show the eruption columns of total ash (size classes: light gray: 10, gray: 200, dark gray: 4000, all in [μm] diameter) on the left hand side (figures 2a, 2c, 2e), and of finest ash and hydrometeors (light gray: 10 μm ash, gray: ice, dark gray: liquid water) on the right hand side (figures 2b, 2d, 2f). Three time levels are given (top: 5 min (figures 2a and 2b), middle: 30 min (figures 2b and 2d), and bottom: 70 min (figures 2e and 2f)). Only a fraction of the model domain is depicted; the pale lines at the ground and in the background indicate distances of 50 km in the horizontal and 25 km in the vertical direction. Visualizations by Michael Boettinger, Deutsches Klimarechenzentrum, Hamburg, Germany.

VOLCANIC ASH AND AEROSOL DETECTION VERSUS DUST DETECTION USING GOES AND MODIS IMAGERY

Bernadette Connell
Cooperative Institute for Research in the Atmosphere, Colorado State University
Fort Collins, Colorado, USA
connell@cira.colostate.edu

Abstract

Case examples of the various volcanic ash/aerosol and dust aerosol detection techniques utilizing infrared wavelengths in the 8-12 µm region are presented for the moderate resolution imaging spectroradiometer (MODIS) imagery and compared with available products from the geostationary operational environmental satellite (GOES) imagery. Information gained by using the short wavelength region (3-4 µm) will also be presented. A question that is posed, and partially answered is: How is ash, sand or aerosol detected with the various channel combinations?

Introduction

Volcanic eruptions are extremely variable in intensity and composition, they are difficult to predict, and they are hazardous. Because of this they are often difficult to measure directly and it is difficult to track their emissions. Examples are limited. Dust and ash tend to be comprised of silicates and it is expected that remote sensing techniques for detection to be similar. Volcanic eruptions are often associated with sulfur based aerosols while blowing dust is not.

Within this paper, easy to implement techniques are utilized for detecting volcanic ash and aerosol and dust using GOES and MODIS imagery. The easy to implement techniques use channel differencing of brightness temperature or a "normalized" radiance difference product. A volcanic ash and a dust example highlight a few of the many subtle aspects of detecting ash and dust. Because of the variability of the eruption event and variability of the weather, no one detection technique will work 100% of the time. The brightness temperature (BT) difference: 11.0 - 12.0 µm works the best in distinguishing ash from meteorological clouds under ideal conditions. This technique will be used to compare against techniques from the other channels in the shortwave and longwave infrared region.

Techniques

Prata (1989a, 1989b) used the brightness temperature (BT) difference between the bands centered near 11.0 and 12.0 µm to detect ash while Shenk and Curran (1974) used this difference to detect dust storms. The BT11.0 – BT12.0 is generally negative for ash and dust and positive for ice and water clouds.

The use of the 3.9 µm channel for detection of ash has been demonstrated by Ellrod et al. (2003) and has been shown by Ackerman (1989) for the detection of dust. The 3.9 µm channel senses solar radiation as well as emitted radiation; hence the imagery is interpreted differently during the day than at night. For the daytime scenes, scattering by particles of shortwave radiation enhances the reflectance. For water particles, the reflectance is inversely proportional to the drop size. Small water droplets are strongly reflective, larger ice particles are less reflective. Volcanic ash and dust samples show higher reflectance in the 3.9 µm region than in the 10.7 or 12.0 µm regions (Schneider and Rose, 1994; Salisbury and Walter, 1989). The reflectance is estimated by: R3.9-$R3.9_{(BT10.7)}$. The emitted radiance component at 3.9 µm is estimated using the planck function with the measured BT10.7. This is then subtracted off the measured radiance at 3.9 µm.

At night, the detection of an optically thick cloud with the 3.9 µm channel is difficult, particularly for temperatures colder than -40C, where instrument noise becomes large and overwhelms the signal. For optically thin clouds, transmission plays and important role and the BT3.9 – BT10.7 is positive for ash cloud (Ellrod et al., 2003). The

BT3.9-BT10.7 at night is generally positive for ice cloud and negative for water cloud. In summary for the 3.9-10.7 products, during the day ash and dust have a signature similar to that observed for water cloud. At night, ash and dust have a signature similar to that observed for non-opaque ice cloud.

Baran et al. (1993) and Ackerman and Strabala (1994) looked into the use of the 8.3 µm channel on the high resolution infrared sounder (HIRS) system for the detection of H_2SO_4 aerosol from the Pinatubo eruption. Over oceans there is a small negative BT8.3 – BT12.0 background signature due to moisture. The BT8.3 – BT12.0 becomes more negative for H_2SO_4 aerosol, and also becomes more negative for an increase in atmospheric water vapor. The BT8.3-12.0 is positive for ice.

For dust, Ackerman (1997) found that increasing the optical depth increases BT8-BT11 over clear sky conditions. A thick optical depth results in positive BT8-BT11. Wald et al. (1998) simulated the MODIS capabilities of the detection of mineral dust over desert using the 8.0 - 12.0 µm region. Using various particle sizes of quartz and varying the optical depth, they found that the BT12.0 – BT 8.0 was the smallest (ie. negative) (positive for BT8.0 – BT 12.0) for 2 µm particles and small optical depth and was positive for large optical depth, taking on the signature of the quartz sand background. All authors mentioned in this paragraph discuss the difficulties encounter over land surfaces where diurnal temperature variations and variable surface emissivities affect BT8.

Examples

The eruption of the Popocatepetl volcano in Mexico on 22-23 January 2001 was chosen because the eruption started later in the day on the 22nd, providing a brief example of the reflectance seen in the 3.9 µm channel, with drifting ash continuing through the night when the first MODIS imagery is available. According to the volcanic ash advisory issued by the Washington Volcanic Ash Advisory Center, the explosive event started at approximately 22:15 UTC on 22 January 2001. Figure 1 shows the erupting plume at 22:45 UTC. The outline of the plume is shown on the visible imagery in Figure 1a. The stratus cloud to the east is also labeled. In the reflectance product (figure 1b), enhanced reflectance is noted for the eruption plume and appears brighter than

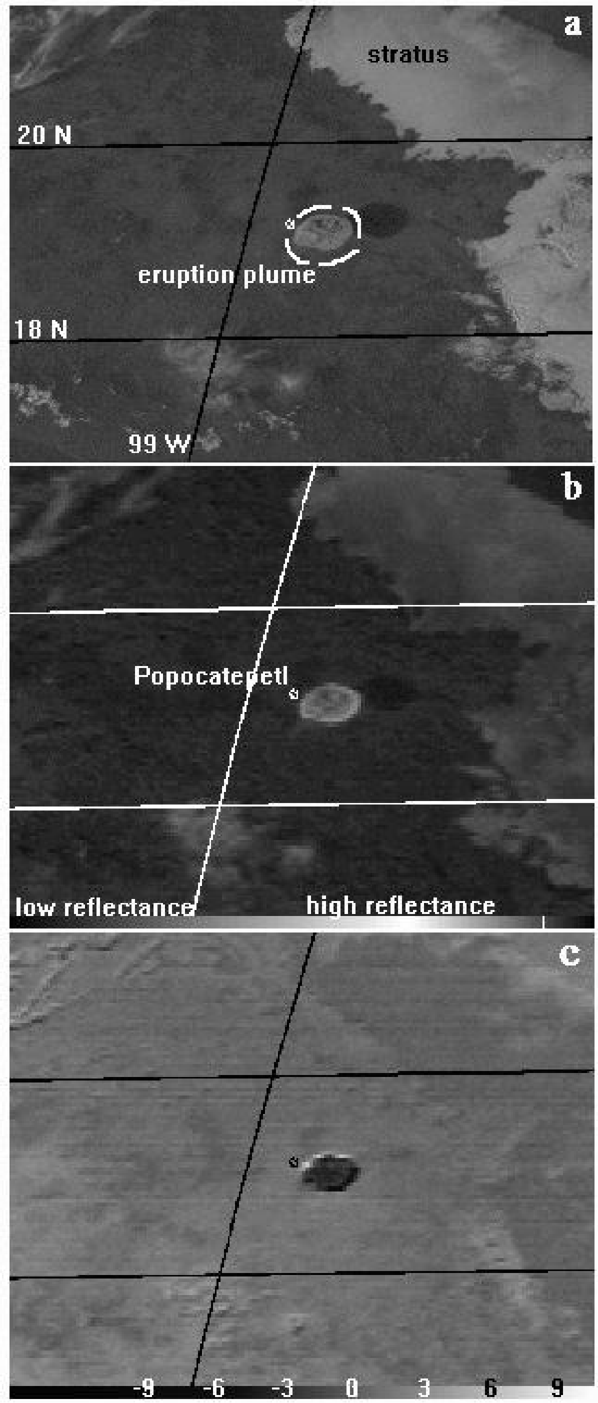


Figure 1. GOES imagery showing the erupting plume from the Popocatepetl volcano in Mexico on 22 January 2001 at 22:45 UTC. a) visible imagery, b) reflectance product using the 3.9 and 10.7 µm imagery, and c) BT10.7-BT12.0

the stratus cloud. The cloud shape resembles a convective cloud and would normally appear darker because of the presence of less reflective ice particles. The BT10.7-BT12.0 product (figure 1c) shows negative values for the plume with the most negative value (-7.7) along the southeastern edge where the plume is thinner.

A night scene of the eruption plume is displayed in figure 2. The GOES imagery (figure 2 a, b) are from 04:45 UTC on 23 January 2001, and the MODIS Terra imagery (figure 2 c, d) are from 04:50 UTC. The pattern of the GOES and MODIS BT11-BT12 shown in figure 2a and 2c are very similar. The GOES product produced more negative differences in background regions as well as in various parts of the plume. The differences were generally relatively small (0.5C) as in the circled regions x and y, but got as large as 2.0C in circled region Z (-5.5C for GOES and -3.3C for MODIS. At this point it is unclear as to whether the differences are a result of the sampling differences associated with different spectral coverage, spatial coverage, or viewing angle. The GOES 10.7 channel has a bandwidth of 10.2-11.2 µm, while the MODIS 11.0 µm channel has a bandwidth of 10.78-11.28 µm. The GOES 12.0 µm channel has a bandwidth of 11.5-12.5 µm, while the MODIS 12.0 µm channel has a bandwidth of 11.77-12.27 µm.

The GOES BT10.7-BT3.9 shown in figure 2b shows the plume quite well. In this case it is because of the contrast of the plume with the brighter lower level stratus and ground surface. Tracking of the plume with the GOES imagery

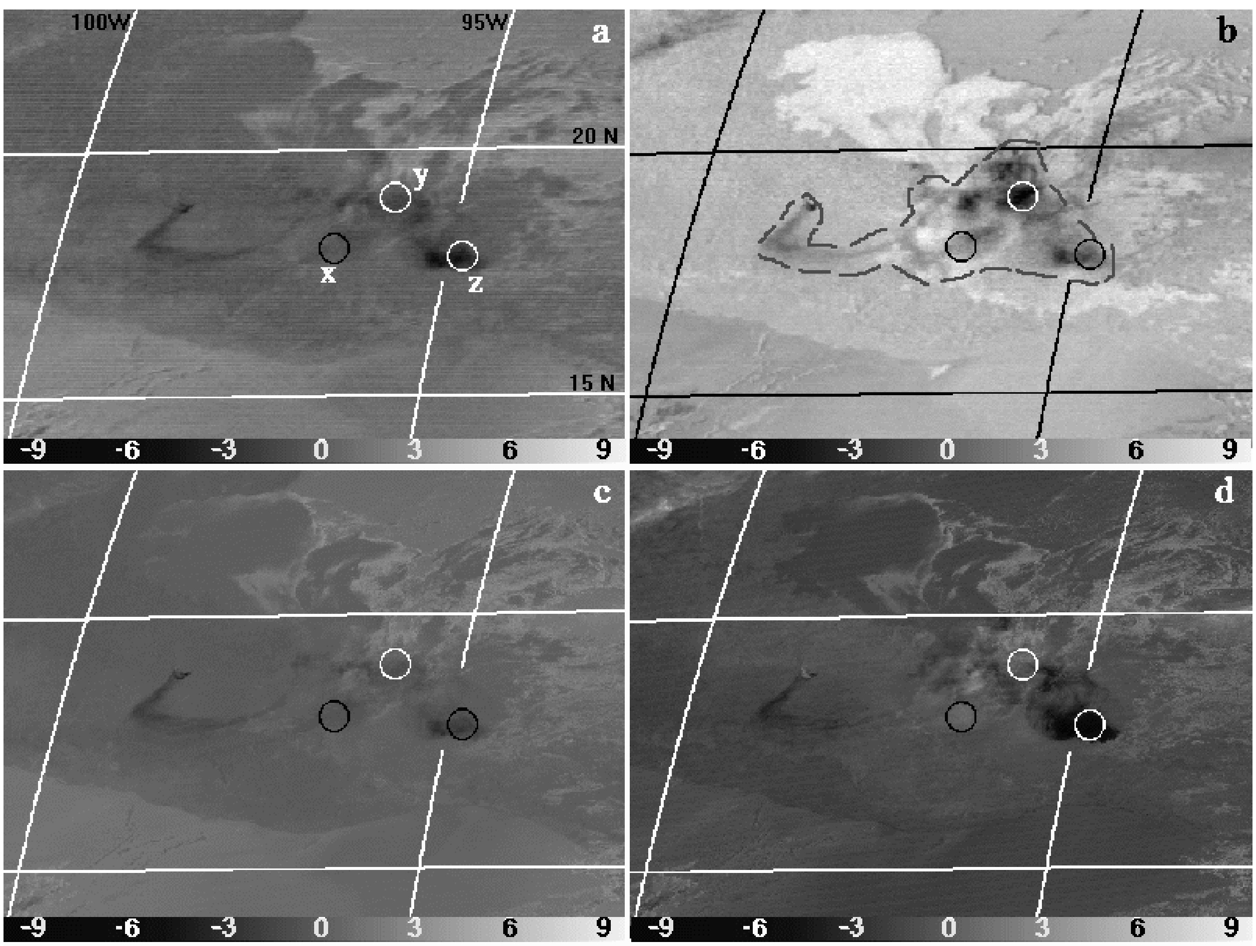


Figure 2. Satellite imagery products showing the erupting plume from the Popocatepetl volcano in Mexico on 23 January 2001, GOES at 04:45 UTC and MODIS Terra at 04:50 UTC. a) GOES BT10.7-BT12.0, b) GOES BT10.7-BT3.9, the dashed line indicates the plume outline c) MODIS BT11.0-BT12.0, and d) MODIS BT8.5-BT12.0.

through time helped significantly in discerning various portions of the plume that are outlined in figure 2b. The BT8.5-BT12.0 image provides another view of the plume and its characteristics. It has many regions of negative difference similar to BT11.0-12.0 (figure 2c) and one region in particular indicated by circle z has much stronger negative differences (-14.0C). Regions circled as x and y show slightly positive differences. The modeling efforts referenced in the previous section suggest that the regions of positive differences in circles x and y contain smaller particles and small optical depth. The more negative differences observed in circle z reflect the presence of SO_2 and sulfates and a larger optical depth.

An example of blowing dust during the day is shown in figure 3 for 18 April 2004 at 19:30 UTC. The extent of the plume is highlighted with dashed lines in the MODIS BT11.0-BT12.0 (figure 3c) image. Both the MODIS and the GOES difference product for BT11-BT12 (figure 3c and 3a respectively) show similar values (most negative value = -2.5, average = -2.0 and -1.5 respectively) for the thicker part of the plume, represented by the circle labeled y. They also show similar values (1.0 and 0.0 = the most positive values respectively, average=-0.5) for the thinner portion of the plume labeled as circle x. The extent of the dust plume for these difference products agrees with that shown by the GOES reflectance product in figure 3b. In this product, the dust as well as low level water clouds appear more reflective. In contrast, the MODIS BT8.5-BT12.0 product shown in figure 3d represents the plume with values -1.0 – 0.0 in what appears to be the densest

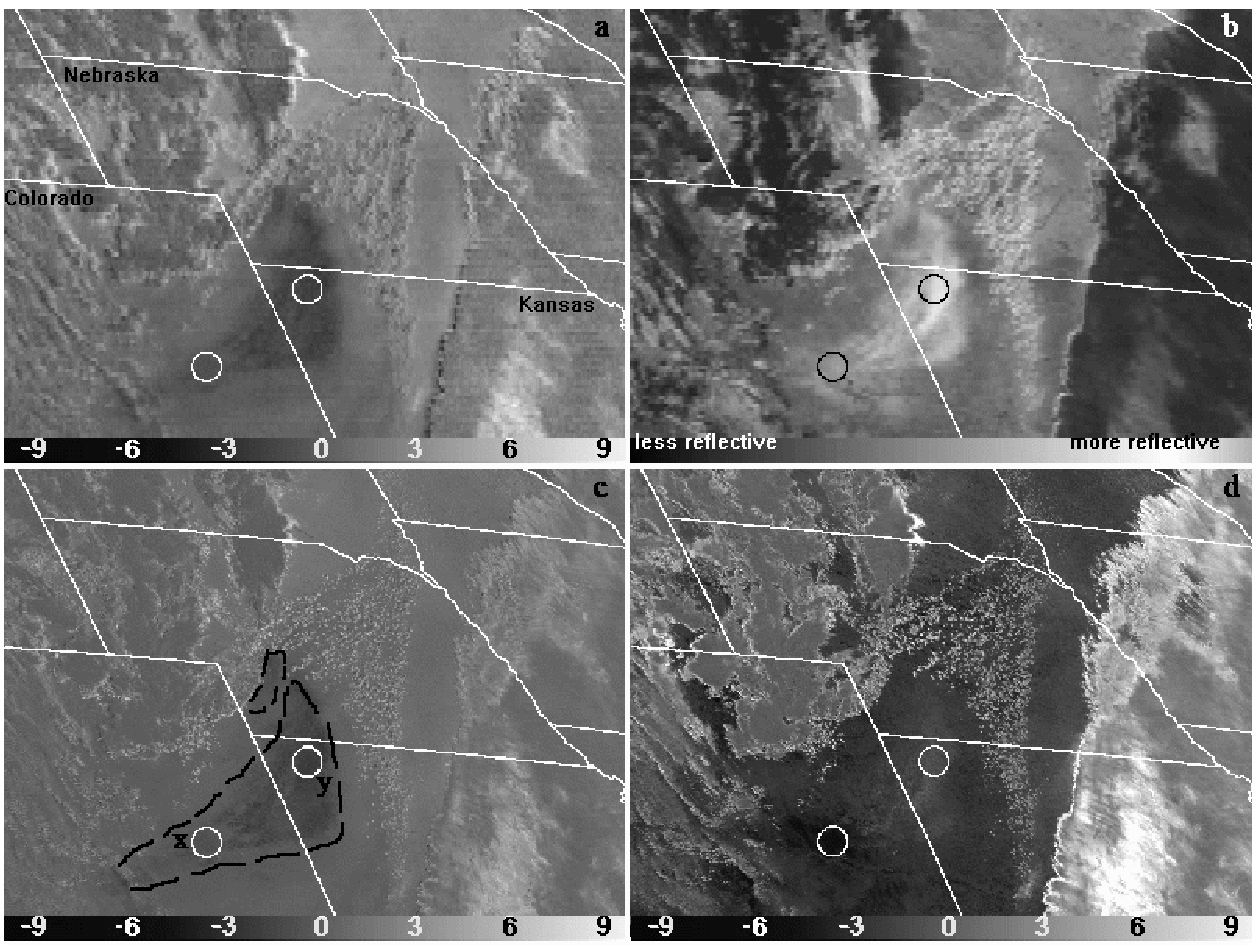


Figure 3. Satellite imagery products showing the dust plume extending from Colorado into Kansas and Nebraska on 18 April 2004, GOES and MODIS Aqua at 19:30 UTC. a) GOES BT10.7-BT12.0, b) GOES reflectivity product using the 3.9 and 10.7 channels c) MODIS BT11.0-BT12.0, the dashed line indicates the plume outline, and d) MODIS BT8.5-BT12.0.

region labeled as circle y. In the circled region labeled as x, the most negative value is -7.0 with an average value of -5.0. These observations are opposite what is expected from the modeling results referenced in the previous section. Further information is needed on the effect of surface emissivities, particle size, and opacity of the plume.

Summary

Blowing dust has characteristics similar to volcanic ash and techniques used for its detection can be extended to volcanic ash detection. The BT11-BT12 technique is the most widely used technique in the detection of volcanic ash. It has also been used with success in detection of blowing dust. There are many instances when the 3.9 µm products enhance the ash plume and blowing dust plumes. Even though the signature does not uniquely distinguish it from meteorological cloud, it can be used in conjunction with the other products to better delineate the extent of coverage.

The 8.5 µm channel is currently available on the MODIS satellites. It has the capability to detect SO_2 and sulfates as well as ash and dust. In general, the presence of SO_2 and sulfates will make the BT8.5-BT12.0 signal negative. The presence of small (2 µm) quartz dust (or ash) particles and a low optical depth will result in a positive BT8.5-BT12.0 signal. High optical depth results in a negative BT8.5-BT12.0, similar to viewing a quartz ground signal. The night volcanic ash case viewed here showed features that seemed to be consistent with both the presence of ash and aerosol. The day dust case had negative and positive regions that were not consistent with what was expected.

Since the detection of SO_2 and sulfates is desirable along with the detection of ash, further research is needed to determine regional sensitivities to the background surface emissivity and particle size as well as optical depth in the 8.5 µm region. This will help to develop a more robust and comprehensible product to be used in monitoring volcanic emissions.

Acknowledgements

This work is supported by NOAA Grant NA17RJ1228.
The MODIS data used in this study were acquired as part of the NASA's Earth Science Enterprise and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) Distributed Active Archive Center (DAAC).

References

Ackerman, S. A., 1989: Using the radiative temperature difference at 3.7 and 11 µm to track dust outbreaks. *Remote Sens. Environ.* **27**:129-133.

Ackerman, S. A., 1997: Remote sensing aerosols using satellite infrared observations. *J. Geophys. Res.,* **102** (D14): 17,069-17,079.

Ackerman, S. A., and K. I. Strabala, 1994: Satellite remote sensing of H2SO4 using the 8- to 12- µm window region: Application to Mount Pinatubo. *J. Geophys. Res.*, **99** (D9): 18,639-18,649.

Baran, A. J., J. S. Foot, and P. C. Dibben, 1993: Satellite detection of volcanic sulphuric acid aerosol. *Geophys. Res. Lett.,* **20** (17):1799-1801.

Ellrod, G. P., B. H. Connell, D. W. Hillger, 2003: Improved detection of airborne volcanic ash using multi-spectral infrared satellite data. *J. Geophys. Res.*, **108** (D12): Art. No. 4356 Jun 21.

Prata, A. J., 1989a: Observations of volcanic ash clouds in the 10-12 µm window using AVHRR/2 data. *Int J. Remote Sensing*, **10**(4-5):751-761.

Prata, A. J., 1989b: Infrared radiative transfer calculations for volcanic ash clouds. *Geophsy. Res. Lett.,* **16**(11): 1293-1296.

Salisbury, J. W., and L. S. Walter, 1989: Thermal infrared (2.5-13.5 um) spectroscopic remote sensing of igneous rock types on particulate planetary surfaces. *J. Geophys. Res*., **94**, No. B7, 9192-9202.

Schneider, D. J., and Rose, W. I., 1994: Observations of the 1989-1990 Redoubt volcano eruption clouds using AVHRR satellite imagery. In: Volcanic ash and aviation safety: Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety. U. S. Geological Survey Bulletin 2047, 405-418.

Shenk, W. E., and R. J. Curran, 1974: The detection of dust storms over land and water with satellite visible and infrared measurements. *Mon. Weather Rev.,* **102**: 830-837.

Wald, A. E., Y. J. Kaufman, D. Tanré, and B. –C. Gao, 1998: Daytime and nighttime detection of mineral dust over desert using infrared spectral contrast. *J. Geophys. Res.,* **103** (D24): 32,307-32,313.

Ice in Volcanic Clouds: When and Where?

William I Rose, Gregg JS Bluth and I Matthew Watson
Michigan Technological University, Houghton, MI 49931 USA

Volcanic clouds are suspensions of particles, analogous to meteorological clouds. In volcanic clouds the particles include volcanic ash, *hydrometeors* (raindrops, snow, hail, graupel, sleet, etc), sulfate aerosols and particles that are mixtures or conglomerations of all the other particle types present. *Ash fall* is analogous to rain, hail or snow, and consists of large ash particles in descent. Ash fall occurs most markedly from the high energy first stage of volcanic clouds, with or without precipitation, near the vent and soon (<1hr) after eruption (Rose et al, 2000). Volcanic clouds exhibit a second stage of evolution, lasting a day or so, where rapid physical and chemical changes occur and when ash fall occur and when ash fall (and precipitation) is muted and controlled by aggregation of ash particles too small to fall by themselves. A third stage of volcanic clouds lasts several more days and consists of drifting over hundreds or thousands of km and very slow fallout (Rose et al, 2003).

This paper explores published data from remote sensing and other sources concerning the existence of ice particles in volcanic clouds, to attempt to reveal patterns in its variability. We use data from a variety of satellite sensors and using several different algorithms for retrieval of information about ice, ash, sulfate and SO_2 (Table 1), applied to eruptions of the last few decades.

If one type of particle is dominant in the volcanic cloud, it is challenging to use these remote sensing algorithms to quantify the subordinate particles. We discuss in this paper cases when ice is the dominant particle type, when ash is dominant and when ash and ice are similar in mass proportions.

Table 1 Algorithms used for volcanic cloud sensing retrievals, see also Watson et al (2004)

Name	Sensor (s)	Objective	Reference(s)
2 band BTD	GOES, AVHRR, MODIS	Mass of fine (> 15 μm radius) ash, Particle size	Wen & Rose, 1994; Yu et al, 2002 (atmospheric corrections; Rose et al, 1995 (ice retrievals)
8.6 μm SO_2	MODIS, ASTER	SO_2 mass	Realmuto et al, 1997
7.3 μm SO_2	MODIS, HIRS/2	SO_2 mass	Prata et al, 2003 (HIRS/2) Prata et al, in prep (MODIS)
UV SO_2	TOMS	SO_2 mass	Krueger et al, 1995
Multiband IR	MODIS	Fine ash, ice, sulfate masses	Yu & Rose, 2000

GOES = Geostationary Operational Environmental Satellite; AVHRR= Advanced Very High Resolution Radiometer; MODIS= Moderate Resolution Imaging Spectroradiometer; ASTER= Advanced Spaceborne Thermal Emission and Reflection Radiometer; TOMS= Total Ozone Mapping Spectrometer

Ice Dominant Volcanic Clouds

Rabaul, Papua New Guinea 1994

The Rabaul eruption was the event which made us realize that ice could be the dominant particle in volcanic clouds. The eruption came from dual vents on opposite sides of a caldera breached by the ocean and resulted in a 20 km high eruption cloud which was detected by satellite sensors such as the polar orbiting AVHRR. Numerous conventional photographs from the Space Shuttle (http://www.geo.mtu.edu/volcanoes/rabaul/shuttle/) show that this cloud had a bright white color like a meteorological cloud. Infrared remote sensing showed that the cloud contained >2 MT of ice. Salty rain falls occurred in a wide arc N and NW of the volcano and there were wet ash and mud falls which contained sea salt, although ash could not be detected by satellite remote sensors. The Vulcan vent (the main source of the Rabaul eruptions) was itself breached, and so the ocean flowed directly into the active vent during eruption. Thus the ice in the great cloud may have largely been the result of evaporation of the ocean (Rose et al, 1995). Remote sensing also revealed that the Rabaul volcanic cloud contained relatively low levels of SO_2 (80 $\pm$ 50 kT), which suggested that ice sequestered much of the volcanic gas and removed it from the volcanic cloud by precipitation in the early stage of the volcanic cloud. Overall this example showed that ice could reduce the residence time of both ash and SO_2 in the volcanic cloud, an idea suggested by Pinto et al (1989).

Hekla, Iceland 2000

The Hekla eruption was a small (ash volume ~ 0.01 km3; total magma volume ~0.17 km^3 and mass about $3x10^5$ MT) fissure eruption of lava preceded by a brief (1-2 hr) explosive phase that produced an eruption cloud which suddenly reached 10-12 km. Meteorological radar was a useful monitoring tool to document the explosive eruption and the growth of ice in the volcanic cloud (Lacasse et al, 2004). The volcanic cloud was mapped by a variety of satellite sensors as it drifted N of Hekla toward Svalbard for 2 days (Rose et al, 2003). It was also traversed by a research aircraft with in situ atmospheric sensors. In spite of the small scale of the eruption, the Hekla volcanic cloud contained >1 MT of ice and 160-240 kT of SO_2. Ash was a minor component and was detected by remote sensors only in the first hour of the eruption (~100 kT or .1 Tg). The ice mass in the volcanic cloud declined by an order of magnitude before the aircraft encounter 35 hours after eruption (figure 1).

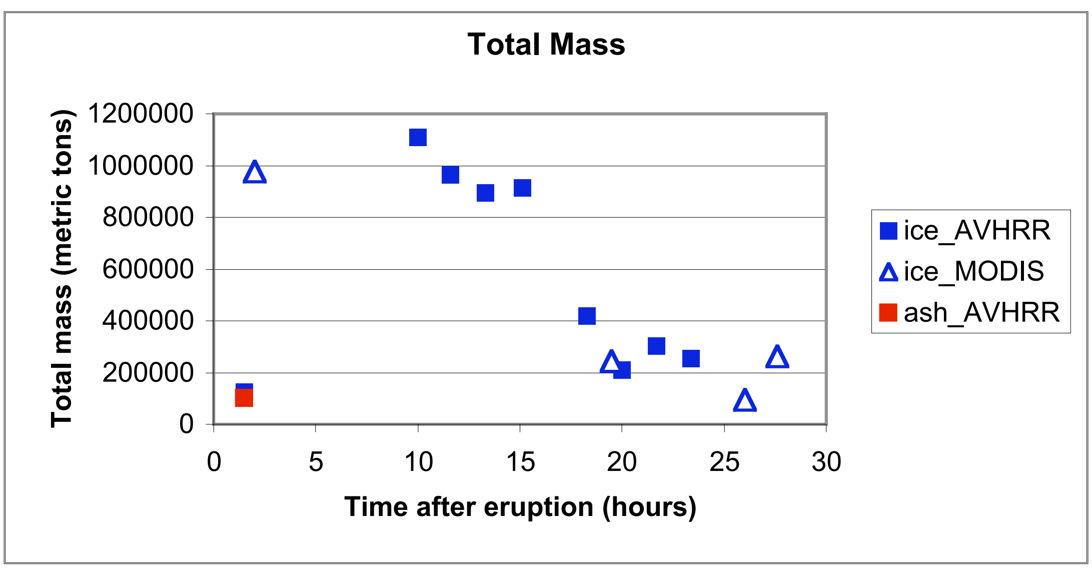


Figure 1: Time based determinations of particle masses determined using the multispectral IR retrieval of Yu & Rose (2000) for the Hekla Volcanic Cloud (Rose et al, 2003).

Examples where ice is clearly subordinate
Spurr, Alaska 1992

Crater Peak, Mount Spurr Alaska had 3 similar VEI=3 eruptions in 1992. Each resulted in a volcanic cloud which reached the lower stratosphere (~14 km asl) and had eruptive volumes of about 0.01-0.02 km^3 (Rose et al, 2001). All three events were studied with AVHRR sensors which enabled us to estimate masses of several hundreds of kilotonnes of fine (<15 μm radius) ash particles. These particle masses declined markedly during the first 18-24 hours due to aggregate formation and fallout. No ice could be detected with remote sensing in any of these clouds. We used atmospheric profile information and a numerical model called ATHAM which includes microphysical processes (Textor et al, 2003) to determine the likely amounts of ice in the Spurr volcanic clouds and found that the model results showed that ice concentrations in the Spurr Clouds were of the order of a few % of the fine ash concentrations. One factor that limits the ice is the low concentrations of H_2O in tropospheric air at high latitudes, which limits the entrained water vapor in the column. The low proportions of ice in Spurr volcanic clouds may limit the fallout of icy aggregates which accelerate ash removal in other clouds. We also note that the Spurr clouds did not show separation of ash and SO_2 (See discussion in Rose et al, 2001).

Cleveland, Alaska 2001

Cleveland is a stratovolcano 1730 m high located 1500 km SW of Anchorage in the east central Aleutians. With 11 eruptions since 1893 and ash eruptions in 1987 and 1994, it is relatively active. As it is unmonitored seismically and remote, satellite observations of thermal anomalies and eruption clouds play a vital role in monitoring (Dean *et al,* 2004). In 2001, Cleveland erupted on February 19, March 11 and March 19. On February 19, the largest of the three events produced ash eruptions that lasted 8-9 hours and which were observed by satellite sensors (GOES, AVHRR and MODIS) for 48 hours. The fine (<15 μm radius) ash masses in this volcanic cloud was found to be ~30 kT and the SO_2 mass was ~10 kT. There was a sight separation of ash and SO_2, suggesting that the SO_2 was emitted earlier and higher. No ice signal could be detected. The most important new observation about the Cleveland eruption was the enhanced sensitivity of the infrared detection from the large satellite zenith angles (Gu et al, in prep).

Other ice subordinate examples.

We have observed more examples of ash dominant volcanic clouds, such as Augustine, 1986 (Holasek & Rose, 1991) and Kluychevskoi, 1994 (Rose et al, 1995). We note that these examples are all at latitudes >40, which suggests that tropospheric water vapor, which is much higher at tropical latitudes, influences volcanic cloud ice through the entrainment process (Glaze et al, 19xx).

Subequal Proportions of ice and ash in volcanic clouds
Pinatubo, Philippines 1991

The largest eruption of the past 25 years, Pinatubo produced truly global scale atmospheric changes from its climactic eruption on 15 June 1991 (McCormick et al, 199x). About 80 MT of ice, about 50 MT of fine ash (<15 μm radius), and 18-19 MT of SO_2 were found in Pinatubo's huge volcanic cloud by Guo et al (2004a, 2004b). The coexistance of ice and fine ash makes retrieval using the two band BTD method of Wen & Rose difficult or impossible (Figure 2). This observation highlights an important issue for volcanic cloud detection, and provides a need for further development of multispectral infrared retrieval algorithms such as Yu & Rose (2000). The effects of ice in the Pinatubo cloud were marked: 1. SO_2 was apparently significant sequestered by ice (Figure 3) during the first day of atmospheric residence (Guo et al, 2004a) and 2. The ice and the ash fell out of the cloud quickly (about 90% removed in 3 days) and at very similar rates, suggesting that they fell out as ice/ash aggregates (Guo et al, 2004b).

Soufrière Hills, Montserrat, 26 December 1997

On 26 December 1997, the volcanic dome at Soufrière Hills, Montserrat collapsed catastrophically, producing a debris avalanche,

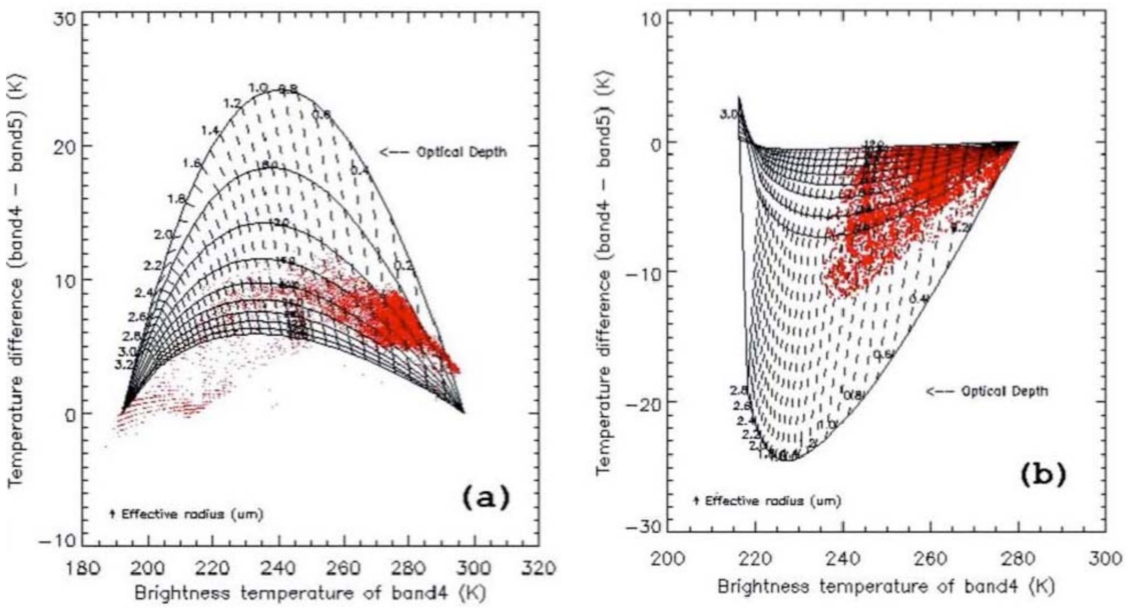


Figure 2: Brightness temperature difference (BTD) of band 4 (λ=11 μm) and Band 5 (λ=12 μm) data from AVHRR plotted against band 4 brightness temperature for two eruption clouds: a: Rabaul, 19, Sept, 1994, which was interpreted as ice dominant and b: Kluchevskoi, 1 October 1994, which was interpreted and ash dominant (Rose et al, 1995).

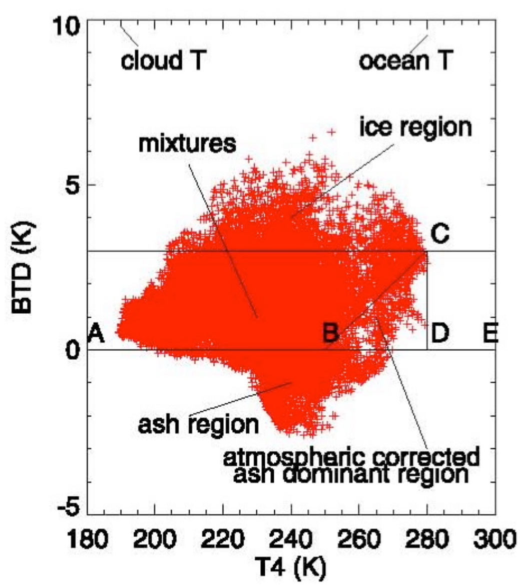


Figure 3: BTD plot, as in figure 2, but for the volcanic cloud of Pinatubo, 15 June 1991. This volcanic cloud is extremely variable and plots mainly in region labeled “mixtures”, and only partly in the fields labeled “ash region” and “ice region”. Compare with figure 2.

a pyroclastic density current and an ash cloud which rose to 15 km (Sparks et al, 2003). Because the density current carried hot andesite directly to the sea, the evaporation of the ocean led to the formation of a volcanogenic meteorological cloud, which also rose to stratospheric levels. The mapping of two stratospheric clouds and their particle masses (~45 kT fine ash (<15 μm radius) in the volcanic cloud; ~150 kT ice in the volcanogenic meteorological cloud) was demonstrated by Mayberry *et al* (2003). The two clouds overlapped in their two dimensional extent as they drifted SE for more than 6 hours.

El Chichón, Mexico 1982

The El Chichón eruption consisted of 3 large phases (the first and smallest on March 29 and the other two on April 4, 1982). The April 4 events produced a volcanic cloud which dramatically separated into a higher (22-26 km high) westward-drifting SO_2 rich volcanic cloud and a lower (19-21 km high) which contained most of the fine ash erupted (Schneider *et al*, 1999). The April 4 events produced ~ 7 MT of SO_2 and about 7 MT of fine ash (<15 μm radius) and the mass map of the cloud is obscured along its eastern edge (figure 4). By analogy with the Pinatubo example, we suggest that this is due to ice, which is present in proportions subequal to fine ash. The existence of ice may also explain the very rapid ash fallout observed by the satellite sensors, where >90% was lost in 3 days.

Conclusions

Ice is present in all cold volcanic clouds and this has important implications for hazards. For detection using infrared remote sensing, ice presence in the volcanic cloud interferes with volcanic ash, which means that the simplest detection schemes (2 band brightness temperature differencing) may be less sensitive or even ineffective.

Ice may be dominant, subordinate or subequal to ash in terms of mass in volcanic clouds and we have found good examples of each of these cases in the last 25 years. High latitude volcanoes are likely to be ice poor, perhaps because entrainment of tropospheric H_2O by the eruption column is limited by the drier high latitude troposphere.

Besides entrained tropospheric water vapor, sources of H_2O for volcanic cloud ice includes, magma, various hydrospheric reservoirs (ocean, crater lakes, glaciers, groundwater) and hydrothermal systems.

Ice in volcanic clouds enhances ash fallout by forming composite aggregates.

Ice forms immediately after eruption, and then decreases markedly by an order of magnitude in only a few days, apparently sublimating as well as precipitating from the drifting volcanic cloud.

Ice sequesters SO_2, and can remove it by precipitation or release it during sublimation, so that SO_2 masses in volcanic clouds have been observed to increase for 1-2 days after eruption.

References

Dean, K G, J Dehn, K R. Papp, S Smith, P Izbekov, R Peterson, C Kearney and A Steffke, 2004, Integrated satellite observations of the 2001 eruption of Mt. Cleveland, Alaska Journal of Volcanology and Geothermal Research Volume 135, Issues 1-2 , 15 July 2004, Pages 51-73

Glaze, LS, S M Baloga and L Wilson, 1997,Transport of atmospheric water vapor by volcanic eruption columns, Journal of Geophysical Research, D, Atmospheres 102, no. 5: 6099-6108

Guo, S, W I Rose, G J S Bluth and I M Watson, 2004, Particles in the great Pinatubo volcanic cloud of June 1991: the role of ice, Geochemistry, Geophysics, Geosystems, Vol 5, no 5 Q05003, doi: 10.1029/2003GC000655

Guo, S, GJS Bluth, W I Rose, I M Watson and A J Prata, 2004, Reevaluation of SO2 release of the climactic June 15, 1991 Pinatubo eruption using TOMS and TOVS satellite data, Geochemistry, Geophysics,

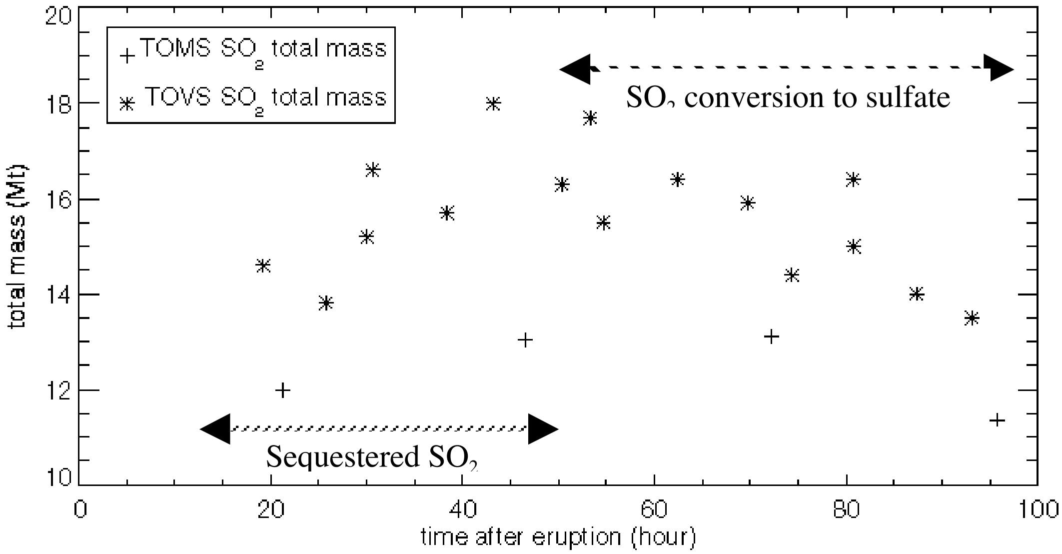


Figure 4: Plot of SO_2 mass retrievals for the 15 June 1991 eruption of Pinatubo, showing time periods where SO_2 sequestration is dominant and where SO_2 conversion is dominant. (from Guo et al, 2004b)

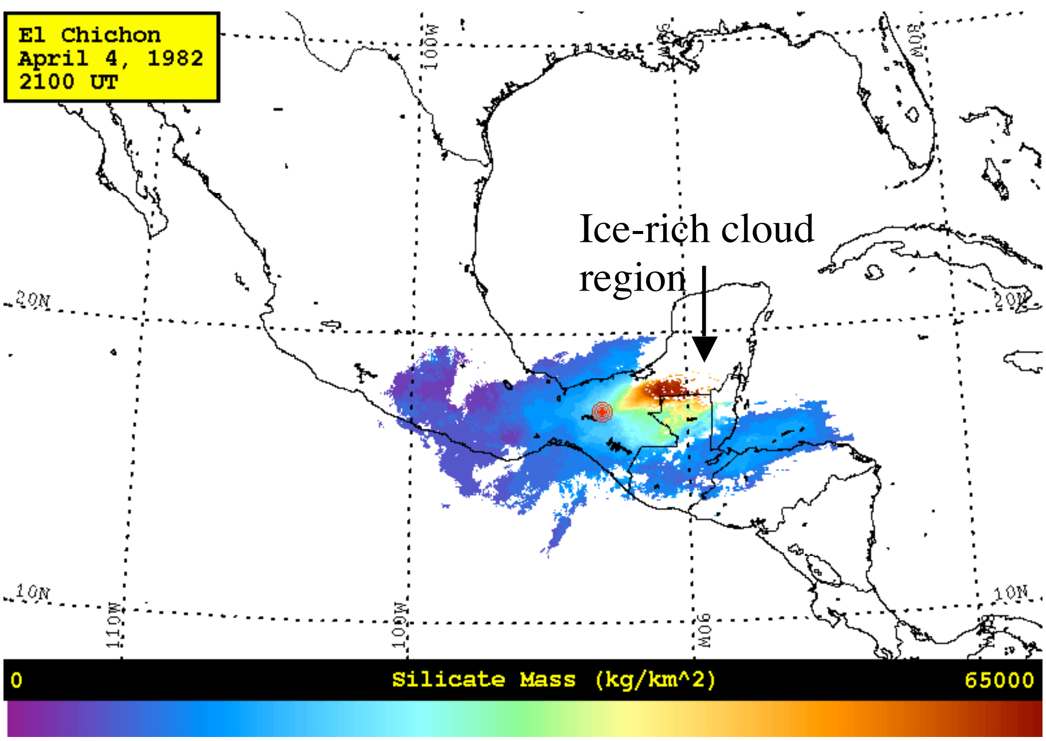


Figure 5: Map of fine ash (<15 μm radius) burden for the El Chichón eruption cloud of 4 April 1982, showing a region where the ash signal is masked by large ice masses. Note how contours of similar burden are terminated. From Schneider et al (1999).

Holasek, R. E., and W. I. Rose, 1991, Anatomy of 1986 Augustine Volcano eruptions as revealed by digital AVHRR satellite imagery, Bull. Volcanol., 53: 420-435.

Krueger A J, L S Walter, P K Bhartia, C C Schnetzler, N A Krotkov, I Sprod and G J S Bluth, Volcanic sulfur dioxide measurements from the Total Ozone Mapping Spectrometer (TOMS) instruments. *J Geophys Res 100:* 14057-14076, 1995.

Lacasse, C, S Karlsdóttir, G Larsen, H Soosalu, W I Rose and G G J Ernst, 2003, Weather radar observations of the Hekla 2000 eruption cloud, Iceland, Bulletin of Volcanology, 66:457-473.

Mayberry, G C, W I Rose and G J S Bluth, 2003, Dynamics of the Volcanic and Meteorological Clouds Produced by the December 26, 1997 Eruption of Soufrière Hills volcano, Montserrat, W.I., in The Eruption of Soufrière Hills Volcano, Montserrat, 1995-99, ed by T Druitt and P Kokelaar, Geological Society of London, Memoir 21: 539-555.

Pinto J P,, R P Turco and O B Toon, 1989, Self limiting physical and chemical effects in volcanic eruption clouds, J Geophys Res 94: 11165-11174.

Prata A J, W I Rose, S Self and D O'Brien, 2003, Global, long-term sulphur dioxide measurements from TOVS data: A new tool for studying explosive volcanism and climate, AGU Geophysical Monograph 139: Volcanism and the Earth's Atmosphere, ed by A Robock and C Oppenheimer, pp. 75-92. ISBN 0-87590-998-1

Realmuto, VJ, AJ Sutton and T Elias, Multispectral thermal infrared mapping of sulfur dioxide plumes - a case study from the East Rift Zone of Kilauea volcano, Hawaii, *Jour. Geophys. Res., 102:* 15057-15072, 1997.

Rose, W I, G J S Bluth and G G J Ernst, 2000, Integrating retrievals of volcanic cloud characteristics from satellite remote sensors--a summary, Philosophical Transactions of Royal Society, Series A, vol. 358 no 1770, pp. 1585-1606.

Rose, W I, G J S Bluth, D J Schneider, G G J Ernst, C M Riley and R G McGimsey 2001, Observations of 1992 Crater Peak/Spurr Volcanic Clouds in their first few days of atmospheric residence, J Geology, 109: 677-694.

Rose, W. I., D. J. Delene, D. J. Schneider, G. J. S. Bluth, A. J. Krueger, I. Sprod, C. McKee, H. L. Davies and G. G. J. Ernst, 1995, Ice in the 1994 Rabaul eruption cloud: implications for volcano hazard and atmospheric effects, Nature, 375: 477-479.

Rose, W I, Y Gu, I M Watson, T Yu, GJS Bluth, A J Prata, A J Krueger, N Krotkov, S Carn, M D Fromm, D E Hunton, G G J Ernst, A A Viggiano, T M Miller, J O Ballentin, J M Reeves, J C Wilson, B E Anderson D Flittner, 2003, The February-March 2000 eruption of Hekla, Iceland from a satellite perspective, AGU Geophysical Monograph 139: Volcanism and the Earth's Atmosphere, ed by A Robock and C Oppenheimer, pp. 107-132. ISBN 0-87590-998-1

Schneider, D. J., W. I. Rose, L. R. Coke, G. J. S. Bluth, I. Sprod and A. J. Krueger, 1999, Early Evolution of a stratospheric volcanic eruption cloud as observed with TOMS and AVHRR, J. Geophys. Res., 104; 4037-4050.

Sparks RSJ, J Barclay, ES Calder, RA Herd, J-C Komoroski, R Luckett, GE Norton L J Ritchie, B Voight and AW Woods, 2003, Generation of a debris avalanche and violent pyroclastic density current 0n 26 December 1997 at Soufriere Hills Volcano, Montserrat, in The Eruption of Soufrière Hills Volcano, Montserrat, 1995-99, ed by T Druitt and P Kokelaar, Geological Society of London, Memoir 21: 409-434.

Textor C, H-F Graf M Herzog and JM Oberhuber, 2003, Injection of gases into the stratosphere by explosive volcanic eruptions, J Geophys Res 108: No D19, 4606.

Watson, I. M., V. J. Realmuto, W. I. Rose, A. J. Prata, G. J. S. Bluth, Y. Gu, C. E. Bader and T. Yu, 2004, Thermal infrared remote sensing of volcanic emissions using the moderate resolution imaging spectroradiometer, J Volcanol Geoth Res 135: 75-89.

Wen, S and W I Rose, 1994, Retrieval of Particle sizes and masses in volcanic clouds using AVHRR bands 4 and 5, J. Geophys. Res., 99:5421- 5431.

Yu, T W I Rose and A J Prata, 2002, Atmospheric correction for satellite-based volcanic ash mapping and retrievals using "split window" IR data from GOES and AVHRR, J Geophys Res, 106: No D16, 10.1029.

Yu, T and W I Rose, 2000, Retrieval of sulfate and silicate ash masses in young (1-4 days old) eruption clouds using multiband infrared HIRS/2 data, AGU Monograph 116 --Remote Sensing of Active Volcanism, ed by P Mouginis-Mark, J Crisp and J Fink, pp. 87-100.

FIRST MEASUREMENTS OF VOLCANIC SULPHUR DIOXIDE FROM THE GOES SOUNDER: IMPLICATIONS FOR IMPROVED AVIATION SAFETY

Fred Prata[1],
Tony Schreiner[2], Tim Schmit[2],
Gary Ellrod[3],
[1]CSIRO Atmospheric Research, Aspendale, Victoria, Australia
[2]NOAA/NESDIS, Office of Research and Applications, Madison, WI, U.S.A.CIMSS, University of Wisconsin-Madison, Madison, WI 53706, U.S.A.
[3]NOAA/NESDIS, Office of Research and Applications, Camp Springs, Maryland, U.S.A.

Abstract

The GOES sounder is a multi channel imaging filter radiometer operating in the infrared to 15 µm, providing up to hourly data at 10x10 km^2 spatial resolution and covering large parts of the globe. The principal aim of the sounder is to provide vertical profiles of atmospheric temperature and moisture for global weather applications. Analysis of data acquired during the July, 2003 eruptions of Soufriere Hills, Montserrat, suggests that some of the channels can be used to detect upper tropospheric SO_2. We provide qualitative and quantitative assessments of GOES' ability to detect SO_2, illustrated with examples and suggest its advantages and limitations compared to other satellite measures of SO_2. Currently three GOES sounders are operational at longitudes: 134.85^{o}E, 99.66^{o}W, and 74.78^{o}W. The temporal frequency and constant viewing angles of the GOES platform make them an ideal system for providing timely aircraft warnings of the presence of upper tropospheric/lower stratospheric SO_2, and consequently are useful for monitoring hazardous volcanic clouds.

Introduction

Satellite measurements of volcanic gases and particles (volcanic ash) are increasingly used by the aviation community to alert them of the possibility of a hazardous encounter. It is well recognized that an encounter with a volcanic ash cloud is likely to cause severe damage to jet engines with the likelihood of loss of power and ultimately loss of the aircraft and lives. A tragedy of this kind has not occurred, yet. However, jet aircraft continue to intercept ash clouds at alarming frequency. Many airline operators are cognisant of the dangers and take very conservative measures to avoid volcanic clouds, when their presence is known. This sensible action comes at the cost of increased mileage through re-routing and consequently airlines incur an economic penalty.

An encounter with a volcanic cloud is often first noticed by the pilot, cabin crew and passengers through the sensing of the presence of sulphur odours. The characteristic pungent odour of sulphur dioxide is an effective indicator. Occasionally, other signs of an ash encounter will be noticed; for example, "St Elmo's Fire", "smoke" in the cabin or observation of a darker than usual cloud. Later inspection of external surfaces will confirm whether an encounter has occurred. The severity of the encounter may require expensive engine checks or repairs to be carried out. In exceptional circumstances these checks and repairs may cost many millions of dollars. In many cases it is not known how severe the encounter has been until the checks have been undertaken. If the tell-tail signs of an encounter have been reported by the pilot and crew and advisories have indicated the possible presence of a volcanic cloud within the flight path, then thorough checks on the aircraft would seem warranted. However, not all encounters with volcanic clouds are necessarily encounters with volcanic ash. Recent research suggests that volcanic eruptions that produce ash and SO_2 may deposit these substances at different heights in the atmosphere. Vertical wind-shear will then cause transport of the ash and SO_2 clouds along different trajectories. This separation of the ash and gas appears to be common (see Bluth *et al*., 1994 for an example).

An encounter with an SO_2 cloud, as opposed to an ash cloud, will not cause engines to stall, will not cause abrasion of surfaces, and will not clog up pitot static tubes. While still to be avoided, encounters with SO_2 clouds are likely to lead to much less airframe damage and may call for a quite different overhaul procedure and repair. The costs of checks and repairs for an encounter with an SO_2 cloud are likely to be much less than those for an encounter with an ash cloud. These factors suggest that airlines need to know whether a volcanic cloud is predominantly SO_2 or predominantly ash. The current state of the science indicates that it is possible to detect both SO_2 and ash clouds from satellite-borne instruments simultaneously and monitor their progress through the airways. This paper and a complementary paper by Schreiner *et al*. (2005) report a new observation of SO_2 clouds detected by the operational GOES sounder and suggest that use of the GOES sounder data will provide airlines with useful additional information on the composition of volcanic clouds.

The GOES Sounder

The Geostationary Orbiting Environmental Satellites (GOES) series provide frequent imagery and soundings for large parts of the globe. The current series are operationally known as GOES-8 through to GOES-12. The platform houses two instruments that view the earth – an imager and a sounder. Table 1 lists the band numbers and their respective central wavelengths for the GOES-12 platform.

GOES-12 Imager band	Central wavelength (µm)
1	0.65
2	3.9
3	6.48
4	10.7
5	13.3

GOES-12 Sounder band	Central wavelength (µm)
1	14.71
2	14.37
3	14.06
4	13.64
5	13.37
6	12.66
7	12.02
8	11.03
9	9.71
10	7.43
11	7.02
12	6.51
13	4.57
14	4.52
15	4.46
16	4.13
17	3.98
18	3.74

Table 1. Band numbers and central wavelengths for the GOES-12 imager and sounder. Note that the GOES sounder also has one broadband visible channel, not listed above.

The imager is used widely to provide frequent qualitative images for meteorological weather forecasting and analyses. The sounder is used for quantitative retrieval of atmospheric temperature and moisture profiles. This paper reports a new use for some of the sounder channels and the following discussion is restricted to the sounder. The spatial resolution of the sounder is ~10x10 km^2 and the temporal frequency is up to once per hour. Although the spatial scale is poorer than many of the polar orbiting satellites (e.g. AVHRR and MODIS), its temporal sampling is better.

SO_2 Retrieval

Sulphur dioxide has strong absorption bands in the infrared near to 4, 7.3 and 8.6 µm. The GOES sounder has bands at 3.98 and 7.43 µm (see Table 1). The band at 3.98 µm measures both reflected solar radiation and thermal emission, in approximately equal amounts under standard conditions. The band at 7.43 µm while not ideally situated for SO_2 detection does not include solar reflected radiation and covers the much stronger 7.3 µm SO_2 band. Sounder band 10 is also negligibly affected by volcanic ash, which can be detected independently by using the 11 and 12 µm bands (7 and 8) through the 'reverse' absorption effect (e.g., Prata, 1989).

A difficulty associated with retrieving SO_2 from band 10 arises because this band is responsive to mid-tropospheric water vapour. Indeed, the band is intended for studies of tropospheric water vapour. If the SO_2 cloud is high and concentrated however, then band 10 will respond to absorption due to SO_2. Typically for optimum detection, the SO_2 cloud should be situated near 200-300 kPa (5-8 km) and be relatively free of in-cloud water vapour. When such conditions are met then band 10 should register an anomalously low radiance (or brightness temperature). In practice, the height of the cloud is unknown and there is always likely to be some water vapour (or large amounts) in the volcanic cloud. To account for some absorption due to water vapour, a temperature difference image can be made. The difference removes some of the variations in radiance due to the heterogenous radiance field impinging onto the lower part of the SO_2/H_2O cloud. The heterogeneity may be due to variations in the radiation from the surface or atmospheric layers below the cloud, or may be due to horizontal variations in lower troposphere water vapour. We used several band differences to determine an optimum second band that maximised the SO_2 response. Ideally, three bands should be used:- two centred outside the 7.3 µm absorption feature and one band situated on the absorption feature. Bands 9, 11 and 10 seem obvious choices for the GOES-12 sounder. The approach taken for GOES SO_2 retrieval follows the method outlined by Prata *et al*. (2004). In this method a *synthetic* radiance (or brightness temperature) is computed by linear interpolation of channels either side of band 10. The difference between the brightness temperature in band 10 and the synthetic value calculated for this band is a measure of the absorption due to SO_2. The reasoning behind this follows from the assumption that only SO_2 gas is causing the anomalous behaviour of band 10, and that water vapour effects have been removed through differencing with the synthetic estimate. The reader is referred to Prata *et a.l* (2004) for an in depth discussion of the veracity of these assumptions and for further information on the retrieval scheme, including the effects of water/ice clouds. Figure 1 shows the results of applying the retrieval scheme to four image frames of GOES-12 data for the July eruption of Soufriere Hills volcano on Montserrat.

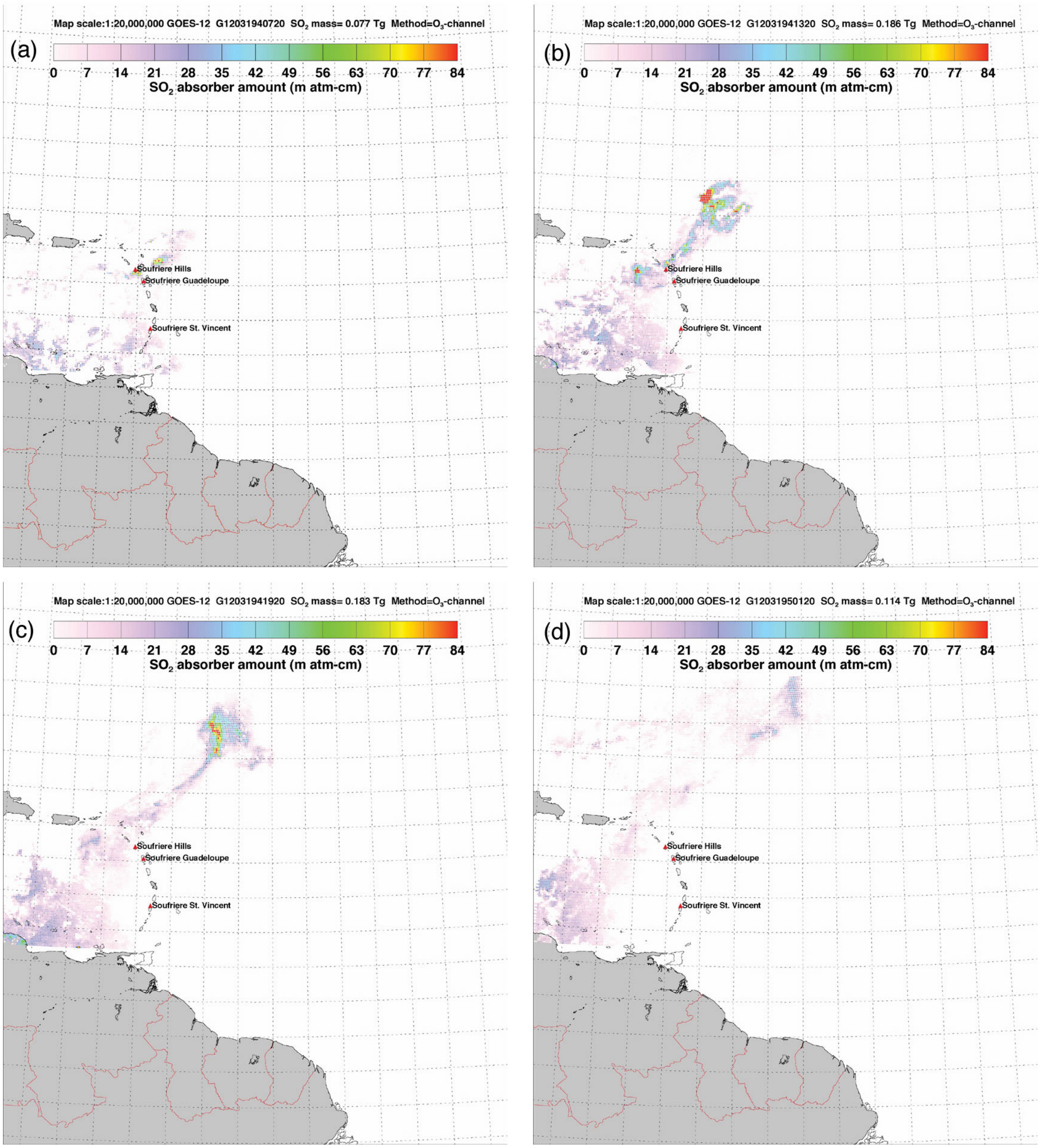


Figure 1. Sequence of GOES-12 SO_2 retrievals for the Soufriere Hills eruption, Montserrat. Each frame is separated by 6 hours in time (see the captions for day of year and time in UTC). SO_2 units are milli atm-cm.

The Soufriere Hills eruption is described in detail in the BGVN (2003). Analysis of the movement of the ash from this eruption suggests that it travelled predominantly to the west and west-northwest (Figure 2). By contrast the (higher) SO_2 cloud travelled northeast. This separation of the ash and SO_2 is a common feature of volcanic clouds that reach well into the upper troposphere (Bluth *et al*., 1994) and is a consequence of wind shear and the difference in densities of gases and particulates.

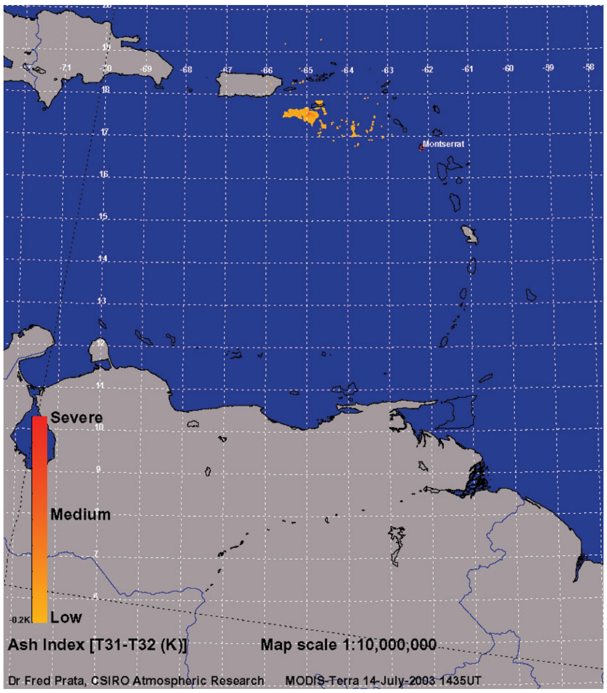


Figure 2. Volcanic ash from Soufriere Hills volcano. This MODIS image shows that the ash from Soufriere Hills moved westwards, whereas the SO_2 moved towards the northeast.

Validation

The Soufriere Hills eruption was monitored by several satellite instruments capable of measuring SO_2. These include, TOMS, MODIS and AIRS. Ground-based SO_2 flux measurements were also made during the eruption. The TOMS instrument estimated about 80 kT of SO_2 and the AIRS instrument retrieved values from 10 kT up to 290 kT, compared with the GOES retrievals of 77 kT up to 186 kT The errors in the SO_2 retrievals from these instruments are generally of the order 10-30%, and differences in timing, spatial coverage and footprint size preclude a comprehensive validation. However, the GOES retrievals are within the expected range of variation and compare quite favourably with AIRS and TOMS. We also note that the GOES band 10 is not optimum for quantitative SO_2 detection–the band centre is too far towards the long wavelength side of the SO_2 absorption and the band is a little broad.

For use by the aviation industry, quantitative SO_2 estimates may be of much less value than the certainty of identification; here the question of GOES sensitivity may be more important. Schreiner *et al*. (2005) show that GOES was able to track the SO_2 cloud for at least two more days at 6 hour time resolution.

Conclusion and implications for aviation safety

Work reported by Schreiner *et al* (2005) and in this paper, demonstrate that GOES may be useful in detecting volcanic SO_2 clouds that persist in the upper-troposphere/lower stratosphere and consequently may intersect airways. We have argued that clear identification of SO_2 from ash in volcanic clouds may be of economic benefit to the airline industry. Use of the 7.2-7.6 μm region for SO_2 detection looks promising as the effects of volcanic ash are much less; although water vapour absorption limits the detection to SO_2 residing at altitudes above 10,000 feet or so. It seems quite possible that a simple SO_2 index could be determined from GOES sounder data and transmitted to VAACs for dissemination to the airlines. Information in such images could be used in conjunction with trajectory models and other satellite data that detect volcanic ash, to allow airline operators to determine safe air routes. Furthermore, information gleaned from pilots and crew that believe they have encountered a volcanic cloud can be fused with the SO_2 and ash images to determine appropriate aircraft checks and maintenance procedures. An encounter with an SO_2 cloud is unlikely to warrant expensive aircraft repair, while it is known that an encounter with an ash cloud can lead to major engine damage.

References

Bluth, G.J.S., Casadevall, T.J., Schnetzler, C.C., Doiron, S.D., Walter, L.S., Kruger, A.J., and M. Badruddin, Evaluation of sulphur dioxide emissions from explosive volcanism: the 1982-1983 eruptions of Galunggung, Java, Indonesia, *J. Volcanol. Geotherm. Res.*, **63**, 243-256, 1994.

BVGN, *Bulletin of the Global Volcanism Network*, Vol. **28**, No. 7, 5-7, 2003.

Prata, A. J., Infrared radiative transfer calculations for volcanic ash clouds, *Geophysical research letters*, **16**, 1293-1296, 1989.

Prata, A. J., Rose, W. I., Self, S., and D. M., O'Brien, 2003, Global, long-term sulphur dioxide measurements from TOVS data: A new tool for studying explosive volcanism and climate, *Volcanism and the Earth's Atmosphere*, Geophys. Monograph **139**, AGU, 75–92.

Schreiner, A. J., Schmit, T. J., Ellrod, G., and Prata, A., Can upper-level SO2 be monitored using the GOES sounder?, Submitted to 85^{th} Annual AMS meeting, 9-13 January, 2005, San Diego, CA. USA.

GROUND-BASED DETECTION OF VOLCANIC ASH AND SULPHUR DIOXIDE

Fred Prata and Cirilo Bernardo
CSIRO Atmospheric Research, Aspendale, Australia

Matthew Simmons and Bill Young
Tenix Investments, Sydney, Australia

Abstract

We present the first ground-based thermal infrared image data showing detection and discrimination of volcanic ash and sulphur dioxide gas emitted from erupting volcanoes. The images are acquired from a new multichannel uncooled thermal imaging camera suitable for deployment within ~10 km of an active volcano. Algorithms for ash and SO_2 detection are described. Images from the system, named G-bIRD (Ground-based InfraRed Detector) are acquired rapidly (within a few seconds), analysed and transmitted via satellite or landline to a computer with access to the Internet and utilising a standard web browser. Tests of the system have been undertaken at Etna and Stromboli, Italy, at Anatahan, Northern Mariana Islands and at Tavurvur, Rabaul, Papua New Guinea. G-bIRD offers a new means for monitoring hazardous volcanic substances from the ground and could provide complementary information for providing volcanic ash and SO_2 warnings to the aviation industry.

Introduction

Volcanic ash is a hazard to jet aircraft, causing engines to stall when ingested, scouring windows and the leading edges of the wings and causing instrument malfunctions (Casadevall, 1994 and references therein). Damage to aircraft can be counted in the millions of dollars. Most serious aircraft encounters with ash clouds have been at cruise altitudes (e.g. Tupper *et al.*, 2004), but there is also a hazard to aircraft at airports affected by volcanic ash (Guffanti *et al.,* 2004 this volume). These airports are usually close to an active volcano (e.g. Anchorage and Kagoshima) but they can also be at some distance from the source of the eruption due to atmospheric transport that brings ash into the region. This paper addresses the problem of detecting volcanic ash in the vicinity of airports and suggests a practical design for an infrared device that can monitor the sky overhead. The cost of ash hazards to airport operations is not known, but must be significant if the costs include those due to delays to landings and take-offs as well as re-routing costs incurred by airline operators (Cantor, 1998). Other environmental hazards consist of the toxic gases emitted by volcanoes. Of particular importance and abundance is sulphur dioxide gas. This gas is colourless, but has a characteristic pungent odour. Eye irritation and inflammation of the respiratory tract occurs at relatively low concentrations. Amounts of 6-12 ppm will cause immediate irritation of the nose and throat. Long term exposure can exacerbate asthma and can be dangerous to persons with pre-existing cardiopulminary diseases. Thus monitoring near strong sources of SO_2 (e.g. from industrial sources and at volcanoes) is important, as is longer term monitoring at some distance from the source. Currently there are no regulatory requirements for airport operators to provide warnings of ash hazards. Warnings are issued based on information from volcano observatories, meteorological advisories and, in some cases, radar observations of eruption columns. Radar information is generally only reliable at the start of an eruption when the ash cloud is thick and usually such information is only available at airports in close proximity to an erupting volcano. For airports distant from the source of ash there are few direct observations available. Some observations come from satellite systems and other sources of information come from trajectory forecasts based on wind data and cloud height information. Much of this information is sporadic and untimely and there is a need for better coordinated information systems and better observational systems. A detector placed on the ground at an airport affected by volcanic ash would provide a useful adjunct to existing information sources. The device would be capable of viewing the sky overhead at horizontal distances of several kilometers in all directions. Given that ash clouds and gases travel at the mean speed of the winds the system would provide crucial advance warning. For example, a cloud moving at 10 ms^{-1} (36 km hr^{-1} at an altitude of 3 km (~10,000 feet) would be observed by the detector ~16 minutes before it appeared overhead. At 30 ms^{-1} (108 km hr^{-1}) the warning time shortens to ~5 minutes. The G-bIRD system detects ash clouds by their unique signature in the infrared window between 8–12 µm (see Prata and

Barton, 1993 for details). SO_2 is detected by exploiting the absorption caused by the gas near 8.6 µm.

Wind-blown dust from desert regions or semiarid lands can be a hazard to aircraft, reduces visibility significantly and can cause eye and throat irritation to humans. Large parts of the habitable earth are prone to dust storms, including northern Africa, the Mediterranean islands, southern Italy, Spain and France, southwestern USA, central and southern Australia, western parts of South America, central China, Japan and south and north Korea and the central deserts of Asia. The wind blown dust can also be transported long distances–dust from China has been detected in north America. The dust can consist of nearly spherical particles of SiO_2 in concentrations that will limit visibility to a few 10's of metres. Fine (1-10 µm diameter) particulates of SiO_2-bearing minerals have characteristic absorption features (Restrahlen effects) in the region 8-9 µm and can be detected by G-bIRD.

Principle of operation.

The Ground-based InfraRed Detector–G-bIRD (Prata and Bernardo, 2004; Prata, 2004) is a new passive thermal infrared imaging camera based on uncooled microbolometer technology and is a natural extension of earlier precision radiometers developed by Prata and Barton (1993) and Prata *et al.* (1991). The device operates by comparing infrared signals from the sky above, at up to 5 pre-defined wavelengths (the central wavelengths and wavelength intervals are given in Table 1). The infrared radiation measured by the detector is linearly proportional to the resistance change in the detector, which is recorded and logged by a signal processing unit. The instrument concept is made possible by the recent commercial availability of relatively cheap uncooled focal plane detector arrays (FPAs). An uncooled microbolometer staring array sensitive to radiation in the 6-14 µm wavelength interval is used to detect filtered radiation by use of a filter wheel (or similar mechanism). The radiation from the sky is focussed onto the array by means of focussing optics (a Ge lens or mirror) and the field-of-view is a cone of up to 90 degrees. The use of a filter-wheel mounted with circular interference filters is an option.

The G-bIRD camera

The prototype G-bIRD camera consists of an uncooled focal plane infrared array of dimensions 320x240 pixels, with F0.86 optics and a custom built filter wheel holding up to five narrow band (<1 µm width) interference filters. The detector has a nominal noise temperature of no less than ~50 mK in the broadband channel. To achieve sufficient temperature sensitivity in the narrow band channels, frame averaging is employed. Table 1 shows the theoretical noise equivalent temperatures (NEΔT's) expected for various frame averaging values in 5 narrow bands or channels and one broadband channel.

Band (λ)	High (λ)	Low (λ)	No of frames (NEΔT, mK)			
			4	16	32	64
7.3	7.05	7.55	1346	476	337	238
8.6	8.35	8.85	890	315	223	157
10.1	9.85	10.35	643	227	161	114
11.0	10.75	11.25	657	232	164	116
12.0	11.75	12.25	900	318	225	159
8-14	8	14	65	23	16	11

Table 1. Noise equivalent temperatures (NEΔT, mK) for different amounts of frame averaging.

Calibration

The G-bIRD camera provides raw digital counts as output from the FPA; the output has some corrections applied. These counts can be related to the scene temperature through a linear calibration process. A two point blackbody calibration procedure was developed which uses the output from the FPA corresponding to two cooled and heated blackbody cavities placed in front of the lens. The combined effect of the filters and detector response is considered in the calibration procedure. No account has been taken of the effects of off-axis viewing through the filters and the filter responses are single measurements of the response of the central portion of the filter (50 mm diameter). To convert from the calibrated radiances to scene temperature, the calibration equation must be inverted. This is a nonlinear problem that requires a minimisation procedure. The approach adopted is to generate a series of look-up tables that give radiances equivalent to pre-specified temperatures. The procedure is accurate to 10 mK over the range of observable temperatures 220 K to 330 K. The calibration procedure is repeated several times and average look-up tables are generated. In actual use the calibration is performed in the laboratory and not done in the field. This is possible because once a calibration file has been derived under idealised conditions this can be used in all future measurements to convert the raw signals into temperatures. However, in practice the optics (particularly the lens) may heat up or cool down and thus produce a different temperature to its value when calibrated in the laboratory. This causes an off-set in the measured signals. To overcome this problem we have devised an innovative field calibration procedure that makes use of a single shutter measurement. The shutter fills or slightly overfills the field-of-view of the instrument and provides a uniform radiation source to the detector. The temperature of the side of the shutter facing the lens is continuously monitored using a contact temperature probe. The shutter side facing the lens is blackened so that its infrared emissivity is high (exceeding 0.96) and uniform across the region 6-14 µm. In the field, the calibration is performed by making a single measurement of the shutter, followed by a measurement of the scene and then application of the calibration equations and shutter measurement that accounts for the off-set generated by any change in temperature of the lens. Fig. 1 shows a photograph of the camera in use in the field.

Field Testing

The G-bIRD camera has been field tested at several active volcanoes and sites where ash and SO_2 emissions are observed. The complete field program, testing and analyses cannot be reported here and only a summary of the main results is given.

Figure 1. The G-bIRD camera on site at Etna.

The field program was divided into three parts: (A) testing of the camera hardware, processing system, communications and real-time image delivery, (B) testing the camera in elevated SO_2 conditions, and (C) testing the camera in elevated volcanic ash conditions. To achieve the goals of the field program the following sites were visited:

(1) Kilauea, Hawaii - system testing,
(2) Anatahan, NMI - system testing and measurement site for goals (A, B, C),
(3) Port Pirie, South Australia–SO_2 measurements goal (B)
(4) Etna and Stromboli, Italy–SO_2 measurements and system test goals (A, B),
(5) Tavurvur, Rabaul, PNG–ash measurements goal (C).

To give an indication of the results of the trials we present data for field tests (4) and (5), which clearly show the usefulness of the system for volcanic SO_2 and ash monitoring.

Mt Etna and Stromboli, Sicily, Italy. Mt Etna (3300 m ASL) has been active since starting an eruptive phase in November 2002. The G-bIRD camera was deployed about 15 km from the active crater in the town of Nicolosi (1015 m ASL) on the south-western flank of the volcano. When measurements were made during September 2003, the emissions from Etna were predominantly SO_2 with a few minor ash eruptions, never attaining significant height and rarely visible beyond a few 100 m's away. The viewing elevation angle of the camera was varied from 10 to about 30 degrees above the horizon. The G-bIRD camera was tested for monitoring SO_2 and for communications trials. At Stromboli, the emissions were also SO_2 and the activity there provides a more or less continuous gaseous plume. Intermittent explosions of ash were observed, but these also rarely attained heights of more than a few 10's m above the summit and the ash did not get transported any significant distance in the air. G-bIRD was mounted ~3 km from the active crater on Stromboli. Results are provided in Figures 2 and 3.

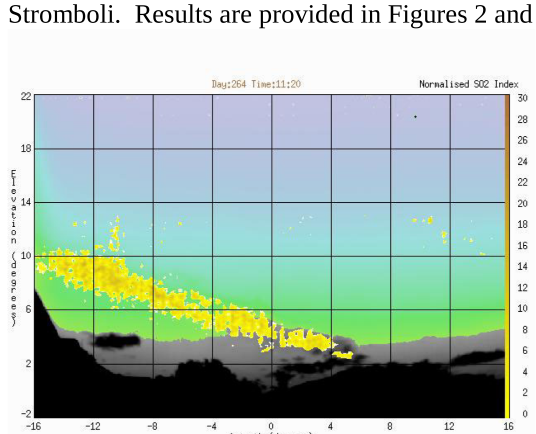


Figure 2. SO_2 plume observed over Mt Etna. The SO_2 index is a qualitative measure of the SO_2 concentrations in the plume.

Each of the Figures shows a single frame of data identifying the plume as SO_2-laden. Consecutive frames of data can be looped to form a movie-style animation of the plume.

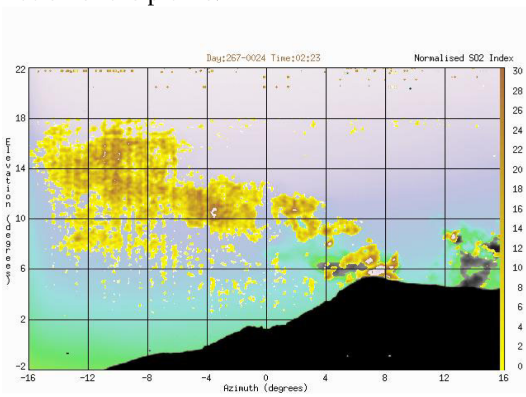


Figure 3. SO_2 plume from Stromboli.

These movies reveal typical plume dynamical features such as: thinning, turbulent eddies, puffs, fumigation and vertical and horizontal mixing. On many occasions G-bIRD detected large changes in the apparent concentrations of SO_2; most notable were instances where the SO_2 concentrations would dip below the detection level of G-bIRD and the plume appeared to be predominantly water vapour. A whole sequence of data was collected where a white-looking water-laden plume from Etna was indistinguishable to the naked eye (or a web-cam) from an SO_2-laden plume. The G-bIRD imagery made a distinct discrimination between these two plumes.

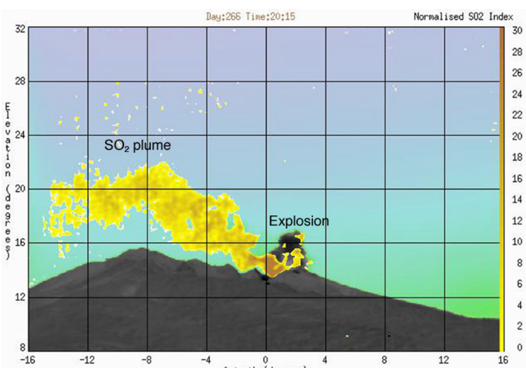


Figure 4. G-bIRD camera viewing a plume of SO_2 and an explosion (coloured grey to black) from Stromboli.

The results for Stromboli (Fig. 4) were similarly striking and unambiguous, although much less water vapour was apparent in the Stromboli plume and the strength of the SO_2 signal was greater due to the closer proximity of the camera deployment there. That there is water vapour in both plumes is undeniable and obvious through observation of the white-coloured plumes from both volcanoes. Less obvious is the detection of separate regions of SO_2 above the craters, where no plume is visible at all to the naked eye (or web-cam). Measurements were also made during the night at both volcanoes. If anything, the data are clearer during the night than during the day–the reason, perhaps, being due to less evaporation and subsequent lower water vapour loadings in the plumes at night compared to during the day. The G-bIRD camera was also able to capture discrete explosions from Stromboli. In the case of the explosion, the pyroclastic material is mostly hot rocks, cinders and ash and reveals itself as grey to black colours when the SO_2 algorithm is used. In contrast when the ash algorithm is used, that is, by taking temperature differences using only two channels, the resulting image appears as shown in Figure 5.

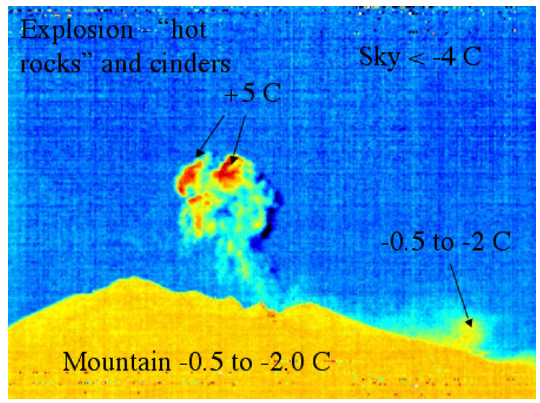


Figure 5. Ash algorithm used on an image with an explosion obtained at Stromboli.

In this case the algorithm identifies the hot rocks and cinders as positive differences (high ash content), and resuspended ash as slightly negative (similar to the material on the surface of the mountain slopes). The sky has markedly negative differences. The interference effects of water vapour at these low elevation viewing angles has not been accounted for.

There is a nonlinear relation between the temperature differences and the SO_2 amount measured in atm-cm or other suitable units. This relation is of the form:

$$u = \ln [\alpha \Delta T + \beta],$$

where α and β are parameters that depend on the absorption coefficient of SO_2 around 8.6 µm and on instrumental characteristics. ΔT is a temperature difference formed between two channels and u is the absorber amount in suitable units. The parameters α and β are determined from modelling studies and from calibration data for the instrument, including the response functions of each filter. An SO_2 index has been derived to account for the minor nonlinearity and provide a fast, non-quantitative measure of the SO_2 content in a G-bIRD image. Quantitative estimates of the SO_2 loadings from the G-bIRD camera, while possible, were not attempted at Etna or Stromboli, principally because no independent validation data were acquired and the lack of a meteorological station close to the camera precludes accurate modelling of the interfering effects of water vapour.

Tavurvur, PNG. The Tavurvur crater at Rabaul has been in near-continuous activity since the catastrophic and near simultaneous eruptions from Tavurvur and Vulcan on opposite sides of Rabaul harbour in September 1996. Tavurvur activity is characterised by ash-rich explosions occurring at intervals of between 10-30 minutes. G-bIRD measurements at Tavurvur were conducted during 4 days in November 2003 from locations with line-of-sight of the crater and from distances of 1-10 km. A good example of ash identification is shown in Figure 6; Fig 7. Shows the corresponding visible camera image

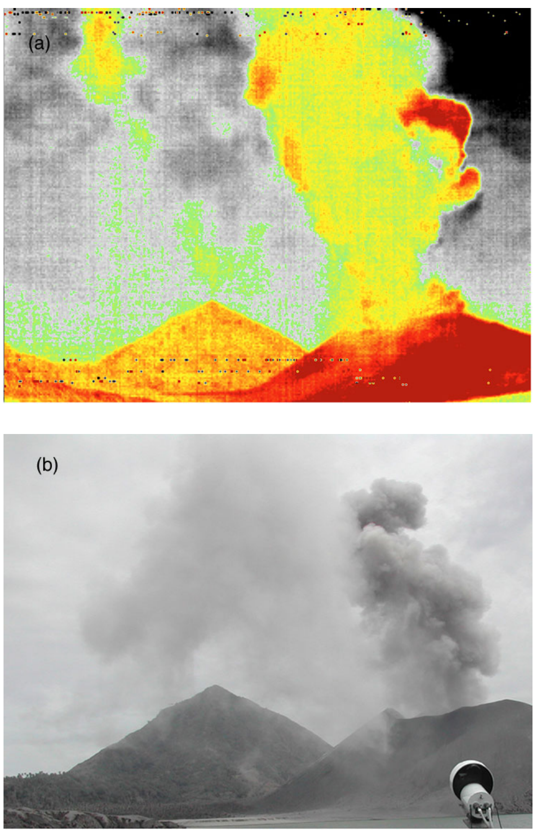


Figure 6. (a) Ash discrimination by G-bIRD for the Tavurvur plume (*upper panel*). (b) Visible camera image of the ash plume from Tavurvur, taken at almost the same time as the G-bIRD image (*lower panel*).

Although present, SO_2 was not detected by G-bIRD at Tavurvur. The reasons for this are thought to be due to the excessively high water vapour loadings, the interference from ash effects within the SO_2 channel (~8.6 μm), and possibly the much lower SO_2 concentrations (in comparison to H_2O). Excellent results were acquired at the "hot springs" within 2 km of the crater and from Rabaul observatory, some 6 km distant. Beyond 10 km or so, identification became increasingly difficult due to obscuration by water vapour over such long path lengths.

Variation with elevation

In clear and cloudy skies when there is no ash or SO_2 present, water vapour causes differential absorption of radiation in the atmospheric window between 6–14 μm. Theoretical calculations and modelling studies indicate that this difference will be negative when the camera views the sky above the horizon. The exact value of the difference depends on the amount of water vapour, but also on the path length that the radiation traverses through the atmosphere. Figure 7(a) shows the variation of the temperature difference (11–12 μm) with elevation for a cloudless atmosphere containing about 3 cm of precipitable water. At low elevation angles the temperature difference is slightly negative, but gets progressively more negative until at around 60 degrees elevation when the difference decreases slowly. A consequence of this behaviour is that it is not possible to set a constant threshold for deciding whether G-bIRD images contain ash-affected pixels

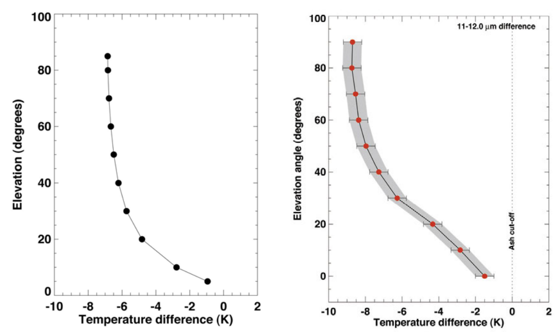


Figure 7. (a) Variation of elevation angle with temperature difference (11-12 μm) for clear skies determined from radiative transfer modelling, and (b) the difference as determined from measurements made at Saipan.

Figure 7(b) shows results using a series of G-bIRD images taken on Saipan island in clear skies. The variation with elevation angle mimics the theoretical behaviour. The same effect with elevation can be seen for 8.6–12 μm temperature differences, except that after 60 degrees the difference starts to increase rather than decrease. This is not seen in the modelling results, and more data are required to determine the cause of this effect. These data show more variation than the theoretical studies because the scene also contains clouds and unmodelled water vapour variations. Nevertheless, the temperature difference decreases with elevation angle in all cases studied and agrees with the theoretical behaviour.

Conclusions

G-bIRD is a new thermal imaging passive infrared camera capable of detecting SO_2 and volcanic ash. The prototype camera has been successfully field tested at several active volcanoes and it has been demonstrated that SO_2 and ash can be discriminated from meteorological clouds. Rapid imaging, remote, autonomous operation and secure communications have also been successfully achieved. The camera works well up to distances of ~10 km from the volcano. It provides information 24 hours a day in clear conditions, but can also work well in slightly cloudy conditions. During rain or snowfall or heavily overcast skies, G-bIRD suffers the same limitations as other passive devices and may not provide reliable detection under these adverse circumstances.

There remains some work to be done in assessing the quantitative value of the G-bIRD imagery, particularly with respect to SO_2 concentrations. To this end, it would be most valuable to conduct field validations against established SO_2 monitors (e.g. COSPEC or mini-DOAS devices). Laboratory and field investigations aimed at quantifying the minimum ash concentrations detectable by G-bIRD would also be of great value. Regardless of the ability of G-bIRD to quantify SO_2 and ash, a rapid-imaging, thermal infrared camera for use at volcano observatories, ash-affected airports, and at the sites of active volcanoes seems warranted if timely hazard warnings of airborne volcanic emissions are required.

References

Cantor, R., Complete avoidance of volcanic ash is only procedure that guarantees flight safety, ICAO Journal, **53**(7), 18, 1998.

Casedevall, T. J., Proceedings of the *First International Symposium on Volcanic Ash and Aviation Safety*, USGS Bull. **2047**, U.S. Geological Survey, Washington, DC, 450p, 1994.

Guffanti, M., Casadevall, T., and Mayberry, G., Reducing Encounters of Aircraft with Volcanic Ash Clouds, *This Volume*.

Prata, A. J. and I. J. Barton, Detection system for use in an aircraft, *Australian Patent* **No PJ9518**, *European Paten*t **No. 91907594.5**, *U.S. Patent* **No. 5,602,543**, 1993.

Prata, A. J., Barton, I.J., Johnson, W., Kingwell, J., and Kamo, K., Hazard from volcanic ash, *Nature*, **354**, 25, 1991.

Prata, A. J., Sulphur dioxide detection method. *Australian Provisional Patent* **No. 2004900213**, 2003.

Prata, A. J. and C. Bernardo, An infrared detection apparatus. *Australian Provisional Patent* **No. 2004900214**, 2003.

Tupper, A, Carn. S., Davey, J., Kamada, Y., Potts, R., Prata, A., and Tokuno, M., An evaluation of volcanic cloud detection techniques during recent significant eruptions in the western 'Ring of Fire', *Remote Sensing Environ*, **91**, 27–46, 2004.

Acknowledgements. This work was supported by Tenix Investments and Tenix Electronics Systems Division. We thank Nigel Basheer and Simon Langsford for their help with system design and field testing. Georgina Sawyer and Mike Burton provided generous assistance for the Etna field tests.

UW-MADISON ADVANCED SATELLITE AVIATION-WEATHER PRODUCTS MODIS/AVHRR/GLI SATELLITE VOLCANIC ASH DETECTION

Steven A. Ackerman*, Wayne F. Feltz*, Michael S. Richards*, Timothy J. Schmit[@],
Anthony J. Schriener*, John Murray[#], and David Johnson[%]

* Cooperative Institute for Meteorological Satellite Studies (CIMSS),
University of Wisconsin-Madison, Madison, WI
[@] NOAA/NESDIS, Office of Research and Applications, Madison, WI
[#] NASA LaRC, Langley, VA
[%] NCAR, Boulder, CO

1. Introduction

Geostationary satellite instrumentation offers relatively good temporal resolution for the monitoring of airborne ash resulting from volcanic eruptions. While geostationary platforms provide better temporal resolution, their large fields of view and limited global coverage over volcanically active regions act as disadvantages for the tracking of volcanic ash in the atmosphere. In contrast, polar orbiting satellites provide high spatial resolution and better global coverage but, in general, poor temporal sampling. At any given time there are several polar orbiting satellites, each capable of detecting volcanic ash with fairly frequent time intervals at upper latitudes. This ongoing study focuses on determining how best to optimize satellite platform and infrared channel selection from different IR instruments aboard satellites in both polar and geostationary orbits in an effort to better monitor volcanic ash in the atmosphere.

This paper provides results obtained by Schreiner et al. during their investigation of upper-level SO_2 monitoring by the current GOES sounder. A separate investigation of volcanic ash monitoring by the MODIS, NOAA AVHRR and the Japanese Global Imager (GLI) instruments is also presented. Both investigations focus on volcanic eruptions of Soufriere Hills on the island of Montserrat, located in the eastern Caribbean, during the period 13-15 July 2003.

2. Methodology

The methodology used in this research to detect the presence of volcanic ash plumes consisted of utilizing measurements from instruments onboard several polar orbiting satellites. These instruments include MODIS (Terra), AVHRR (NOAA 15, 16 and 17) and GLI (ADEOS-II). The ash detection method used is based on knowledge of spectral signatures resulting from the presence of suspended particulates. These particulates produce spectral signatures caused by differential scattering, absorption and/or emission of infrared radiation by the plume constituents. The spectral signatures from the ash cloud are driven by the microphysical properties and index of refraction of the aerosols. Spectral measurements near 11 and 12 μm have been successful at detecting these volcanic ash aerosols.

Detection of SO_2 can also be useful in monitoring ash clouds when SO_2 is released along with ash during a volcanic eruption. While both SO_2 and ash do not always follow the same post-eruption trajectories (Seftor et al. 1997), monitoring SO_2 clouds does provide insight for locating possible regions of volcanic ash. Considering the aforementioned spectral signature methodology, spectral measurements at 7.3 and 8.5 μm have been successful at detecting volcanic plumes containing SO_2. Both SO_2 and volcanic ash detection examples from the Soufriere Hills volcanic eruption follows.

Corresponding author address:
Steven A. Ackerman, CIMSS/SSEC,
1225 West Dayton Street Room 251,
Madison, WI, 53706
stevea@ssec.wisc.edu

3. Using the GOES Sounder to detect SO_2

The first major eruption of Soufriere Hills occurred around 0230 UTC on 13 July. This eruption was triggered by a major collapse of the Soufriere Hills lava dome with the resulting ash cloud reaching a level of approximately 16 kilometers[1]. A calculation of SO_2 concentration (Dobson Units) based on AIRS radiance information (**Figure 1**) from 13 July at 1653 UTC shows that SO_2 concentrations from the volcanic plume approached 300 milli atm-cm and extended towards the northeast from Monsterrat Island. Using a trajectory model (NOAA HYSPLIT Model), forward trajectories were calculated (**Figure 2**). Utilizing bands 10 (7.4 μm) and 5 (13.3 μm) on the GOES sounder, a series of "band differenced" images (BT_{10}-BT_5) were derived (**Figures 3-6**). The derived images were obtained in order to subtract out the background temperature difference, since these two bands are "sensing" the same layer of the atmosphere. The resulting difference band shows the "SO_2 plume" (dark areas) over an eighteen-hour period following the eruption.

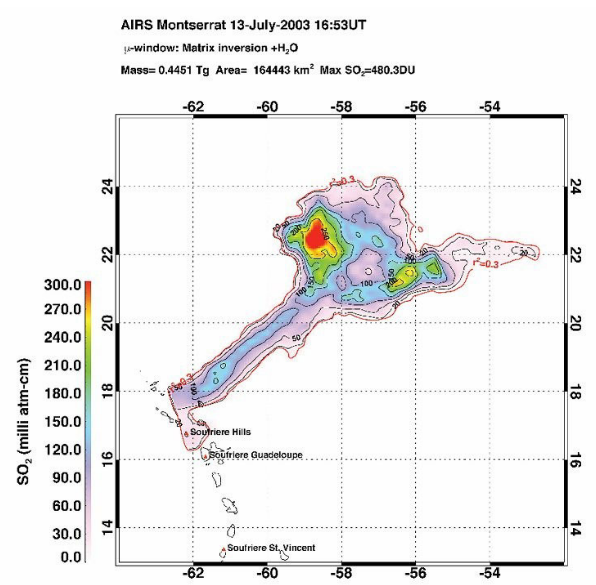


Figure 1: ***Calculation of SO_2 concentration (Dobson Units) based on AIRS radiance information from 13 July at 1653 UTC. Figure provided by Dr. Fred Prata CSIRO.***

[1] based on estimates from the Volcanic Ash Advisory Center in Washington, D.C.

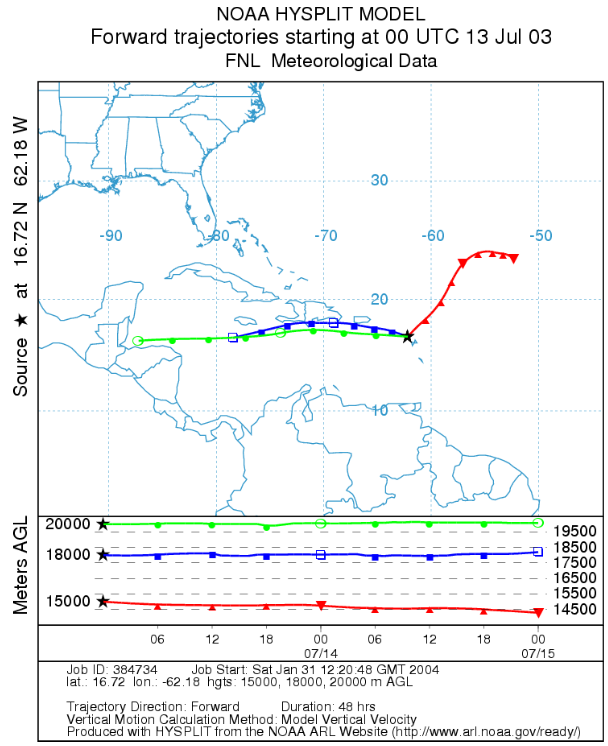


Figure 2: ***NOAA HYSPLIT 24 hour trajectory model beginning 00 UTC 13 July 2003. Figure provided by Dr. Fred Prata CSIRO.***

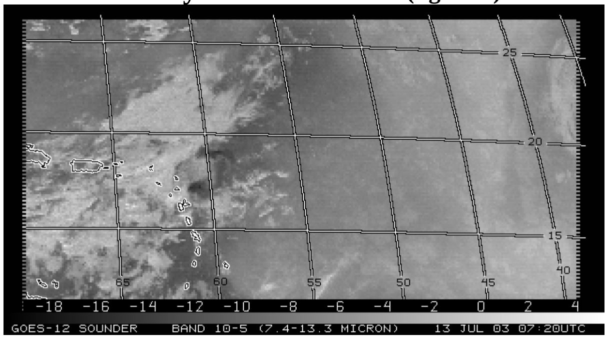
4. Using MODIS, AVHRR and GLI to Detect Volcanic Ash and SO_2

Between the dates of 13-15 July 2003, numerous explosive events occurred at the Soufriere Hills volcano on Montserrat. During this period, ash was observed to have reached altitudes greater than 10 kilometers on more than one occasion[2]. Instruments aboard polar orbiting satellites Terra, NOAA 15, NOAA 16, NOAA 17 and ADEOS-II were able to scan the Caribbean in the hours immediately following Soufriere Hills's explosive volcanic activity.

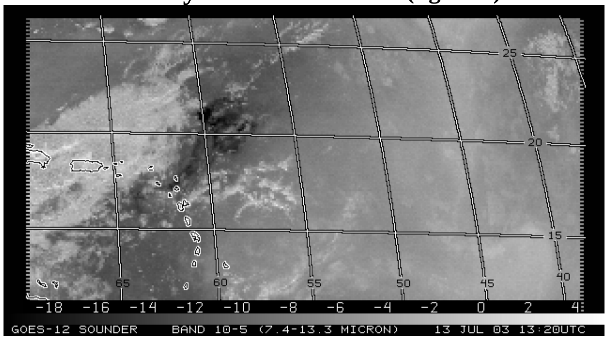
Presented here are images derived from the MODIS, AVHRR and GLI instruments. All instruments have channels near 11 and 12 μm, and the MODIS and GLI yield spectral measurements sensitive to SO_2, near 8.6 and 7.4 μm. The following derived images show the polar orbiting

[2] Smithsonian Institute – Global Volcanism Project

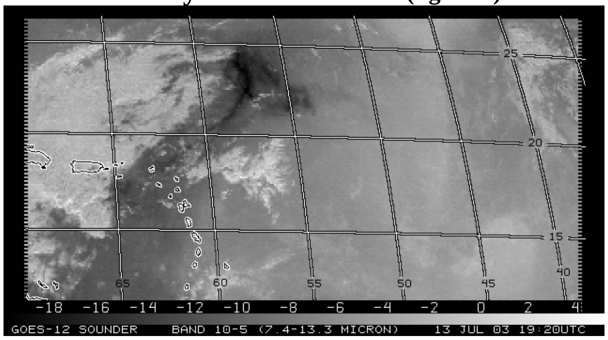
13 July 2003 0720 UTC (figure 3)



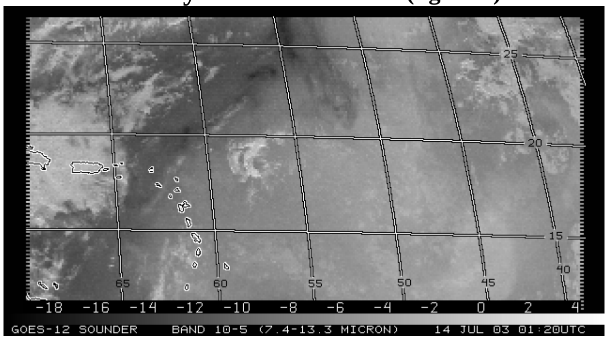
13 July 2003 1320 UTC (figure 4)



13 July 2003 1920 UTC (figure 5)



14 July 2003 0120 UTC (figure 6)



Figures 3-6: ***GOES sounder images from 13-14 July 2003 Images are sounder band*** *10 (~7.4 μm) minus sounder band 5 (~13.3 μm).*

satellites' perspective of the Soufriere Hills' eruptions from several different instruments and viewing angles. The series of MODIS (**Figures 7-8**), AVHRR (**Figures 9-11**) and GLI (**Figures 12-13**) images are band differenced (11-12μm) brightness temperatures. These so-called "split-window" channels are used to "observe and quantify silicate ash" (Elrod and Im 2003, Watson et al. 2004). Corresponding band subtractions for MODIS, AVHRR and GLI are 31-32, 4-5 and 35-36, respectively. Negative differences in the band differenced images show likely locations for airborne volcanic ash. It should be noted that the changing satellite viewing geometries and instrument spectral response functions lead to instrument differences.

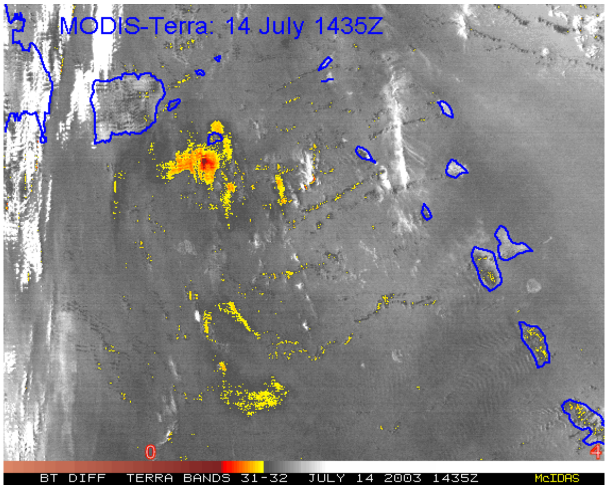


Figure 7: *MODIS (Terra) image from 1435 UTC 14* ***July 2003. Images are band*** *31 (~11 μm) minus band 32 (~12 μm).*

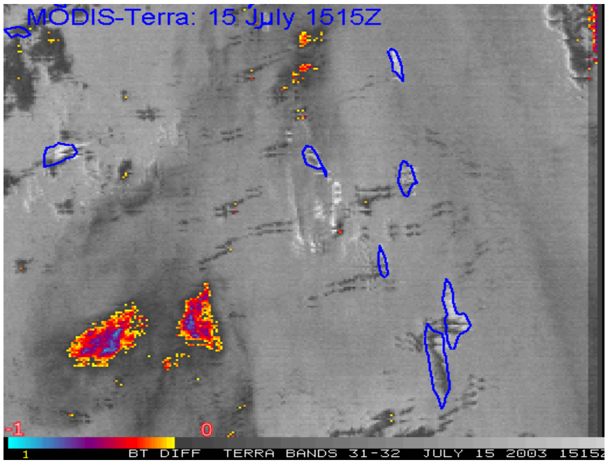


Figure 8: *MODIS(Terra) image from 1515 UTC 15* ***July 2003. Images are band*** *31 (~11 μm) minus band 32 (~12 μm).*

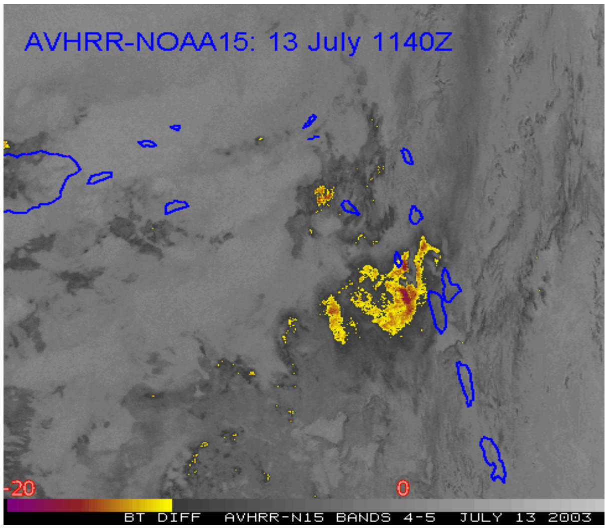


Figure 9: *AVHRR(NOAA15) image from 1140 UTC 13* ***July 2003. Images are band*** *4 (~11 μm) minus band 5 (~12 μm).*

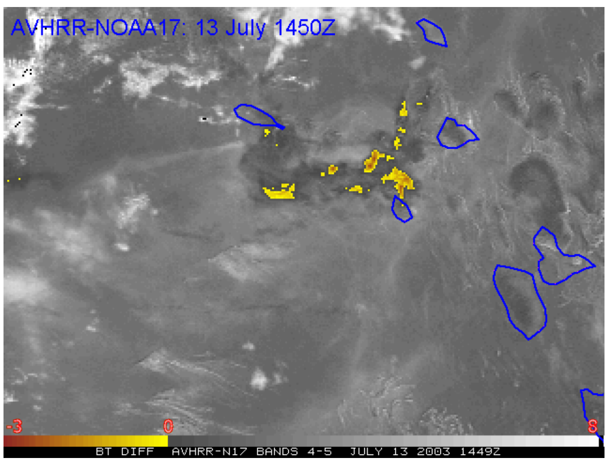


Figure 10: *AVHRR(NOAA17) image from 1450 UTC 13* ***July 2003. Images are band*** *4 (~11 μm) minus band 5 (~12 μm).*

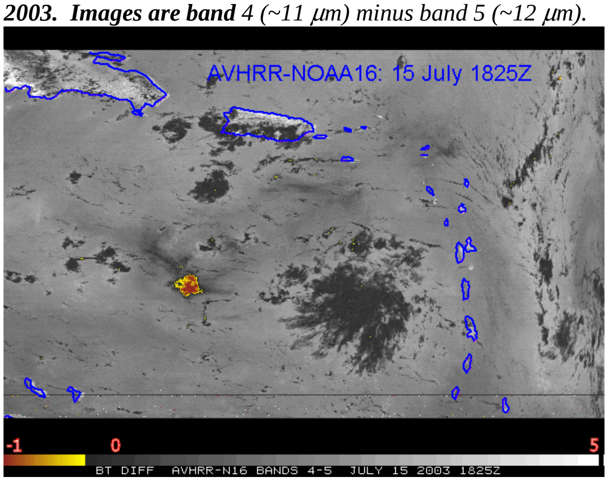


Figure 11: *AVHRR(NOAA16) image from 1825 UTC 15* ***July 2003. Images are band*** *4 (~11 μm) minus band 5 (~12 μm).*

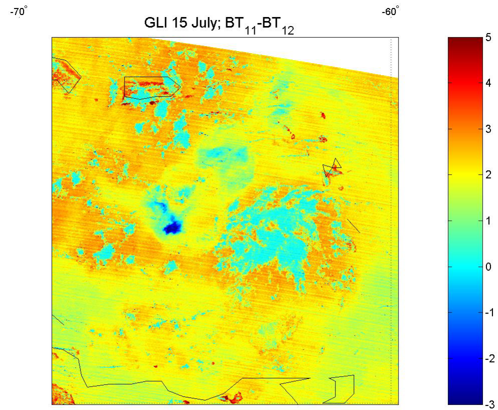


Figure 12: *GLI(ADEOS-II) image from 15* ***July 2003. Images are band*** *35 (~11 μm) minus band 36 (12 μm).*

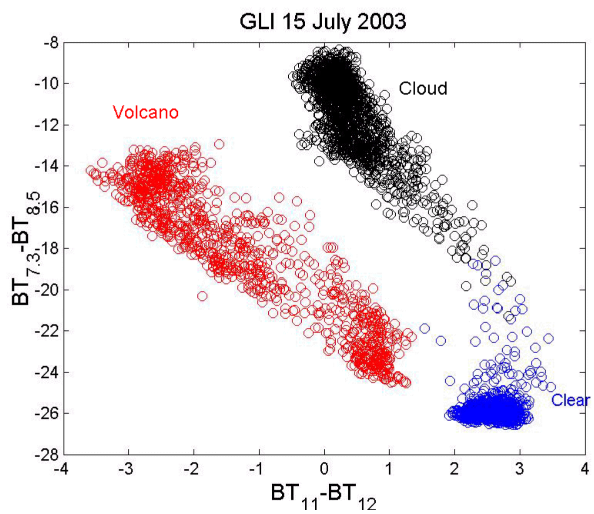


Figure 13: *GLI(ADEOS-II) from 15* ***July 2003.***

The advantage of GLI and MODIS measurements is that both instruments have channels at the 7.3 and 8.5 μm region. This provides the ability to distinguish volcanic ash, clear, and cloudy scenes from one another as presented in figure 13.

5. Conclusions and Future Work

Instruments in both geostationary and polar orbits provide unique methods for the detection and tracking of volcanic ash in the atmosphere. Results by Schreiner et al. presented here reveal that the current GOES Sounder is able to detect upper-level SO_2 over areas of normally low probabilities of volcanic eruption. In this case the sounder scan sector only provided a six hour temporal resolution. Optimally a high spatial and temporal resolution with spectral coverage in volcanically sensitive IR regions is desired. Trajectories illustrated in **Figure 2** indicate the SO_2 detected by the GOES sounder, a plume of relatively negative band differences (7.4-13.3μm) to the northeast of the island **(Figures 3-6)**, might have existed at a height of approximately 15 kilometers a.s.l. While AVHRR imagery (**Figure 9**) does indicate the likely presence of a volcanic ash plume (relatively negative 11-12μm band difference) to the northeast of the island, the highest concentrations of airborne ash exist to the immediate south and west of the island (**Figures 9-10**). As illustrated here, the polar orbiting platform provides a necessary compliment to geostationary instruments such as the GOES sounder when monitoring volcanic ash in the atmosphere.

Future work includes optimizing the operational Geostationary and Polar infrared instrument (GOES and AVHRR) volcanic eruption detection algorithms to sense SO_2, volcanic ash, and plume height. In fact, good estimates of volcanic ash altitude are not routinely available via satellite remote sensing systems and is a major concern to the aviation community.

In addition, polar research satellites (MODIS, GLI, and AIRS) will be used to provide insight for improvement of volcanic ash tracking and dissipation rates for high latitude volcanic eruptions with emphasis places on determining the altitude of the volcanic ash cloud.

The next generation geostationary infrared weather instruments (ABI, GIFTS and HES) will have spectral coverage similar to existing instruments on polar orbiting satellites. This investigation, therefore, provides an opportunity to lay the ground work for future "volcanic ash detection" algorithms.

6. References

Elrod, G. P. and J. Im, 2003: Development of Volcanic Ash Image Products Using MODIS Multi-spectral Data. Preprints, 12^{th} Conference of Satellite Meteorology and Oceanography, 9-13 February 2003. Boston, MA, American Meteorological Society,

Schreiner A. J., T. J. Schmit, J. Li, G. P. Ellrod, M. Gunshor, and K. Karnauskas, 2004: Using GOES-R to Help Monitor SO_2. Presented at the GOES-R Users Conference. 10-13 May, 2004. Broomfield, CO.

Seftor, C. J., N. C. Hsu, J. R. Herman, P. K. Bhartia, O. Torres, W. I. Rose, D. J. Schneider and N. Krotkov, 1997: Detection of volcanic ash clouds from Nimbus-7/TOMS, *J. Geophys. Res., 102: 16749-16760.*

Watson, I. M., V. J. Realmuto, W. I. Rose, A. J. Prata, G. J. S. Bluth, Y. Gu, C. E. Bader and T. Yu, 2004: Thermal infrared remote sensing of volcanic emissions using the moderate resolution imaging spectroradiometer, *J. Volcanol Geoth Res 135: 75-89*

REMOVAL PROCESSES OF VOLCANIC ASH PARTICLES FROM THE ATMOSPHERE

Gregg J.S. Bluth and William I. Rose, Michigan Technological University

INTRODUCTION

The use of satellite techniques provides valuable information for mapping ash hazards, as well as the means to study and predict the fates of volcanic clouds. We have used ultraviolet (TOMS – *Total Ozone Mapping Spectrometer*) and infrared (e.g., AVHRR – *Advanced Very High Resolution Radiometer*; HIRS2 – *High Resolution Infrared Radiation Sounder/2*; GOES – *Geostationary Operational Environmental Satellite*; MODIS – *Moderate Resolution Imaging Spectroradiometer*) satellite sensors to examine the solid, liquid and gas species in numerous volcanic clouds over the past 25 years. Each sensor provides a somewhat different perspective of volcanic clouds, depending on their spatial, spectral and temporal resolutions. Thus, when combined these techniques provide important constraints on the interactions and fates of species within the clouds. Quantitative infrared techniques can provide information on how the size, size distribution, and total mass of fine ash particles evolve as a cloud mixes with the atmosphere. Here we present a review of past relevant observations and research, and the results of ongoing satellite studies.

VOLCANIC CLOUD PARTICULATES

Volcanic clouds are typically composed of a variety of particulates, derived from:

-volcanogenic sources (silicate particles, erupted gases and liquids)

-the atmosphere (water/ice, dust, sea salt, gases)

-products from volcano-atmosphere reactions (aerosols, coatings, adsorbed species on existing particles)

(1) Particle compositions

-silicates: glassy pyroclasts and minerals, which represent the crystalline fraction of the magma. Their shapes are highly angular, and in fact can be composed of shards, bubble fragments, as well as microcrystals. The silicate particles reflect the magmatic origins, ranging from rhyolitic (high silica) to basaltic (low silica).

-non-silicates: the most common type is sulfate aerosols. Many other minor and rare phases have been observed (Rose et al., 1982).

(2) Shapes and Sizes:

A thorough examination of particle size, geometry, and composition by Riley et al. (2003) revealed:

-extremely high surface areas relative to volume, due to roughness and vesicularity (up to 2 orders of magnitude greater areas than calculated using shape alone).

-aspect ratios of 1.5 – 2.6 (long-to-short 2D dimensions, compared to 1 for a perfect sphere). See Figure 1.

Erupted materials are composed of a full spectrum of particle sizes, which quickly becomes differentiated through gravitational settling and physical interactions in the clouds. Based on satellite studies, about 1-2% of the total ash mass erupted is 1-12 microns (μm) in radius (Rose et al., 2001), which is the fraction which can be most easily tracked by satellite.

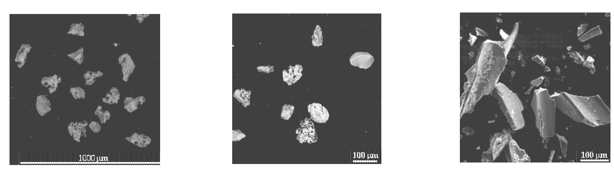


Figure 1. SEM photos of (l-r) Fuego, Guatemala basaltic ash; Mt. Spurr, Alaska andesitic ash; bubble wall shards from the rhyolitic ash of the Ash Hollow Member, Nebraska (Riley et al., 2003). Scale bars are 1000μm for Fuego, 100μm for Mt. Spurr and Ash Hollow Member.

THREE STAGES OF VOLCANIC CLOUD EVOLUTION

Rose et al. (2001) developed three general stages based on satellite observation of evolving clouds from the Mt. Spurr (Alaska) eruptions in 1992:

(1) High energy and growth

During the eruption and for the first few hours afterward, the clouds resemble thunderstorms, and are often opaque to IR sensors. Most of the coarse (>50 microns diameter) material falls out near the vent source (Figure 2).

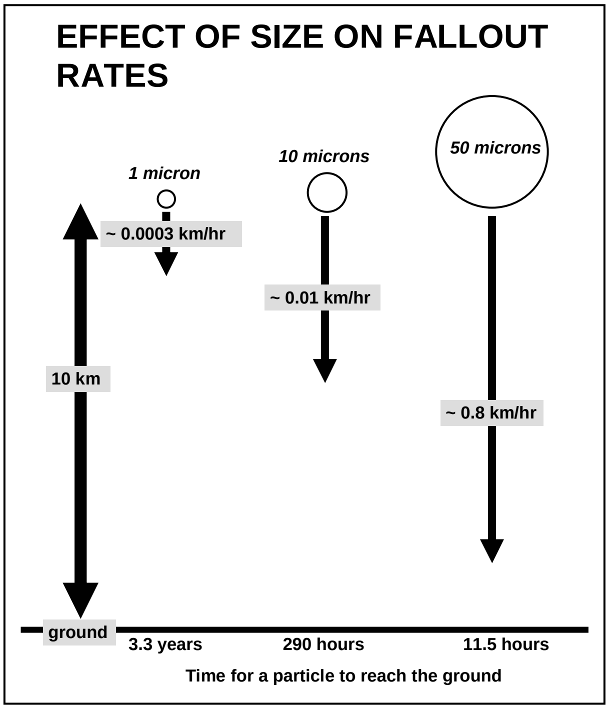


Figure 2. This simple calculation (after Bonadonna et al., 1998) shows that most large (>50 micron diameter) particles will fall out of a volcanic plume within the first day at rates of around 0.8 km/hr; on the other hand, very small particles (<1 micron) could persist in the atmosphere for years. "Particles" may be composed of a single fragment; aggregates of various sizes; particles with coating of water or ice; particle with adsorbed gas or liquid. Clearly, the shape and density of a particle or group of particles will affect how it falls (laminar or turbulent), and how fast it will fall, but this calculation gives a rough estimate, assuming laminar flow and high latitude atmospheric conditions.

(2) Rapid physical and chemical changes

Lasting approximately one day, the cloud expands in areal extent, but the optical depth and fine-particle size concentrations decrease rapidly (by 1 or more orders of magnitude). Fine ash is rapidly removed from the cloud, most likely by aggregation or as icy ash balls (see next section).

(3) Drifting aircraft hazard

This stage lasts 3-5 days, during which the cloud can move thousands of kilometers. Ash concentrations and optical depths decrease very slowly, and ash masses slowly decrease to below sensor detection limits.

PARTICLE REMOVAL RATES

Table 1 compares the removal rates of ice and ash for several different eruptions. The measurement periods vary owing to instrument

Table 1. Ash and ice removal rates measured by satellite

Volcano	Meas. Period (hrs after eruption)	Particle type	Mean Removal Rate (kt/hr)	E-folding (hrs)	Sensor	Ref
El Chichón, Mexico (1982a)	5 – 68	ash	34	13	AVHRR	a
El Chichón, Mexico (1982b)	7 – 70	ash	99	15	AVHRR	a
Pinatubo, Philippines (1991)	5 - 111	ash	482	24	HIRS/2	b
Pinatubo, Philippines (1991)	5 - 111	ice	819	30	HIRS/2	b
Pinatubo, Phillipines (1991)	6 - 104	ash	363	27	AVHRR	b
Pinatubo, Philippines (1991)	6 - 104	ice	648	27	AVHRR	b
Hudson, Chile (1991)	2 – 132	ash	21.8	30	AVHRR	c
Spurr, USA (Jun 1992)	13 – 152	ash	2.3	143	AVHRR	d
Spurr, USA (Aug 1992)	14 – 84	ash	3.7	43	AVHRR	d
Spurr, USA (Sept 1992)	8 – 70	ash	4.9	52	AVHRR	d
Hekla, Iceland (2000)	6 – 24	ice	48	8	AVHRR	d
Cleveland, USA (2001)	6 – 20	ash	1.6	10	GOES + MODIS	e

a) Schneider et al., 1999; b) Guo et al., 2004b; c) Constantine et al., 2000; d) Rose et al., 2001; e) Gu, 2004.

temporal resolution, and the period reflects the time between when ash decrease is measured to the end of sensor detection. While this represents only a small portion of volcanic eruptions, it appears that the large events (El Chichón, Pinatubo, Hudson) exhibit fast removal rates of ice or ash and consequently much shorter residence times than the smaller events (Spurr, Hekla). However, note the exception from the Cleveland event, which was small, yet underwent rapid removal. In contrast to ash cloud decrease (e-folding, which is the time for the cloud to reduce to 1/e of its original mass), sulfur dioxide gas e-folding rates are on the order of 2 – 25 *days*, rather than hours (e.g., Figure 3).

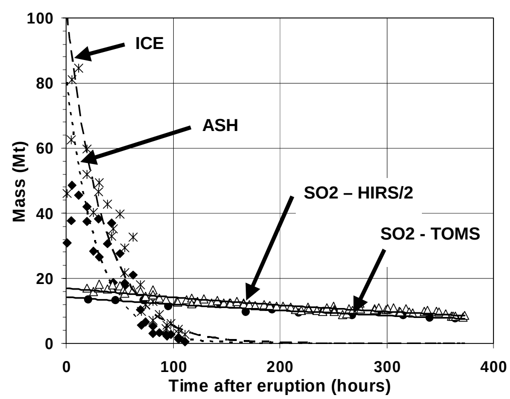


Figure 3. Mass removal patterns of ash, ice and sulfur dioxide in the 1991 Pinatubo volcanic cloud (Guo et al., 2004a; 2004b).

REMOVAL PROCESSES

(1) Ash/ice hydrometeors

Satellite studies find that the radii of suspended particles can *increase* over the first 36 hours after eruption, which we interpret as indicative of ice formation on ash particles (Rose et al., 2000). Modeling studies suggest that these aggregates may be over 80% ash by weight (e.g., Herzog et al., 1998; Textor, 1999).

(2) Particle aggregation (sticking)

The rate of fine ash removal during the first 1-2 days shows a rapid decrease (Figure 3), which cannot be explained through discrete particle settling rates (Figure 2). These fine particles must be removed by either adsorption onto larger particles or aggregation as a result of particle collisions.

REMOVAL RATES OF DIFFERENT CLOUD SPECIES

Note that in Figure 3 the ice and ash have similar removal rates, which are much faster than gas removal. Sulfur dioxide removal is largely a function of its chemical conversion rates to sulfate aerosol, rather than any kind of gravitational process. The resulting formation of sulfate aerosol is essentially the inverse of the gas decay. Other eruption clouds have shown similar patterns where fine ash removal is much faster than the sulfur dioxide gas (Table 1). The similarity of ice and ash removal rates, together with slow fallout calculated for discrete particles of this size, strongly suggest that both of these species undergo aggregation which drives their relatively rapid removal from the atmosphere.

DOES ASH IN LARGE ERUPTIONS FALL OUT FASTER?

For Pinatubo, about 90% of the 1-15 micron sized ash fell out within the first 4 days of eruption (Figure 3). Approximately 99% of the fine ash was removed within 6 days. We have observed that several large eruptions have a significantly faster removal rate than smaller eruptions. How might this occur?

(1) The more intense eruption columns typically involve greater upward velocities. These stronger events are therefore more efficient at re-entraining particles in the rising ash and gas plumes than low-intensity eruption columns (Ernst et al., 1996).

(2) More intense eruptions have higher eruption rates (volume emitted per time), so that the emitted volume of fragmented ash is higher.

(3) More fragmentation, and a higher ash volume, results in more electric charge generated in the volcanic plume, producing more electrostatic “sticking” of particles.

(4) Higher columns entrain more moist air and experience higher temperature gradients leading to the formation of hydrometeors, resulting in further charge generation by processes similar to electric charge formation in thunderstorms.

(5) The combination of processes magnified by the more intense eruption columns produce more efficient particle removal by ash aggregation, ice coating and rapid removal as icy pyroclasts.

CONCLUSIONS

Satellite sensors have the ability to detect and quantify the 1-12 micron radius size fraction of drifting volcanic ash clouds. Studies of removal rates and processes for a range of volcanic eruptions reveal that ash and ice particles fall out at much faster rates than do the co-emitted sulfur dioxide gas. The rapid fallout of fine particulates is best explained by aggregation processes, and in some cases, the formation of ice on ash particles.

ACKNOWLEDGEMENTS

Our satellite-based studies over the past several years have been supported by NASA's Solid Earth and Natural Hazards program, NASA Headquarters, and the TOMS Science Team; and the National Science Foundation's Petrology and Geochemistry program.

REFERENCES

Bonadonna, C., G.G.J. Ernst, and R.S.J. Sparks (1998) Thickness variations and volume estimates of tephra fall deposits: the importance of particle Reynolds number. J. Volc. Geotherm. Res., 81, 173-187.

Constantine, E.K., G.J.S. Bluth, and W.I. Rose (2000) TOMS and AVHRR observations of drifting volcanic clouds from the August 1991 eruptions of Cerro Hudson. AGU Geophys. Mon. 116, 45-64.

Ernst, G.G.J., M.I. Bursik, S.N. Carey and R.S.J. Sparks (1996) Sedimentation from turbulent jets and plumes. J. Geophys. Res., 101, 5575-5589.

Gu, Y. (2004) Particle Retrieval Using Satellite Remote Sensing. Ph.D. thesis, Michigan Technological University.

Guo, S., G.J.S. Bluth, W.I. Rose, I.M. Watson, and A.J. Prata (2004a) Re-evaluation of SO2 release of the 15 June 1991 Pinatubo eruption using ultraviolet and infrared satellite sensors. Geochem. Geophys. Geosys., 5, Q04001, doi:10.1029/2003GC000654.

Guo, S., W.I. Rose, G.J.S. Bluth, and I.M Watson (2004b) Particles in the great Pinatubo cloud of June 1991: The role of ice. Geochem. Geophys. Geosys., 5, Q05003, doi:10.1029/2003GC000655.

Herzog, M.,H.-F. Graf, C. Textor, and J.M. Oberhuber (1998) The effect of phase changes of water on the development of volcanic plumes. J. Volc. Geotherm. Res., 87, 55-84.

Riley, C.M., W.I. Rose and G.J.S. Bluth (2003) Quantitative shape measurements of distal volcanic ash. J. Geophys. Res., 108, n. B10, 2504.

Rose, W.I., R. Chuan, and D.C. Woods (1982) Small particles in plumes of Mount St. Helens. J. Geophys. Res., 87, 4956-4962.

Rose, W.I., G.J.S. Bluth and G.G.J. Ernst (2000) Integrating retrievals of volcanic cloud characteristics from satellite remote sensors: a summary. Phil. Trans. Roy. Soc. London A, 358, 1585-1606.

Rose, W.I., G.J.S. Bluth, D.J. Schneider, G.G.J. Ernst, C.M. Riley, L.J. Henderson, and R.G. McGimsey (2001) Observations of volcanic clouds in their first few days of atmospheric residence: The 1992 eruptions of Crater Peak, Mount Spurr Volcano, Alaska. J. Geology, 109, 677-694.

Schneider, D.J. et al. (1999) Early evolution of a stratospheric volcanic eruption cloud as observed with TOMS and AVHRR. J. Geophys. Res., 104, 4037-4050.

Textor, C. (1999) Numerical simulation of scavenging processes in explosive eruption clouds. Ph.D. thesis, Max Planck Institute for Meteorology, Hamburg, Germany.

SOUNDING OF VOLCANIC CLOUDS WITH BALLOON-BORNE INSTRUMENTS: IMPROVING ALGORITHMS FOR ASH AND SO_2 IN REMOTE SENSING IMAGERY

John Chadwick, Idaho State University, Pocatello, ID, USA
Zach Lifton, Idaho State University, Pocatello, ID, USA
Ken Dean, University of Alaska, Fairbanks, AK, USA
Jim Chadwick, Mitre Corporation, Mclean, VA, USA

The Volcanic Ash Sulfur Dioxide Balloon Experiment (VASDBE) is a set of sampling instruments designed for rapid balloon-borne deployment into a volcanic cloud 24 – 96 hours after a large volcanic eruption. High precision instruments for measuring ash and sulfur dioxide concentrations, as well as meteorological parameters, will be used to characterize the atmospheric column from the surface to 32,000 m. The 4-6 balloon sensor platforms to be built will be tracked using GPS, and recovered after a parachute descent for data collection. For launch planning, volcanic clouds will be tracked using near real-time GOES imagery and meteorological prediction models such as Puff. The results of this study will be used to refine the calibration of algorithms for the measurement of ash and SO_2 from remote sensing imagery, and will thus improve remote sensing based ash warnings for aircraft. GOES imagery is acquired every half-hour, and balloon launches can be synchronized with image collection with little temporal offset to allow for direct comparisons between imagery and sounding data. However, repeat cycles for polar-orbiting MODIS, TOMS, and ASTER platforms will render it more difficult to time balloon data collection to coincide with image acquisition. It is anticipated that this study will help to better constrain the viewing depths into volcanic clouds by various types of satellite imagery, and soundings near the periphery of the cloud will allow for the assessment of the minimum ash and SO_2 concentrations that are detectable using remote sensing.

FALL3D: A NUMERICAL MODEL FOR VOLCANIC ASH DISPERSION IN THE ATMOSPHERE

A. Costa, and G. Macedonio, Osservatorio Vesuviano - Istituto Nazionale di Geofisica e Vulcanologia, Napoli, Italy

Aircrafts may unexpectedly encounter volcanic ash clouds during their flight that often cause engines failure. In order to mitigate the risk related to this accident it is of vital importance for public safety, the knowledge of the temporal evolution of the ash cloud dispersal. For these reasons reliable computational model are needed. Here, we propose a new Eulerian model, called FALL3D, for the simulation of dispersion and deposition of volcanic ashes. The model is based on the solution of an advection-diffusion-settling equation, coupled with a Limited Area Model (LAM) for the wind field, and a parameterization of the turbulent diffusivity tensor based on the K-theory. The equations are solved using a fully explicit third-order upwind scheme in a terrain-following coordinate system. The wind and temperature fields given by the LAM are assimilated to the finer scales using the meteorological processor CALMET. The procedure can be used for forecasting ash concentration from volcanic plumes in the atmosphere and ash loading on the ground. The input to the model are the topography, the meteorological field data as given by the LAM, the mass eruption rate and the settling velocity distribution of volcanic ashes in the source. A test application to the Etna 2001 volcanic eruption is presented.

USE OF DISPERSION MODELS TO TRACK ERUPTION CLOUDS

Ken G. Dean, Rorik A. Peterson, Ken Papp and Jonathan Dehn
Geophysical Institute, University of Alaska Fairbanks, Koyukuk Dr., P.O.Box 757320,
Fairbanks, Alaska 99775-7320, USA

An overview of ash-tracking (dispersion) models will be presented, highlighting their strengths, weaknesses, and usefulness. The models are a tool for rapid response to predict the location, structure and movement of eruption clouds. Three models used in North America are Canerm (Montreal VAAC), Hysplit (Washington VAAC), and Puff (NWS Anchorage, AVO, U.S. Air Force Weather Agency, and universities). All three are similar in that they require gridded wind fields and specification of the initial eruption column size and shape. Wind fields are available with various spatial resolutions, time steps and geographical coverage. For operational eruption response, current wind fields are required. Dispersion models are initiated by releasing hypothetical particles above a volcano that are subsequently transported by advection, diffusion, and gravitational settling. The models diverge in their implementations of these transport mechanisms. Models must be fast, efficient, and easily configurable for diverse conditions, and they must approximate transport physics without becoming cumbersome. Model predictions are validated using satellite images, and are often "tuned" to match clouds observed on images. However, recent observations from the Mt. Cleveland eruption suggest that model predictions may be accurate when satellite images do not detect airborne volcanic material. In general, tracking models have been accurate for moderate altitude plumes (5 km to 16 km), and have had limited success with low and high altitude plumes (<5 km, and > 16km) and in situations with complex ground-relief. Some causes of these limitations are difficulties in accurately modeling diffusion in the near-surface boundary layer and lack of wind data in stratospheric regions. The accuracy of the models depends upon the accuracy of the wind fields, which can be variable between climate models. Furthermore, their course space and time resolution of many wind fields creates difficulties for short-term and nearby hazard forecasts for local communities in the immediate vicinity of a volcano.

LABORATORY MEASUREMENTS OF HETEROGENEOUS ICE NUCLEATION BY VOLCANIC ASH: IMPORTANCE FOR DETECTING AND MODELING VOLCANIC CLOUDS

Adam J. Durant, Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, Michigan, USA, [ajdurant@mtu.edu]
Raymond A. Shaw, Department of Physics, Michigan Technological University, Houghton, Michigan, USA
Youshi Mi, Department of Physics, Michigan Technological University, Houghton, Michigan, USA
William I. Rose, Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, Michigan, USA

Analysis of brightness temperature difference images from thermal infrared measurements on meteorological satellites is a primary method that VAACs around the globe use for detecting volcanic ash clouds and mitigating hazards to aviation. A significant proportion of volcanic cloud particles are ice, and ice may conceal the characteristic spectral absorbance features of ash, making detection challenging. Cloud processes (e.g., lifetime, radiative properties) are sensitive to the competing effects of heterogeneous and homogeneous ice nucleation. We have designed a laboratory experiment that investigates heterogeneous ice nucleation, concentrating on ice formation on volcanogenic particles. The statistical nature of heterogeneous ice nucleation can provide insight into the physical mechanisms responsible for ice formation. In our experiments, we measure the freezing temperature for a single ice nucleus (IN) in a water drop hundreds of times to obtain detailed estimates of the probability density functions (PDFs) for freezing time (or temperature). The PDFs can be compared to the idealized inhomogeneous Poisson process based on the classical model of heterogeneous ice nucleation. We frequently observed a variation in freezing temperature of an IN between two 'modes', representing surface versus immersion freezing: the freezing temperature for the surface mode is ~5 K higher than the immersion mode. The distribution of freezing temperatures is nearly identical in both instances, suggesting the physical mechanisms for ice nucleation are not fundamentally different. Our data support the hypothesis that distinct interfacial and bulk nucleation rates exist for water. We speculate that the total nucleation rate is the sum of a nucleation rate corresponding to the interaction of bulk water with the IN, and a nucleation rate corresponding to the interaction of water at the surface of the drop (i.e., interfacial water) with the IN. Our measurements may have application in the representation of ice formation in models of volcanic plume dynamics.

VOLCANIC ASH DETECTION AND CLOUD TOP HEIGHT ESTIMATION FROM THE GOES-12 IMAGER: COPING WITHOUT A 12μm INFRARED BAND

Gary P. Ellrod[1], Anthony J. Schreiner[2], and Alonzo M. Brown[3]

[1] Office of Research and Applications (NOAA/NESDIS), Camp Springs, MD
[2] Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin, Madison,
[3] Washington Volcanic Ash Advisory Center (NOAA/NESDIS), Camp Springs, MD

1. INTRODUCTION

On 1 April 2003, Geostationary Operational Environmental Satellite (GOES)-12 replaced GOES-8 as the primary spacecraft to monitor weather and environmental hazards over North and South America. Hillger et al 2003 describe the GOES-12 data and products and assess their quality. A major change to the GOES-12 Imager was the replacement of a 4 km resolution 12μm Infrared (IR) band with a lower resolution (8 km) IR band centered near 13.3μm (see Table 1). The 12μm band will not be restored until about 2013 when the GOES-R spacecraft becomes operational. There has been a concern that the loss of the 12μm band will negatively affect volcanic ash detection and aviation safety for the next ten years, since that channel has been effectively used in a two-band "split window" technique (Prata 1989) for over a decade. An impact study (Ellrod 2004) has indicated that there will likely be some degradation of volcanic ash detection, leading to both under-detection of thin ash, and an increase in the area of "false" ash, resulting in possible over-warning for aviation advisories.

	GOES 8-11		GOES M-P	
Band	Wave-length (m)	Res. (km)	Wave-length (m)	Res. (km)
1	0.6	1	0.6	1
2	3.9	4	3.9	4
3	6.7	8	**6.5**	**4**
4	10.7	4	10.7	4
5	12.0	4	**-**	**-**
6	-	-	**13.3**	**8**

Table 1. *Summary of GOES Imager spectral bands showing changes in the new series (M-P) in bold, compared with previous spacecraft (GOES 8-11).*

The first significant opportunity to evaluate GOES-12 volcanic ash detection capabilities occurred with several moderate eruptions of Soufriere Hills Volcano on the island of Montserrat in the Eastern Caribbean from 12-15 July 2003. The eruptions were triggered by a major lava dome collapse, followed by pyroclastic flows (Montserrat Volcano Observatory 2003). Ash was dispersed throughout the troposphere across the region, with maximum ash top heights estimated to range from 8-16 km (Washington Volcanic Ash Advisory Center (W-VAAC)). The VAACs were established during the mid 1990's as part of the International Airways Volcano Watch (IAVW) to provide current advisories on existing volcanic ash clouds. Regional Meteorological Watch Offices then issue warnings (known as SIGMETs) to en route aircraft that are based on the VAAC advisories. The W-VAAC has responsibility for the Caribbean region, as well as large portions of North and South America, and the Central and Western Pacific (International Civil Aviation Organization, 2000).

2. VOLCANIC ASH DETECTION METHODS

Traditional methods for detection of volcanic ash often employ a bi-spectral technique based on the brightness temperature difference (BTD) of two Infrared (IR) bands centered near 11.0 and 12.0 μm (Prata 1989; Holasek and Rose 1991). These two IR bands have been available at 1 km resolution from the Advanced Very High Resolution Radiometer (AVHRR) on the polar orbiting National Oceanic and Atmospheric Administration (NOAA) satellite series since the early 1980's. By the mid 1990s, similar spectral bands also became available on the GOES. Although the spatial resolution of GOES IR sensors is only 4 to 8 km, their advantage is frequent coverage (nominally 30 min) over most volcanically active regions of North and South America, as opposed to four times daily from the AVHRR.

The two-band difference method (hereafter referred to as the Two-Band Split Window (TBSW)) sometimes fares poorly however, due to: (1) the excessive thickness of the eruption cloud, which often contains copious amounts of water and large ejected particles within a few hours after the eruption, (2) a lack of temperature contrast between the airborne ash and underlying surface, and (3) ambient atmospheric moisture that can mask low level ash clouds (e.g. Simpson et al 2000). Despite these shortcomings, the TBSW technique has become an international benchmark for volcanic ash detection. The loss of this channel on GOES-12 created the urgent need for a different approach.

The altitude of the ash cloud is also important to aviation, and estimates of the top of the ash layer are provided in the VAAC messages. At the W-VAAC, the ash cloud heights are determined by matching the trajectory of different portions of the ash cloud with upper level wind profiles obtained from adjacent radiosondes or numerical prediction models. In this paper, we will describe new techniques for detecting volcanic ash clouds and estimating their maximum heights using the new spectral band combination available from the GOES-12 Imager.

3. GOES-12 IMAGER ASH DETECTION ALGORITHM

A new technique has been developed to detect ash from GOES-12 Imager Infrared (IR) brightness temperature (BT) data, using an arithmetic combination of Bands 2 (3.9µm), 4 (11µm) and 6 (13.3µm). Bands 6 and 4 can help discriminate volcanic ash from ice-laden cirrus cloud layers due to emissivity differences at those wavelengths (Ellrod 2004). Thermal differences between Bands 2 and 4 have been used in a three-band method (Ellrod et al 2003) which exploits reflectivity and absorption effects near 3.9 µm. The GOES-12 algorithm was empirically determined using NASA MODerate resolution Imaging Spectroradiometer (MODIS) data (Ellrod and Im 2003) and GOES Sounder data. The new algorithm is:

$$B = 5\,(T_2 - 1.5T_4 + 1.5T_6) - 230 \quad (1)$$

Where B is output brightness count, T_2 is the BT observed in Band 2 (3.9µm), T_4 is BT in Band 4 (10.7µm) and T_6 in BT in Band 6 (13.3µm). Volcanic ash is relatively bright (large values of B) compared to surrounding clouds and terrain volcanic ash. Thresholds for volcanic ash detection using this new approach have not yet been established due to the diurnal variation of T_2. Even in bright daytime scenes, the ash clouds stand out against the background if they are sufficiently dense (see Figure 2). The plot in Figure 1 shows brightness count (B) from Equation (1) obtained on 14 July 2003 at 0915 UTC (0515 Caribbean Standard Time (CST)) for several different types of features. The volcanic ash (solid circles) is clearly distinguishable from the cirrus (open triangles), mid-level clouds (stars), and ocean (diamonds) at this time. Note that if only thermal IR data are used, the ash would be virtually indistinguishable from other cloud types in the region due to similar brightness temperatures.

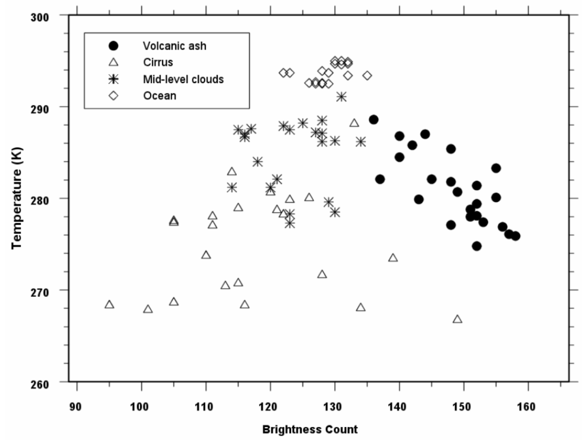


Figure 1. *Scatter plot of brightness count from Equation 1 versus IR band 4 from GOES-12 on 14 July 2003 at 0915 UTC for volcanic ash, ocean surface, cirrus clouds, and mid-level clouds.*

The three-band technique was evaluated for three of the four Soufriere Hills eruptions. For validation and comparison, graphical ash analyses from W-VAAC were available, as well as imagery and derived products from the GOES Sounder. The Sounder is an independent instrument that employs a different scanning strategy, with the goal of producing temperature and humidity profiles (retrievals), as well as image products such as cloud top pressures (CTP), total precipitable water (TPW), and Lifted Index (Menzel et al 1998). The GOES Sounder has nineteen spectral bands, with a resolution of 10 km at nadir compared with 4-8 km for the Imager. For the Eastern Caribbean, Sounder data were only available at 0120 UTC, 0720 UTC, 1320 UTC and 1920 UTC. The GOES-12 Sounder includes the same spectral bands as the Imager (except for the water vapor channel), but they are slightly narrower spectrally.

4. CASE I: 12-13 JULY 2003 EVENT

Triggered by a major collapse of the Soufriere Hills lava dome, first eruption occurred late on the evening of 12 July 2003 (around 0230 UTC, 13 July 2003). The resulting ash cloud reached 15.7 km based on an IR estimate by the Washington VAAC. The development, expansion, and northeastward drift of cold cloud tops associated with the eruption column could easily be seen in GOES-12 Band 4 thermal IR images. However, the three-band IR product described in Section 2 was not effective, probably due to extensive water in the eruption cloud, and because high level non-volcanic clouds in the area obscured most of the dissipating ash. This is a common weakness of IR detection techniques (see Section 2). Minimum cloud top temperatures were around 200K for several hours following the eruption. Later confirmation of a volcanic ash cloud came from the Total Ozone Mapping Spectrometer (TOMS) at around 1530 UTC that day (not shown), which indicated that there were large concentrations of high altitude SO_2 gas to the northeast of the Leeward Islands (image available from the NASA TOMS archive: http://skye.gfsc.nasa.gov/archives.html).

5. CASE II: 14 JULY 2003 EVENT

Shortly after Midnight on 14 July 2003,
another release of ash occurred, with maximum cloud top heights estimated by the VAAC to be 11.3 km. Minimum T_4 cloud top temperatures for this event were about 238K at 0615 UTC, but quickly became warmer as the cloud thinned out. For this case, there was less cloud cover in the region, allowing an evaluation of multi-spectral ash detection techniques. An hourly sequence of the three-band IR images depicted the mid-upper level ash cloud as it drifted toward the west and northwest. Lower level ash was more difficult to distinguish against the ocean background.

6. CASE III: 15 JULY 2003 EVENT

On 15 July 2003 at approximately 0530 UTC, the fourth eruption in this series sent ash to as high as 47,000 ft (14.7 km) as reported by the Washington VAAC. The minimum cloud top temperature (T_4) was 224K at 0645 UTC. Figure 2 provides a two-hour interval sequence of three-band IR images showing the spread of the eruption clouds from 0745 UTC to 1345 UTC. The ash cloud, the background ocean, and

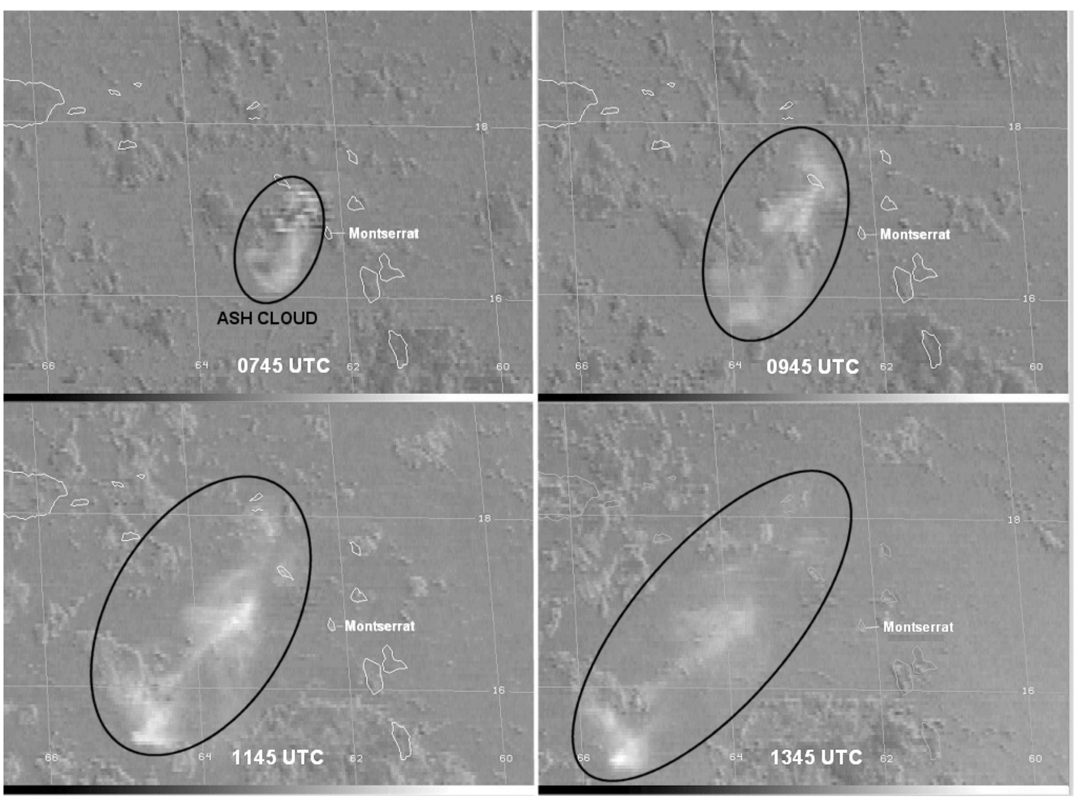


Figure 2. *Two- hourly interval GOES-12 three-band IR volcanic ash product images showing evolution of ash on 15 July 2003 from 0745 UTC to 1345 UTC.*

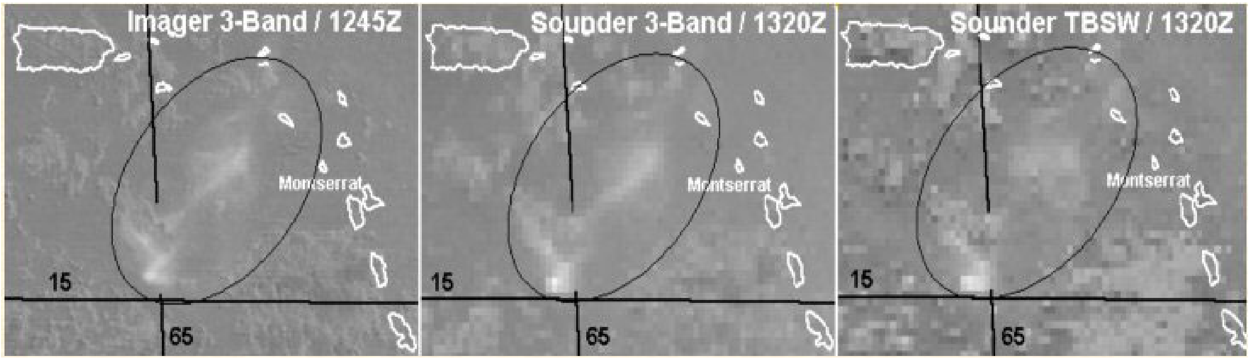


__Figure 3__. Volcanic ash product (based on the 3.9, 10.7 and 13.3 μm bands) from the GOES-12 Imager (left) at 1245 UTC compared with the same product from the Sounder at 1320 UTC (center), versus a two-band difference based on the 12.0 and 11.0 μm channels from the Sounder, also at 1320 UTC (right).

meteorological clouds all brighten around 1145 UTC due to solar reflectance in the 3.9 µm IR band.

7. CLOUD TOP HEIGHT ESTIMATION

The availability of the 13.3 µm IR band from the Imager on GOES-12 and its successors provides the capability of estimating volcanic ash cloud top heights with a CO_2 Absorption Technique (COAT) (Schreiner and Schmit 2001; Schreiner et al 2002). Cloud Top Pressure (CTP), Effective Cloud Amount (ECA), and other derived products have been available hourly from the GOES Sounder for a number of regions since the mid-1990's (Menzel et al 1998). The COAT is a physical relationship based on a special version of the Radiative Transfer Equation. The main assumptions are (1) cloud is opaque but infinitesimally thin (thus allowing application for semi-transparent clouds), and (2) emissivity is the same in both spectral ranges. The latter assumption, when applied to the 13.3 µm and 10.7 µm bands, is only valid when a volcanic cloud is at least partially composed of ice.

A comparison of a GOES cloud height analysis from 14 July 2003 at 0545 UTC with the VAAC graphical height analysis is shown in Figure 4. Based on subjective, textural evaluation of IR data, the high level ash was nearly opaque, while the low-mid level ash was semi-transparent. Cloud top heights from the GOES-12 product ranged from 7.6 km (24 kft) for the mid-level ash, to about 11.1 km (35 kft) for the high level ash, in good agreement with the VAAC analysis (based on an independent technique described in section 2).

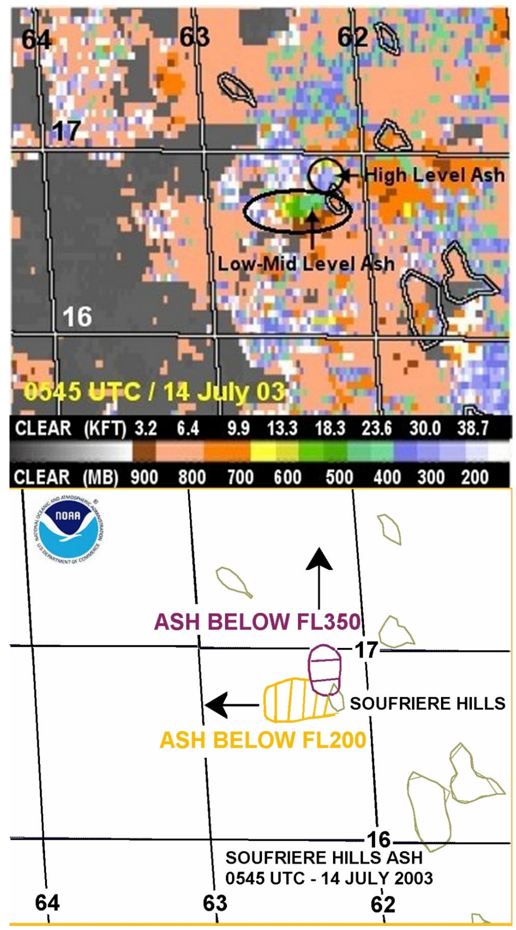


Figure 4. *Cloud top height product based on the GOES-12 Imager CO_2 Analysis Technique (COAT) (top) compared with the VAAC analysis both valid 0545 UTC, 14 July 2003.*

8. SUMMARY AND CONCLUSIONS

The first significant volcanic eruptions observed by the new GOES-12 satellite occurred from 12-15 July 2003 following a lava dome collapse at the Soufriere Hills Volcano, Montserrat. A new IR technique that used the 3.9, 10.7 and 13.3 µm channels (Bands 2, 4, and 6) was able to observe the ash clouds effectively for two of the events during the period, while the strongest event could be monitored by a sequence of Band 4 IR images. Ash cloud heights based on the CO_2 Absorption Technique for the 14 July 2003 case were consistent with those from the VAAC analysis, which employs an independent wind trajectory matching technique. The uniformly warm ocean background, which provided excellent thermal contrast with the airborne ash clouds, was an advantage for observing these events which will not be present for some Continental volcanoes. The presumption that there would be under-detection and increased false alarms for ash detection using GOES-12 was not observed for this particular event. While the loss of the 12 µm IR band is likely to degrade the overall volcanic ash detection capability somewhat, this episode shows that imagery from GOES-12 and its successors will still be an effective means of warning pilots of hazardous ash clouds in many situations.

9. REFERENCES

Ellrod, G. P., (2004): Loss of the 12µm “Split Window” Band on GOES-M: Impacts on volcanic ash detection. *J. Volc. Geothermal Res.*, Elsevier, Inc., Vol. 135/1-2, pp 91-103.

__________, B. H. Connell, and D. W. Hillger, (2003): Improved detection of airborne volcanic ash using multispectral infrared satellite data. *J. Geophys. Res.*, *108*(D12), 4356.

__________, and J-S. Im, (2003): Development of volcanic ash image products using MODIS multi-spectral data. 12th AMS Conference on Satellite Meteorology and Oceanography, 9-13 Feb 2003, Long Beach, California

Hillger, D. W., T. S. Schmit and J. Daniels, (2003): Imager and Sounder Radiance and Product Validations for the GOES-12 Science Test, NOAA Technical Report 115, U.S. Department of Commerce, Washington, DC, URL: http://www.cira.colostate.edu/ramm/goesm/GOES-12_Science_Test_Report.htm

Holasek, R. E., and W. I. Rose, (1991): Anatomy of 1986 Augustine eruptions as revealed by digital AVHRR satellite imagery. *Bull. Volcanol.*, *53*, 420-435.

International Civil Aviation Organization (ICAO), (2000): Handbook on the International Airways Volcano Watch (IAVW): Operational Procedures and Contacts List, First Edition ICAO Doc. 9766-AN/968.

Menzel, W. P., F. Holt, T. Schmit, R. Aune, A. Schreiner, G. Wade, and D. Gray, (1998): Application of GOES-8/9 soundings to weather forecasting and nowcasting. *Bull. Amer. Meteor. Soc.*, *79*(10), 2059-2077.

Montserrat Volcano Observatory, (2003): Summary of the 12-15 July 2003 dome collapse and explosive activity at the SoufriPre Hills Volcano, Montserrat. URL: http://www.mvo.ms/

Prata, A. J., (1989): Observations of volcanic ash clouds in the 10-12 micrometer window using AVHRR/2 data. *Int. J. Remote Sens.*, *10*, 751-761.

Schreiner, A.J., T.J. Schmit, and R.M. Aune, (2002): Maritime inversions and the GOES Sounder cloud product, *National Weather Digest*, *26*, 27-38.

____________ and T.J. Schmit, (2001): Derived Cloud Products from the GOES-M Imager, Preprints, 11th Conference on Satellite Meteorology and Oceanography, Madison, Wisconsin, Amer. Meteor.Soc., 420-423.

Simpson, J. J., G. Hufford, D. Pieri, and J. Berg, (2000): Failures in detecting volcanic ash from a satellite-based technique. *Remote Sens. Environ.*, *72*, 191-217.

Washington Volcanic Ash Advisory Center, (2003) Operational Volcanic Ash Advisories (VAA) for 2003 are available from: http://www.ssd.noaa.gov/VAAC/ARCH03/archive.html

RESUSPENSION OF RELIC VOLCANIC ASH AND DUST FROM KATMAI: STILL AN AVIATION HAZARD

David Hadley, NWS Alaska Aviation Weather Unit, Anchorage AK, USA
Gary L. Hufford, NWS Alaska Region Headquarters, Anchorage AK, USA
James J. Simpson, Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA, USA

Northwest winds were strong enough to continuously resuspend relic volcanic ash from the Katmai Volcano Cluster and the Valley of Ten Thousand Smokes on 20-21 September 2003. The ash cloud reached over 1600 m and extended over 230 km into the Gulf of Alaska. Several factors influenced the resuspension of the ash: (1) the atmosphere and land surface were very dry prior to the event, further enabling the resuspension and subsequent atmospheric transport of the relic volcanic ash; (2) production of winds strong enough to entrain and lift the ash over 1600 m into the atmosphere; (3) complex terrain with numerous mountains interspersed with valleys, channels and gaps; (4) super adiabatic lapse rate for the troposphere below 850 mb; and (5) the presence of a strong subsidence inversion around 1400-1600 m. We propose that the strong winds are due to accelerations in a super adiabatic atmosphere below 850 mb that is buoyant to both upward and downward perturbations resulting in a hydraulic flow that exposes the lee side of the mountains to sweeping, high speed turbulent winds near the base of the lee slope. Some unique features of the ash cloud are also examined, including its hazardous nature to aviation. Finally, this presentation provides the forecaster with the ability to: (1) recognize the conditions needed for relic volcanic ash resuspension; and (2) respond immediately to such an event.

OBSERVING POPOCATEPETL'S VOLCANIC ASH CLOUDS USING MODIS INFRARED DATA

M. Alexandra Matiella, Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, MI, USA [mamatiel@mtu.edu]
Hugo Delgado-Granados, Instituto de Geofisica, Universidad Nacional Autonoma de Mexico (UNAM), Mexico
William I. Rose, Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, MI, USA
I. Matthew Watson, Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, MI, USA

Popocatepetl Volcano, Mexico, is a tropical volcano with significant and persistent emissions of SO_2 and ash that pose significant hazards to the large population in close proximity to the volcano. The country's main international airport, located approximately 55 km northwest of Popocatepetl in Mexico City, services about 800 flights a day and 20 million passengers a year. A large eruption of volcanic ash from Popocatepetl could devastate the city of 8 million inhabitants and shut down Mexico City's international airport. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery provides us with a synoptic perspective of volcanic emissions and atmospheric interactions, information unavailable from ground-based or aircraft studies, which can be useful for hazard mitigation. Ash masses are retrieved using silicate absorption features at 11 µm and 12 µm. A suite of MODIS images was collected for a period of increased activity during December 2000 – January 2001. One particular image collected January 23rd, 2001, at 0450 UT, shows four large eruptions that have dispersed volcanic clouds over an extensive area of Mexico. Using upper air data and monitoring records, the movements of the 4 ash clouds are fit with eruption times and winds, and using retrieval data for ash we can derive a time based fine ash emission record. The results of these retrievals complement ground-based measurements which cannot measure large scale ash eruptions into the atmosphere and provide a possible scenario for the amount of time it would take a large ash cloud to reach Mexico City.

COMPARISON OF ASH DETECTION TECHNIQUES USING TOMS, MODIS, AVHRR, AND GMS: A CASE STUDY OF THE AUGUST 18 AND 28 ERUPTION CLOUDS OF MIYAKEJIMA VOLCANO, JAPAN

Emily McCarthy, Gregg Bluth, I. Matthew Watson, Michigan Technological University
Andrew Tupper, Darwin Volcanic Ash Advisory Center
Yasuhiro Kamada, Tokyo Volcanic Ash Advisory Center

Introduction

Volcanic eruptions can eject ash, sulfur dioxide, and other gases into the atmosphere. Ash eruptions have been recognized as a serious aviation hazard, including engine failure, electronic failures, and poor visibility. Remote sensing techniques allow long-term tracking of volcanic clouds, analysis of eruptions in isolated areas, and measurements of an entire eruption cloud. Both ultraviolet (TOMS) and infrared (MODIS, AVHRR, and GMS) satellite sensors are capable of detecting volcanic ash. However, IR sensors are susceptible to interference of water vapor. Since each sensor uses different wavelengths their ability to detect volcanic clouds varies. For example, ash clouds may be seen using one IR sensor for several days and only one day using another. Therefore, this project also aims to understand and explain the limitations of each satellite sensor in detecting volcanic ash. The moist atmosphere of Miyakejima presents an opportunity to examine their sensitivity to atmospheric water vapor. Ash mass retrievals without a water vapor correction are compared to those run after the effects of water vapor are removed from the system. The mass, extent, and height of the cloud are important factors when considering the mitigation of aviation hazards. In this case study of Miyakejima Volcano, Japan, data from four different satellite sensors are compared and used to produce constraints on the masses and distributions of ash released by the August 18 and 28, 2000 eruptions.

Miyakejima Background

Miyakejima, a basaltic andesite stratovolcano, rises to an elevation of 813 m. Part of the Izu-Bonin volcanic island chain, Miyakejima is located about 200 km south of Tokyo (Figure 1). The summit consists of two calderas, Kuwakidaria and Hatchodaria, and a central cone. Mount Oyama (Geshi et al., 2002). Recent activity began in June of 2000 with small submarine eruptions and continues today with high emissions (average of 11,000 tons/day) of sulfur dioxide (Kinoshita et al., 2002). Several large eruptions occurred on August 18 and 28, 2000. In September 2000, the island was completely evacuated and remains uninhabited. Monitoring responsibilities are shared between the Japan Meteorological Agency (JMA) and the Tokyo Volcanic Ash Advisory Center (VAAC). All observations are made remotely through the use of satellites and video monitoring. SO_2 measurements are taken monthly with the COSPEC.

The 18 August eruption at 08:02 UTC emitted an ash and SO_2 cloud with a height of approximately 15 km, moving south. The 28 August eruption (19:35 UTC) was smaller with the ash and SO_2 cloud reaching 9 km and moving northeast.

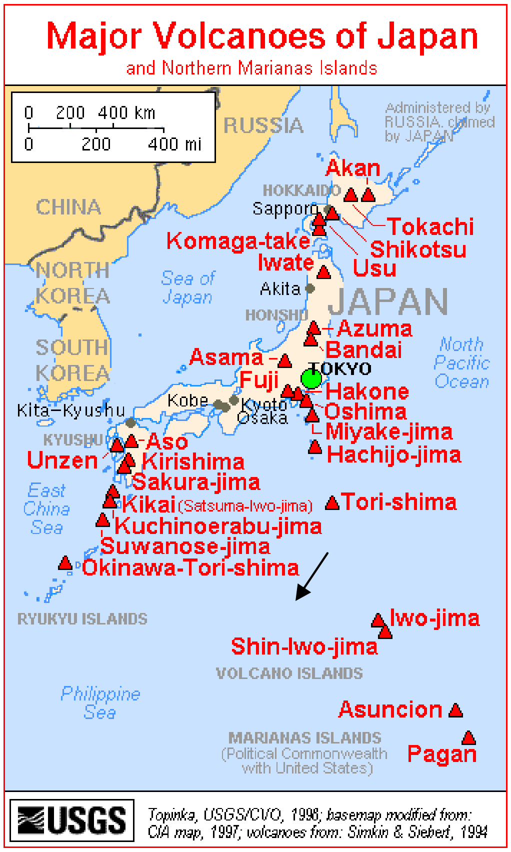


Figure 1. A map of the major volcanoes of Japan. Miyakejima is located about 200 km south of Tokyo in the Izu-Bonin volcanic island chain.

Methods

The Volcanic Ash Retrieval. The infrared channels 4 (11µm) and 5 (12µm) of AVHRR and channels 31 (11µm) and 32 (12µm) of MODIS are used to discriminate volcanic clouds from meteorological clouds. Volcanic clouds generally have a negative brightness temperature difference (BTD) when the 12 µm channel is subtracted from the 11 µm channel, while meteorological clouds generally have a positive BTD (Wen and Rose, 1994). The ash retrieval is based upon a radiative transfer model that allows the estimation of the mass and size of particles in the volcanic cloud. This model assumes that the particles are spherical, the particle size distribution within a pixel is consistent, and the cloud is continuous (Wen and Rose, 1994). User inputs include the temperature of the underlying surface and the top of the cloud, which can be gathered from the satellite image or radiosonde data.

Atmospheric Corrections. A forward model, developed by Watson et al. (2003), was used to correct for atmospheric water vapor. In this model, an atmospheric profile is run through MODTRAN to determine the brightness temperature values of the system. The model was run with different relative humidities, ranging from 0%-100%. Due to the noisiness of the data, the values from 8-12 µm and the sensor response functions for the respective channels were convolved to generate a weighted average and, hence a more accurate brightness temperature. Using the pressure, dry bulb, and wet bulb temperatures of the atmospheric profile, the relative humidity (RH). This new RH was input into the atmospheric profile and run through the forward model again to calculate true values for the brightness temperatures at 11 and 12 µm. A brightness temperature difference (11-12 µm) was calculated and subtracted from the 12 µm channel of the original data used in the ash retrieval.

Results

Volcanic ash retrievals were conducted using original BTDs and corrected BTDs for one MODIS and three AVHRR images. GMS images show ash clouds for both eruptions, however, we are unable to quantify the mass at this time and the images are hence used for locating purposes only. A comparison of the two eruptions, indicates that the 18 August eruption is much more ash-rich than the 28 August eruption.

On 18 August an ash cloud was detected by AVHRR, containing 511,301 metric tons of ash, at 19:48 UTC (Figure 2). Unfortunately, the TERRA/MODIS instrument was not operational, so no cloud comparisons could be made. The TOMS image available for that day, at least 6 hours prior to the eruption, shows no evidence of ash. GMS was able to track the eruption cloud for the entire day following the eruption. Figure 3 shows the infrared image taken approximately 10 minutes prior to the AVHRR image.

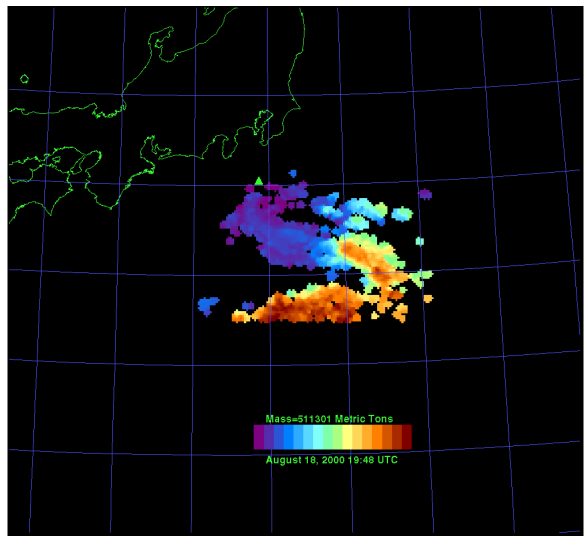


Figure 2. 18 August image (19:48), 12 hours after the eruption, contains 511300 metric tons of ash

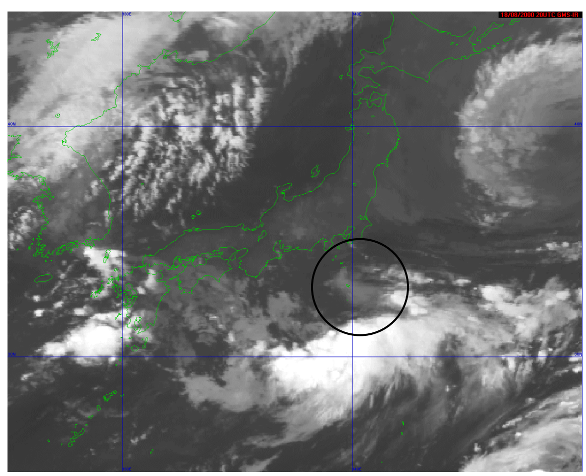


Figure 3. 18 August GMS infrared image (19:38) taken approximately 10 minutes prior to the AVHRR image.

The ash cloud is also detected on 19 August by both MODIS (Figure 4) and AVHRR (Figures 5). Both images, though only 6 hours apart, show drastically different results: MODIS (01:05 UTC) =

20,015 metric tons and AVHRR 07:12 UTC) = 148,939 metric tons. A TOMS Aerosol Index (AI) dataset (00:40 UTC) shows a substantial ash cloud, collocated with the other two sensor clouds (Figure 6). GMS images at near coincident times with the MODIS, AVHRR, and TOMS images are presented in figures 7-9 respectively.

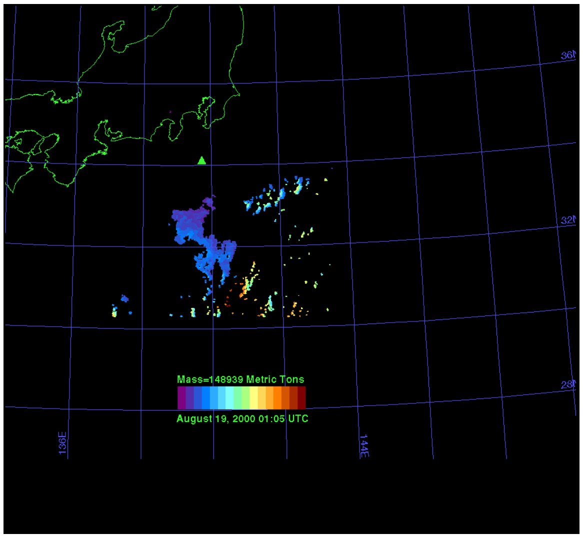


Figure 4. 19 August MODIS ash retrieval (01:05), 17 hours after the eruption. At this time the cloud contained about 150,000 metric tons of ash.

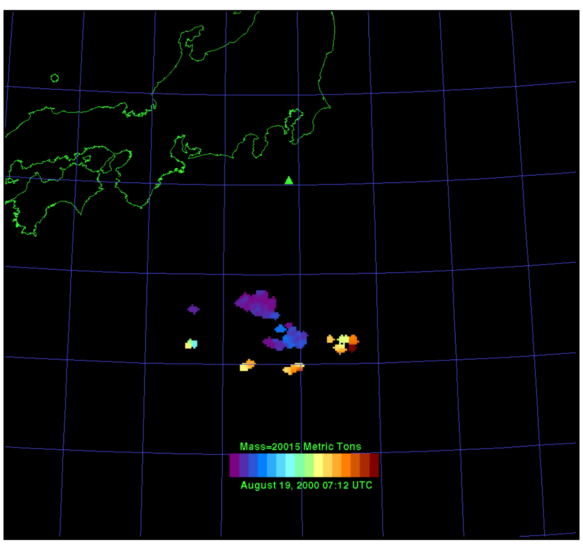


Figure 5. 19 August AVHRR image (07:12), 23 hours after eruption, contains approximately 20000 metric tons of ash.

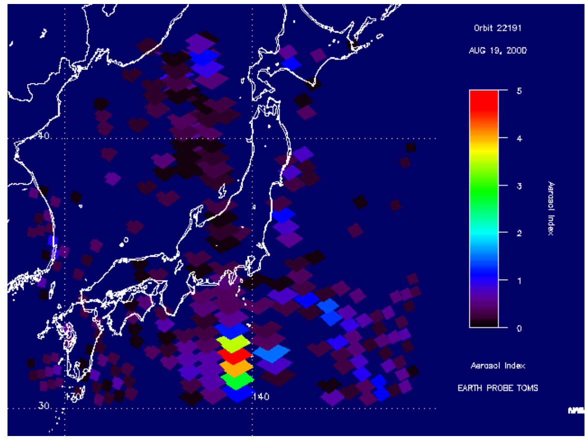


Figure 6. 19 August TOMS AI (00:40). Positive values indicate the presence of volcanic ash.

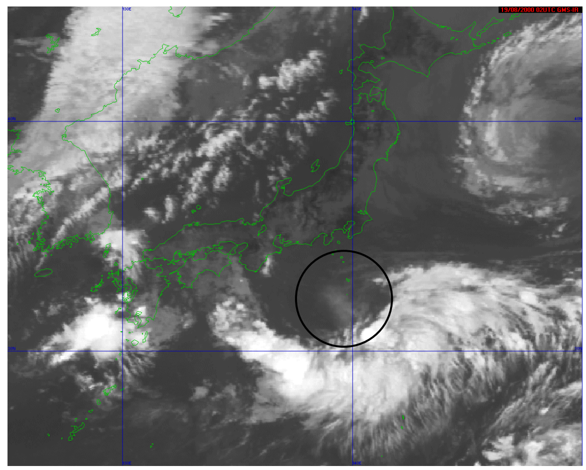


Figure 7. 19 August GMS IR image at 01:38 UTC.

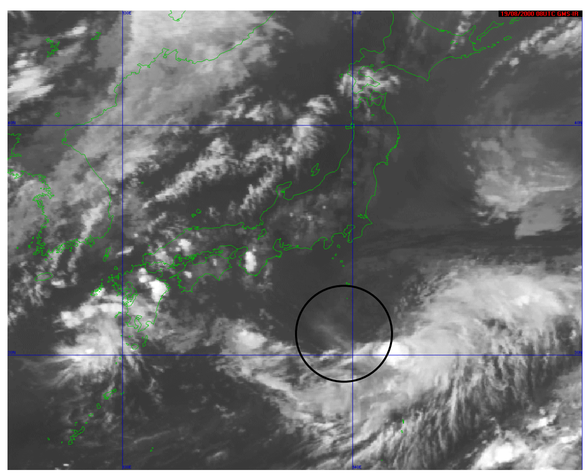


Figure 8. 19 August GMS IR image at 07:38 UTC.

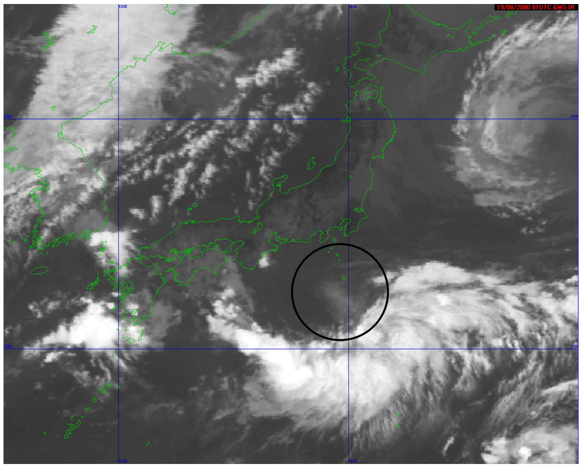


Figure 9. 19 August GMS IR image at 00:40 UTC.

The 28 August ash cloud is significantly smaller than the 18 August cloud. An AVHRR image taken approximately one hour after the eruption shows only 211 metric tons of ash (Figures 10). Four minutes after the AVHRR image, GMS was also able to detect the ash cloud (Figure 11). TOMS was unable to detect this small injection of ash into the atmosphere when the image was taken several hours later.

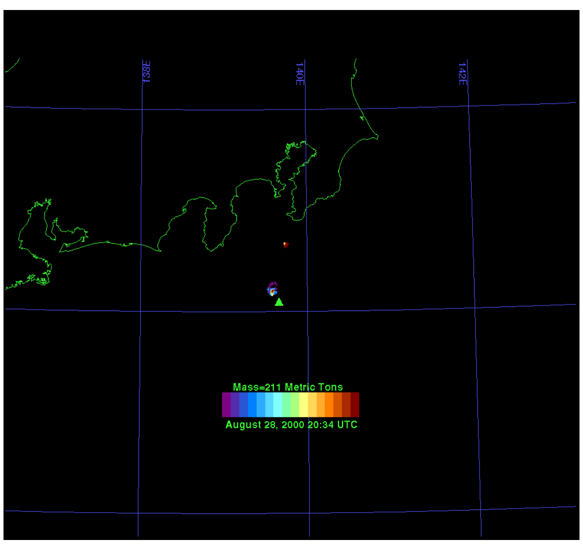


Figure 10. 28 August image (20:34), 1 hour following eruption, contains 211 metric tons of ash.

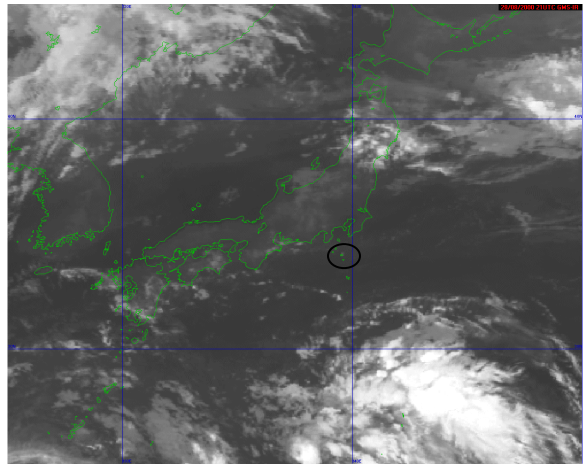


Figure 11. 28 August GMS IR image (20:38), within four minutes of the AVHRR image.

Discussion

Since Miyakejima is located in a moist, marine environment, atmospheric water vapor is a concern when attempting to quantify ash. Table 1 compares the difference seen in the mass, mean effective radius (MER) of the particles, and optical depth of the cloud. In all cases, the three variables increased as water vapor was removed from the system. Mass was the most changed in all four cases, with corrected values ranging from 2.5 to almost 29 times larger than the original result. In an attempt to better understand how the correction works, a plot of corrected mass divided by the original mass versus the change in brightness temperature (which was calculated from the removal of water vapor) was created (Figure 12). While the graph indicates a high R^2 value (0.9137), it is important to note a few points: 1) the highest point represents the large difference between the two retrieved masses and appears anomalously large, 2) only four images detected ash, while typically any sort of convincing correlation should contain a larger dataset, and 3) two of the brightness temperature differences are the same because the images are on the same day. Generally, the trend shown is what one would expect, the ash cloud mass decreases with time and the smaller the brightness temperature difference, the smaller the difference between the two masses. In order to insure the accuracy of such a correction technique, an eruption with a persistent, detectable ash cloud should be used.

Date, Time	Mass (tons)	MER (μm)	Optical Depth
8/18, 19:48	17954	8.41	0.97
	511301	*9.27*	*1.31*
8/19, 01:05	22680	7.27	0.39
	148939	*8.84*	*0.75*
8/19, 07:12	8152	6.35	0.43
	20015	*6.36*	*0.49*
8/28, 20:34	74	6.65	0.31
	211	*6.91*	*0.34*

Table 1. Comparison of original and atmospherically corrected ash retrievals. Corrected retrieval results are in italics.

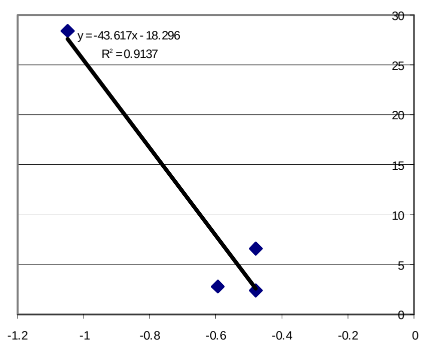


Figure 12. Plot of brightness temperature difference versus the mass from the corrected and original data.

Conclusions

Ash was best detected by and can be quantified using infrared sensors. Geostationary satellites seem to be the best option for tracking ash clouds and therefore for use by VAACs. AVHRR and MODIS are both aboard polar orbiting satellites, which cover the same area earth approximately twice per day. At this time, these are the only satellites available in the Japan area to use for quantification of mass and particle size. GMS will be of use for quantification in the future, however, creating a retrieval method was out of the scope of this study.

Acknowledgments

Financial support for this project was received from the Michigan Space Grant Consortium Graduate Fellowship Program, Sigma Xi Grants-in-aid of Research, and a NASA grant: Validation of TOMS Volcanic Aerosol and SO_2 Products Using MODIS and AVHRR. GMS data is courtesy the Japan Meteorological Satellite Center. We would also like to thank the Japan Meteorological Agency and the Volcanic Clouds Group at Kagoshima for sharing Miyakejima information.

References

Geshi, N., T. Shimano, T. Chiba, S. Nakada, Caldera collapse during the 2000 eruption of Miyakejima Volcano, Japan, Bull. Volcanol, 64, 55-68, 2002.

Kinoshita, K, C. Kanagaki, N. Iino, M. Koyamada, A. Terada, A. Tupper, Volcanic plumes at Miyakejima observed from satellites and from the ground, Remote Sensing of the Atmosphere, Ocean, Environment, and Space, Hangzhou, China, October, 2002.

Wen, S. and W. I. Rose. Retrieval of sizes and total masses of particles in volcanic clouds using AVHRR band 4 and 5, J. Geophys. Res., 99, 5421-5431, 1994.

Watson, I.M., Realmuto, V.J., Rose, W.I., Bluth G.J.S., Forward modeling of volcanic aerosols transmissions at different latitudes; quantifying the effects of varying water vapor on ash detection, Abstract, AGU Meeting, Fall 2003.

PREDICTING REGIONS SUSCEPTIBLE TO HIGH CONCENTRATIONS OF AIRBORNE VOLCANIC ASH IN THE NORTH PACIFIC REGION

Kenneth Papp, Ken Dean, and Jonathan Dehn, Geophysical Institute, University of Alaska, Fairbanks, AK, USA

Airborne ash probability distribution (AAPD) maps have been generated to show the distribution of airborne volcanic ash in the North Pacific (NOPAC) region by simulating volcanic eruption clouds from 22 of the 100 most historically active volcanoes in the region. The PUFF ash-dispersion model was run daily using archived wind field data between 1994–1995 and 1997–2001 for low and high aircraft flight levels. Subsequent statistics are generated representing the distribution of simulated airborne ash at 6 and 24 hr intervals, defining the regions most likely to contain airborne ash and the direction and distance a volcanic ash cloud may propagate from a given volcano. The AAPD maps suggest eruptions originating from the Kamchatkan Peninsula would travel due east into the NOPAC air-traffic routes during summer. During the winter, wind directions over the Kamchatkan Peninsula are more variable, often resulting in a bimodal airborne ash distribution. In contrast, AAPD maps show that eruptions originating from the Aleutians and Alaskan Peninsula are more likely to travel in southeast directions during the summer and E-NE during winter. The results indicate that the paths of many NOPAC air traffic routes coincide with airborne ash distribution probability maxima. The upper atmospheric region most likely to contain airborne ash is located off the eastern coast of the Kamchatkan Peninsula, and is generally centered over the heavy air traffic flight corridor of the NOPAC.

REANALYSIS OF ERUPTION CLOUDS FROM THE NORTH PACIFIC AND THEIR IMPACT ON AIRCRAFT ROUTES

Rorik Peterson, Ken Dean, Jonathan Dehn, Laura Bickmeier,
and Joanne Groves
Geophysical Institute, Univ. of Alaska, Fairbanks

Introduction

The Alaska Volcano Observatory has been monitoring volcanoes in the North Pacific (NOPAC) Region for approximately 15 years using satellite data and dispersion models. Over this period nearly a hundred plumes and eruption clouds have been detected. During this time, detection and monitoring capabilities have evolved and improved significantly, and the growing data archives have been organized and consolidated.

The relatively recent 2001 eruption of Mt. Cleveland, Alaska, was reanalyzed by AVO's University of Alaska, Fairbanks (UAF) site with regard to potential aircraft exposure to airborne volcanic ash. The combination of satellite data, dispersion model forecasts, and flight route data provides an insightful perspective on the impact the ash cloud had on air traffic in the region.

Background

Analysis of aircraft flight-paths during and after the eruption of Mt. Cleveland suggests that some aircraft may have flown through the drifting ash cloud 18-24 hours after the start of the eruption. However, no mechanical problems were reported. To assess these potential encounters, we have compared the flight paths of the aircraft to satellite observations of the ash cloud and to Puff dispersion model predictions. Also, we have developed a relative ash exposure rating for aircraft that may have flown through the ash cloud.

The 19 February eruption of Mt. Cleveland produced a volcanic cloud that formed an arc over 1,000 km long, and drifted to the NE across Alaska (Dean et al., 2004, Dean et al. 2002). The cloud was detected and its movement tracked using data from multiple satellite sensors, including GOES, AVHRR and MODIS for approximately 50 hours. The translucent cloud was detected on the GOES data at half-hour intervals after the start of the eruption, approximately 1430 UTC. These data were processed using the brightness temperature difference (BTD) technique (Prata, 1989). The altitude of the cloud increased over time from 7.5 km a few hours after the start of the eruption to 12 km eight hour later (Dean et al., 2002).

The Anchorage Volcanic Ash Advisory Center (VAAC), working with the Alaska Volcano Observatory (AVO), issued alerts (SIGMET) warning aircraft of the presence of the cloud and its position. The first SIGMET was issued Feb. 19 at 1847 UTC warning of a “possible eruption at Cleveland Volcano”, a short time later an18-hour forecast was issued based on dispersion model simulations. A portion of the cloud was reported at “FL200-FL400” (approximately 20-40 thousand feet). Several pilots reported observing the cloud and gave height estimates, and others reported ash and a sulfur odor in the cockpit (Simpson, et. al, 2002).

Method

Real-time and archived air traffic control data are publicly available from several vendors. These data include the latitude, longitude, altitude and speed of aircraft with a one-minute time resolution. Using archived data obtained from Flight Explorer®, we compared air traffic flight paths in the North Pacific (NOPAC) Region to satellite data and dispersion model simulations for the 48 hour period after the start of the eruption.

For the most part, aircraft avoided the general area of the ash cloud during the first 16 hours (1430 to 0630 the following day), although there is a four-hour gap in the air-traffic data from 0100-0400 on Feb. 20. For the subsequent 18 hour period, some aircraft flew through a vertical plane that included the ash cloud. Figure 1 shows the BTD-processed satellite image at 1345 UTC superimposed with air-traffic routes from 1315 – 1415 UTC. Circles indicate the last recorded location of each flight during this time period. The altitude of aircraft is known and the altitude of the ash cloud-top is estimated using cloud-atmosphere temperature correlations, pilot reports and dispersion models at various times. However, the lower extent of the cloud is nearly impossible to ascertain. Thus, we are able to predict/estimate if a plane flew above the cloud (missing) or near the height of the cloud (possibly an encounter) but it is impossible to determine if the aircraft encountered ash at altitudes lower than the top of the cloud.

To determine the three-dimensional extent of the ash cloud, the Puff volcanic ash dispersion model was used to simulate this event using NCEP reanalysis windfield data. Puff is a Lagrangian model that uses tracer particles, and calculates advection, diffusion, and sedimentation rates for individual tracer particles using a first-order Euler method (http://puff.images.alaska.edu).. Relative concentration information is possible and absolute concentration may be calculated if the eruptive mass rate can be approximated. Simulation results of the two-dimensional lateral extent agree with the BTD data (compare Figures 1 and 2).

A Puff simulation using a 10-minute time resolution was performed in order to analyze the flight paths of some selected flights nearby the ash cloud. A one-hour sequence of forecasts superimposed with flight trajectories are shown in Figure 3. Comparing flight paths to the 4-dimensional (space and time) Puff simulations indicate that some aircraft flew through regions with predictions of elevated ash concentration. Estimating the total tephra volume at $1x10^8$ m^3, the absolute concentration was calculated for the regions through which the planes flew. A total *potential exposure* was then calculated as $E = c \cdot t$, where c is the ash concentration in mg/m^3, and t is time in minutes. The potential exposure for all flights in the vicinity was calculated during the 48-hour period following the event, and the ten highest exposure values are shown in Figure 4. Letters correspond to the flights labeled in Figure 3. Three flights (A, B, and K) traveled through the northern tip of the simulated cloud between 0800-1000 UTC on Feb. 20. Six other flights traveled though the center of the predicted cloud between 1330-1530 UTC of the same day, and one flight (C) through the southern tip.

Dispersion model forecasts also contain particle size and distribution information in addition to concentration. More complicated exposure calculations involving particle size are possible. Although there is limited data concerning the effect of different particle sizes on jet engines, it is reasonable to assume that the smallest fraction, that less than 1 micron, would have negligible effect on jet engines. Since particle fall velocity is proportional to the cube of the particle size (in laminar flow), only the smallest fraction remains airborne at longer times. However, until more precise information about the actual particle-size cutoff for damage is available, a conservative estimate that does not depend on size is presented.

Discussion

The meaning of these results deserves careful scrutiny for three major reasons: (1) model simulations are extremely difficult to validate; (2) absolute ash concentration is based on some potentially tenuous assumptions about effusive rate and initial ash column dynamics; and (3) the concentration of volcanic ash that damages jet engines is unknown. However, further investigation of calculating *potential exposure* has several merits. First, low-level exposure to volcanic ash may be difficult to detect during routine aircraft maintenance. If aircraft that potentially encountered ash are identified, a more thorough inspection can be performed, possibly mitigating a future dangerous situation. Second, potential exposure can be calculated ahead of time for an existing air route during an on-going volcanic event as a tool to determine the degree of avoidance and caution necessary. This may be particularly beneficial in later stages when ash concentrations have dropped to levels that are difficult or impossible to detect with remote sensing techniques.

The exposure rating project is in its early stage of development and our initial analysis of these data is presented here. AVO and UAF will be refining the modeling techniques, and will attempt to validate the exposure rating system based on reports of aircraft-ash encounters in order to further assess possible uses of this information.

References

Dean, K. G., J. Dehn, K. R. Papp, S. Smith, P. Izbekov, R. Peterson, C. Kearney, and A. Steffke, 2004. Integrated satellite observations of the 2001 eruption of Mt. Cleveland, Alaska, Jour. Volc. Geophy. Res., 135, doi10.1016/j.jvolgeores.2003.12.013

Dean, K.G., Dehn, J., McNutt, S., Neal, C., Moore, R. Schneider, D. 2002. Satellite Imagery Proves Essential for Monitoring Erupting Aleutian Volcano. EOS Trans. Am. Geophys. Union, 83, 241, 246-247.

Prata, A. J., 1989. Infrared radiative transfer calculations for volcanic ash clouds. Geophys. Res. Lett., 16, 1293-1296.

Simpson, J. J., Hufford, G. L., Pieri, D., Servranckx, R., Berg, J. S., Bauer, C., 2002. The February 2001 Eruption of Mount Cleveland, Alaska: Case Study of an Aviation Hazard. Am. Met. Soc.V. 17, 691–704.

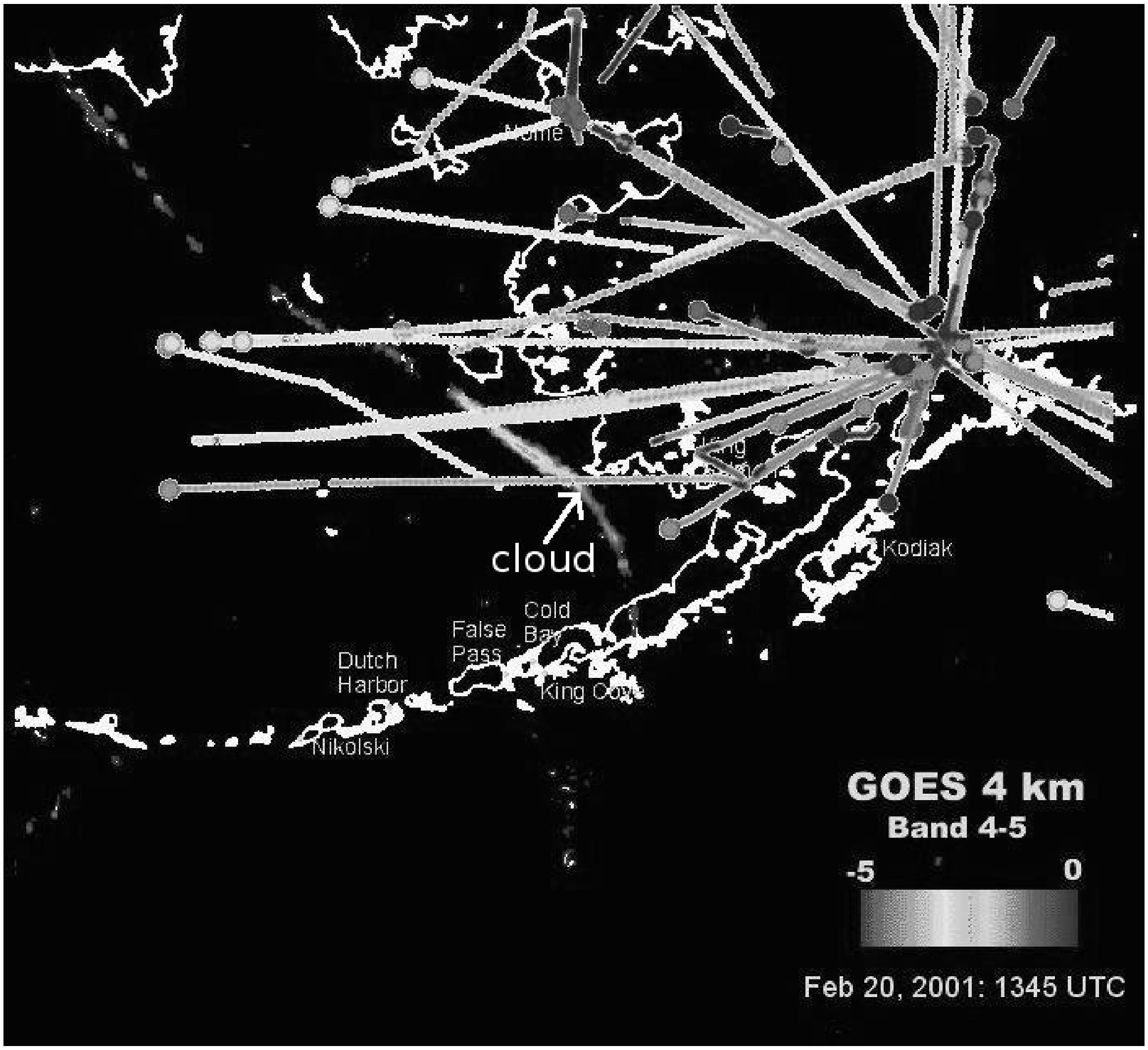


Figure 1 – Composite GOES brightness temperature difference (BTD) image at 1345 UTC on February 20, 2001 overlaid with all flight routes at 1345 ±30 minutes. The last recorded position of each flight is shown with a filled circle. Most all flights are entering or leaving Anchorage Int'l Airport. The ash cloud as detected using BTD is shown just slightly off of the west coast.

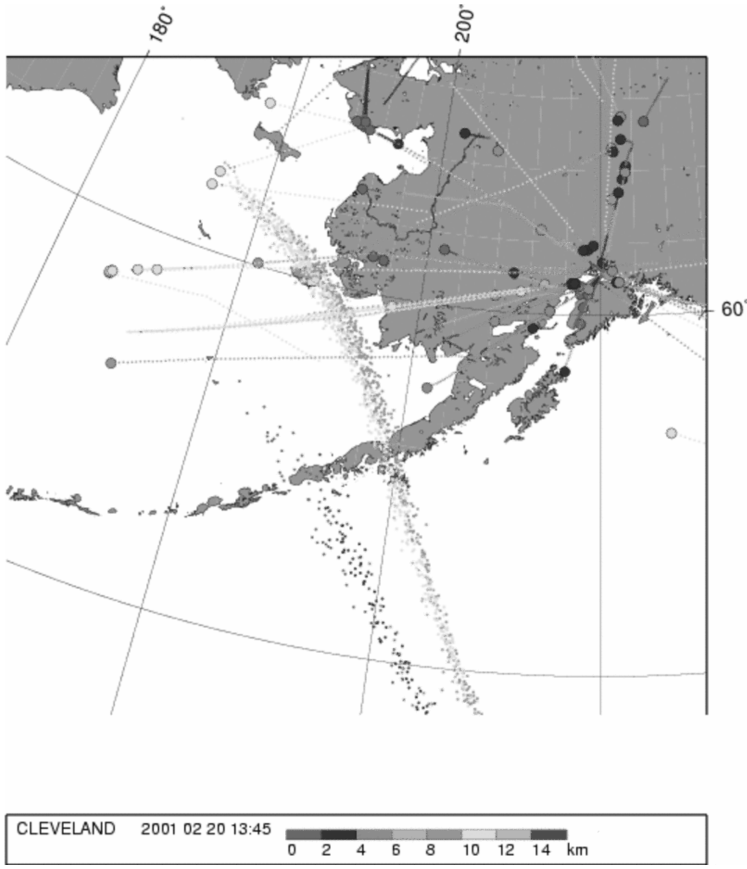


Figure 2 – Puff dispersion model forecast for 1345 UTC on February 20, 2001 overlaid with all flight routes at 1345 ±30 minutes. The last recorded position of each flight is shown with a filled circle. Ash forecasts are color-coded by height and correspond with the color-coding of the flight routes.

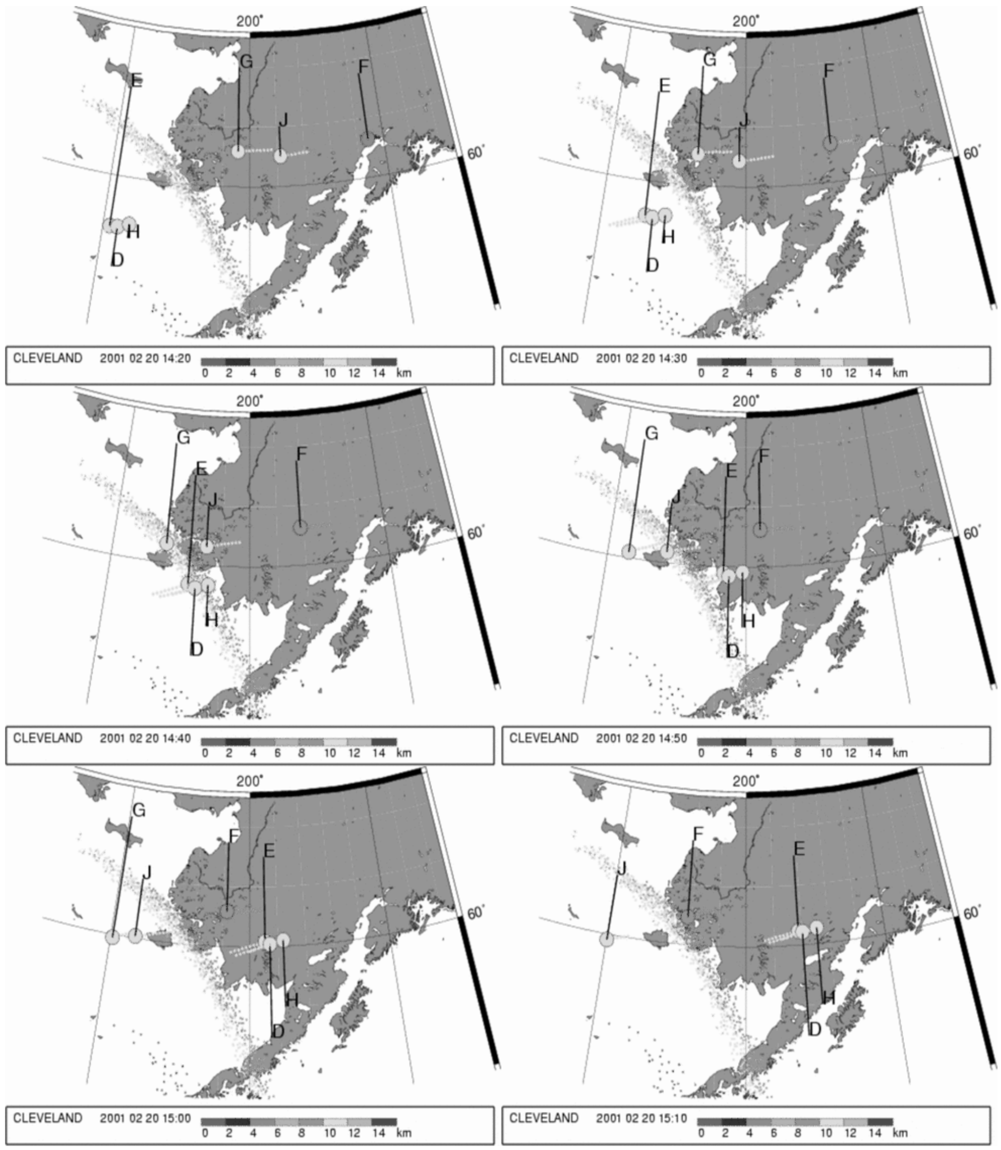


Figure 3 – One hour time-series of Puff dispersion model forecasts superimposed with selected flight routes. Ash forecasts are color-coded by height and correspond with the color-coding of the flight routes. Potential ash exposure calculations recorded the highest values for the flights shown.

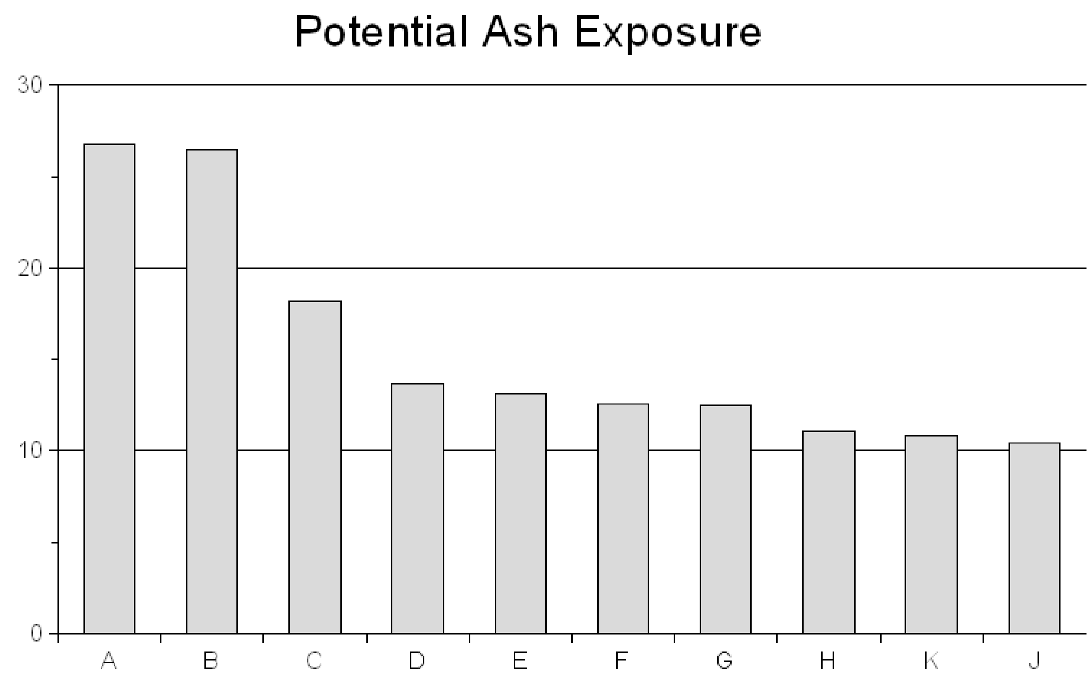


Figure 4 – Potential ash exposure [mg·min/m^3] for the 10 flights with highest values calculated during the 48 hours following the eruption. Letters correspond to flight trajectories shown on Figure 3.

QUANTITATIVE SULPHUR DIOXIDE RETRIEVALS FROM AIRS, MODIS AND HIRS

Fred Prata, CSIRO Atmospheric Research, Aspendale, Australia
Cirilo Bernardo, CSIRO Atmospheric Research, Aspendale, Australia

A new suite of algorithms is proposed for retrieving upper troposphere/lower stratosphere sulphur dioxide from the infrared channels of the AIRS, MODIS and HIRS satellite instruments. The retrieval schemes are tailored to the strengths of each instrument, but all utilise the same principle of detecting the strength of absorption by the anti-symmetric stretch of the SO_2 molecule centred around 1360 cm^{-1} (7.34 µm). The AIRS instrument covers this region of the infrared spectrum with more than 130 channels and is capable of accurate total column amount retrievals with a spatial scale of ~15x15 km^2. We also explore the possibility of using micro-windows and the 8.6 µm and 4.0 µm regions to infer SO_2 height information. The MODIS instrument provides a broadband measure of the 7.34 µm SO_2 absorption feature, but offers unprecedented ~1x1 km^2 spatial resolution and up to 4 measurements per day from two satellites. The retrievals are less accurate than those from AIRS. The HIRS family of instruments also provide broadband measurements and are of lower spatial resolution (~18 x18 km^2 at nadir) than MODIS, but these data span nearly 25 years and are complemented by simultaneous measurements of atmospheric temperature, moisture, clouds, radiative parameters and ozone. Consequently these data are of great value for studies of the effects of volcanic emissions on climate and on the chemical balance of the atmosphere. These new infrared measurements of SO_2 are compared and contrasted to established measurements from TOMS and GOME.

Sakura – AN AIRBORNE INFRARED IMAGING CAMERA FOR THE DETECTION OF VOLCANIC ASH AND SULPHUR DIOXIDE GAS

Fred Prata, CSIRO Atmospheric Research, Aspendale, Australia

Since the early 1990's CSIRO Atmospheric Research have been investigating the use of infrared radiometers for the detection and discrimination of volcanic ash from airborne platforms. The intention has been to develop a forward looking infrared camera system that could be deployed on commercial jet aircraft. Simulations studies and airborne trials at Sakurajima volcano in Japan suggest that infrared radiometry can be used to detect volcanic ash. More recent ground-based trials of an uncooled imaging infrared camera have indicated that sulphur dioxide gas can also be detected and the system is now being improved to provide an indication of other atmospheric hazards, such as clear-air turbulence, low level wind shear, severe weather and desert dust outbreaks. We describe the basic operation of the proposed infrared airborne camera ("Sakura") and demonstrate the overall system performance, "look and feel" and suggest likely operating modes. Results from the airborne trials in Japan will be presented and the operation of the technology from the ground, from an airborne platform and from a satellite platform will be compared and contrasted. Testing of an uncooled infrared imaging camera on board a commercial jet aircraft remains a major goal of this project.

TESTING REAL-TIME REMOTE SENSING FOR MONITORING VOLCANIC ACTIVITY IN CENTRAL AMERICA

Armando Saballos, INETER, Managua, Nicaragua
Peter Webley and Martin Wooster, Department of Geography, King's College, London, UK

We describe the implementation and results of a project to design, install and operate a remote sensing-based monitoring system for Central American volcanoes, locally based in Managua, Nicaragua but capable of monitoring all of Central America. The system is based on AVHRR data capture, and up to eight satellite passes a day are received and processed automatically to provide information on volcanic hotspots, and in future ash clouds, with minimal human intervention. The project aims to assess whether this type of technology is able to significantly improve the capability to locally monitor volcanoes in regions such as Central America. Validation is being conduced against other remote sensing and geophysical datasets, and a social science component is assessing the onward dissemination of the data and its use in hazard assessment.

ADVANCES IN ULTRAVIOLET DETECTION OF VOLCANIC ERUPTION CLOUDS

Stephen J. Schaefer, Joint Center for Earth Systems Technology UMBC, Baltimore MD, USA
Arlin J. Krueger, Joint Center for Earth Systems Technology UMBC, Baltimore MD, USA
Simon A. Carn, Joint Center for Earth Systems Technology UMBC, Baltimore MD, USA

Sulfur dioxide is the most readily quantified material in volcanic eruption clouds due to low background amounts in the atmosphere and strong absorption bands in near ultraviolet wavelengths, which are sampled by polar orbiting Total Ozone Mapping Spectrometers (TOMS). The new hyperspectral Ozone Monitoring Instrument (OMI) has an increased sensitivity and a smaller pixel size (13 x 25 km) than the Nimbus 7 TOMS (50 x 50 km) or the current Earth Probe TOMS (39 x 39 km). The OMI will have a greater than 10^2 improvement in detection limit of SO_2 in eruption clouds relative to the Nimbus 7 TOMS. Pre-eruptive, passive degassing of SO_2 on the order of $10^2 – 10^3$ tons/day should be detectable by OMI and will aid in eruption forecasting. Characterization of aerosol particles by type (e.g. ash, sulfate or ice) and size is expected utilizing the OMI data and will further refine the risk posed to aircraft by different clouds. Current IR instruments have high spatial resolution but may fail to detect volcanic clouds at low altitudes or above high clouds due to water vapor interference or poor thermal contrast. The UV instruments allow for an unambiguous detection of all volcanic clouds, which produces a very low false alarm rate. OMI is on the Aura platform to be launched in June 2004. The data are expected to be processed orbit-by-orbit in near real-time for use in volcanic hazard detection.

REAL-TIME MONITORING OF THE VOLCANIC ASH FALLOUT WILL IMPROVE AIRPORT SAFETY

Simona Scollo, INGV, Catania, Italy
Mauro Coltelli, INGV, Catania, Italy
Marco Folegani, Nubila, Bologna, Italy
Stefano Natali, Nubila, Bologna, Italy
Franco Prodi, ISAC, Bologna, Italy

PLUDIX instrument was tested to measure terminal settling velocity of volcanic particles during the pyroclastic fallout of 2002 Etna's eruption. The instrument is a new generation radar rain-gauge disdrometer, based on the Doppler shift induced by falling particles on the transmitted electromagnetic signal, usually used to investigate the space and the time variability of rainfall, together the total mass of rain accumulated in the ground. The measuring campaign was performed on 18 and 19 December, when explosive activity of Mt. Etna produced a long-lived volcanic plumes high 4000 m a.s.l. During the experiment PLUDIX instrument detected coherently volcanic ash fallout. Data processing permitted to estimated their fall-velocities, using a simple Doppler shift formula. Measured fall velocities have been compared with that obtained from Wilson and Huang experiment for particles with density, dimension and shape similar to Etna's ashes. Both data sets are fully comparable demonstrating that PLUDIX is not only able to detect volcanic ashes but also to characterize in real-time their falling velocities and then the sedimentation rate during the ash fallout. In the next step PLUDIX detection method will be modified reducing the maximum detectable Doppler shift to improve spectral resolution. Moreover a conversion algorithm to estimate in real time the grain size distribution of ash will be implemented. This category of instruments could be very useful for real-time monitoring of the volcanic ash fall rate in the airports close to the active volcanoes in which operations are often disrupted by explosive eruptions like at Catania International Airport during the 2001 and 2002 Etna's eruptions.

DEVELOPMENT OF VOLCANIC ASH IMAGE PRODUCTS USING MODIS MULTI-SPECTRAL DATA

George Stephens, NOAA/NESDIS Office of Satellite Data Processing and Distribution, Camp Springs MD
Gary P. Ellrod, NOAA/NESDIS Office of Research and Applications, Camp Springs, MD
Jung-Sun Im, IM Systems Group, Inc, Camp Springs, MD

1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) on National Aeronautics and Space Administration's (NASA) Aqua and Terra polar-orbiting spacecraft provides a total of thirty-six spectral bands: twenty 1 km resolution Infrared (IR) bands, and sixteen higher resolution (250-500m) visible and near-IR bands available for daytime applications. Based on studies with data from aircraft or other satellite sensors, several of the spectral bands available from MODIS have been shown to be useful for the detection of airborne volcanic ash clouds that pose hazards to aircraft (Miller and Casadevall 2000). For example, the brightness temperature difference (BTD) of MODIS Band 31 (11 μm) and Band 32 (12 μm) is able to distinguish silicate volcanic ash from meteorological clouds (Prata 1989) due to differential absorption. Another longwave IR channel (Band 29 - 8.6 μm) exhibits strong absorption in the presence of volcanic ash as well as sulfur dioxide (SO_2) gas emitted by volcanoes (Realmuto et al 1997).

Due to some degradation in the volcanic ash detection capability of the Geostationary Operational Environmental Satellite (GOES) Imager series beginning with GOES-12 (2002) through GOES-Q (late 2008 launch), there is a need for polar orbiting satellite image products to augment GOES in support of the operational aviation volcanic ash warning system. The reduced capability of GOES is due to the temporary removal of a 12 μm IR band that has a proven capability for volcanic ash detection (Prata 1989; Schneider and Rose 1994). The global aviation warning system consists of Volcanic Ash Advisory Centers (VAACs) established in 1997 by the World Meteorological Organization to provide timely alerts of active volcanic hazards and predictions of ash cloud locations to Meteorological Watch Offices (MWOs) (Miller and Casadevall 2000). Each VAAC has multi-spectral satellite data and derived products at its disposal to help detect and monitor airborne ash clouds.

Work has begun within NOAA/NESDIS to develop prototype volcanic ash image products from MODIS to support the VAACs, as well as to prepare for advanced satellite systems such as the National Polar Orbiting Environmental Satellite System (NPOESS) scheduled for a prototype launch in 2006, and the GOES Advanced Baseline Imager (2012) that will have multi-spectral capabilities and resolutions similar to the MODIS.

2. DATA ANALYSIS

Initial analysis of MODIS data has been completed for two volcanic eruptions: (1) Cleveland volcano in the Aleutian Islands on 19-20 February 2001, and (2) Popocatepetl volcano near Mexico City on 19-20 December 2000. Two data sets were analyzed for each of the first two cases (one daytime, one nighttime) using Man-computer Interactive Data Access System (McIDAS) image processing software on PC workstations. The emphasis in this work was to develop an optimum IR volcanic ash product that could be used twenty-four hours a day, regardless of location. However, visible and near-IR bands were also evaluated for daytime applications.

Various combinations of MODIS IR bands have been evaluated. Some initial tests involved producing multi-spectral ash products used operationally at VAACs such as the Two-Band Split Window (TBSW) based on the BTD of Bands 32 (12.0 μm) and 31 (11 μm) described earlier in this paper, the Three-band Volcanic Ash Product (TVAP) that is based on the TBSW plus Band 22 (3.9 μm) (Ellrod et al 2002) and a four-channel algorithm (Mosher 2000) that also incorporates visible channel information. Other combinations were evaluated that utilized Band 30 (9.7 μm), Band 29 (8.6 μm), Band 28 (7.3 μm), and Band 25 (4.5 μm).

The best results for ash cloud discrimination were obtained from a three-channel combination of Band 32 (12.0 μm), Band 31 (11.0 μm) and Band 29 (8.6 μm) (hereafter referred to as the Longwave Volcanic Ash Product (LVAP)). The most useful shortwave IR channel was determined to be Band 25 (4.5 μm), which supports the results of Hillger and Clark (2002). An advantage of Band 25 is that it exhibits considerably less solar reflectance than the other shortwave bands, which provides more consistent results for both day and night. By examining scatter plots of the BTD's for each of the channels, appropriate BTD ranges were empirically selected to highlight the likely ash cloud, and minimize the meteorological clouds and surface features.

3. CASES ANALYZED

3.1 *Popocatepetl, 18-20 December 2000*

On the evening of 18 December 2000, Popocatepetl Volcano near Mexico City began an eruption of ash that was not explosive, but persisted until the afternoon of the 20^{th}. It was considered to be the largest eruption of the volcano in 75 years**.** Ash spewed southward from the volcano across southern Mexico, reaching the Pacific coast on the south, and the Gulf of Mexico on the east after Midnight, 20 December 2000. Maximum height of the ash was estimated to be about 10.6 km (35,000 ft) (Washington VAAC advisory).

MODIS observed the ash clouds over southern Mexico at 0505 UTC on 20 December 2000. The three-band LVAP (Figure 1) provided depiction of the ash cloud extent that was in good agreement with concurrent GOES imagery, shown in an analysis by the Washington VAAC (Figure 2). Comparison with the TBSW image in Figure 1 indicates that the addition of Band 29 has resulted in a slightly larger area of ash compared with the TBSW alone. The LVAP detects more of the thin ash over southern Mexico, but may also be observing some surface features, possibly due to the presence of underlying silicate soils.

Scatter plots of Band 32 - 31 and Bands 32 - 29 versus Band 31 IR temperature (Figure 3) reveal that the TBSW alone provides the best discrimination, but Band 32 - 29 contains some additional information on the presence of ash.

3.2 *Cleveland, 19 February 2001*

On the afternoon of 19 February 2001, Cleveland Volcano in the Aleutian Islands of Alaska erupted, sending ash as high as 9.1 km (30,000 ft) (Alaska Volcano Observatory (AVO) Web site). The ash cloud bifurcated as it drifted eastward, with the highest portion of the cloud stretching northward across the Bering Sea, and the portion below about 6.1 km moving southeast into the Gulf of Alaska.

A MODIS LVAP image was produced at 2310 UTC, 19 February 2001 (A - Figure 4). The majority of the ash cloud is shown being elongated north and northwest of the Aleutian chain, with a thinner component to the southeast. Comparison with a simple TBSW product (B) indicates that the addition of Band 29 data adds significant value to the analysis by detecting the thinner ash to the east and southeast of the main ash cloud. The ash cloud coverage from MODIS compares favorably with the 2315 UTC analysis based on 30-minute interval GOES TBSW images from the Alaska Volcano Observatory (Figure 5).

A scatter plot of the BTD's for Bands 32 – 31 and Bands 32 – 29 versus Band 31 IR temperature (Figure 6) shows that both allow good discrimination of ash from meteorological water and ice clouds, but the latter provides the best result in this case.

4. ADDITIONAL EXPERIMENTS

Tests were conducted of techniques for detection of sulfur dioxide (SO_2). The SO_2 test involved the use of a multi-channel, stepwise threshold test developed by Crisp (1995). The Crisp technique employs Bands 27, 28, 31, and 36. The tests were negative for all cases, presumably because the technique is only able to detect SO_2 at altitudes between 6 km and 25 km. The eruption cases studied in this paper were relatively weak eruptions that did not emit ash and SO_2 into the Stratosphere.

Experiments with Red-Green-Blue (RGB) color composite techniques were also conducted to produce images that provide optimum colorized depiction of the ash cloud, meteorological cloud types, and surface conditions to aid in interpretation of the event. One result of the tests is a daytime image product that combines information from the three-band IR volcanic ash image with visible Band 1 (0.6 μm) and near-Infrared Band 6 (1.6 μm) data. The latter two channels help distinguish ice versus water clouds due to the lower solar reflectance of ice cloud particles and snow cover in Band 6 than in Band 1. An example of this RGB image for the Cleveland eruption derived using the McIDAS software is shown in Figure 7. Volcanic ash appears red, water droplet clouds as a greenish hue, and ice clouds and snow as blue.

5. ANALYSIS OF REAL-TIME MODIS DATA

Procedures were developed to analyze near real-time "Level 1b" MODIS data downloaded from the NASA DAAC via a file transfer protocol (ftp) site at Federal Building 4 in Suitland, Maryland. Once the data were downloaded, a program written in McIDAS was run to generate LVAP images in an effort to evaluate the MODIS data for "null" events in which no known volcanic activity was occurring. In these images it was discovered that there are some regions over land areas where "false alarms" for ash clouds were observed. These are believed to be due to the radiation characteristics of sandy soils consisting of silicate minerals. In order to avoid this, a sequential test can be used, requiring that a Band 32 – Band 31 threshold be satisfied before information from the Band 32 – Band 29 can be incorporated into the final image product.

6. DATA PROCESSING AND DISTRIBUTION

NESDIS' Satellite Services Division is implementing the product operationally for use in issuance of Volcanic Ash Advisories by the Washington Volcanic Ash Advisory Center (W-VAAC). Level 1b MODIS data are pulled from NOAA computers located at the NASA Goddard Space Flight Center for use in various products, including the Ash Product. LVAP and RGB composites are processed over geographic areas of responsibility of the W-VAAC and the Alaska VAAC in Anchorage AK, and will be made available on a Geospatial Information System compatible web site. (Figure 8.)

7. RECENT EXAMPLES FROM THE W-VAAC

A continuing series of eruptions at Tungurahua Volcano in Ecuador in August, 2003 provided several opportunities to validate the MODIS Volcanic Ash Product, as implemented in the W-VAAC. A comparison, below, of MODIS (Figure 9.), Advanced Very High Resolution Radiometer (AVHRR) (Figure 10.) and Geostationary

Environmental Operational Satellite (GOES) Imager derived graphical analysis (Figure 11.) demonstrates excellent agreement, with the MODIS product providing enhanced detection of thin ash to the west of the volcano.

8. SUMMARY AND CONCLUSIONS

Experimental volcanic ash products have been derived and evaluated using MODIS data from the Terra spacecraft for two volcanic eruptions: Popocatepetl, Mexico (20 December 2000) and Cleveland, Alaska (19 February 2001). The best results, based on subjective comparisons with frequent interval GOES imagery, were obtained from a tri-spectral combination of Bands 29 (8.6 μm), 31 (11.0 μm) and 32 (12.0 μm). Volcanic ash detection using a simple two-band split window (TBSW) derived from Band 32 - Band 31 was only slightly less effective. Optimum color composite images have been developed to provide information on ash cloud location, as well as cloud phase and surface characteristics, to aid in interpretation both day and night. Additional work will attempt to reduce false alarms from silicate soils in Band 29, and develop procedures for real-time production of operational products for use in VAACs.

9. ACKNOWLEDGMENTS

The authors would like to thank Dr. Donald Hillger of the NESDIS Regional and Mesoscale Meteorology Team, Ft. Collins, Colorado, and Drs. Matthew Watson and William Rose, Michigan Technological University, Houghton, Michigan, for providing the MODIS data described in this paper.

10. REFERENCES

Crisp, J., 1995: Volcanic SO2 Alert. EOS IDS Volcanology Team Data Product Document #3288, Jet Propulsion Laboratory, California Inst. of Technology, 13 pp.

Ellrod, G. P., B. Connell and D. W. Hillger, 2002: Improved detection of airborne volcanic ash using multi-spectral infrared satellite data. *J. Geophys. Res.*, In review.

Hillger, D. W., and J. D. Clark, 2002: Principal component image analysis of MODIS for volcanic ash, Part-1: Most important bands and implications for future GOES Imagers. *J. Appl. Meteor*., In press.

Miller, T. P., and T. J. Casadevall, 2000: Volcanic ash hazards to aviation. In: *Encyclopedia of Volcanoes*, H. Sigurdsson, Ed., Academic Press, San Diego, California, pp 915-930.

Mosher, F. R., 2000: Four channel volcanic ash detection algorithm. Preprint Volume, 10th Conf. on Satellite Meteor. and Oceanography, 9-14 January 2000, Long Beach, California, 457-460.

Prata, A. J., Observations of volcanic ash clouds in the 10-12 micrometer window using AVHRR/2 data. *Int. J. Remote Sens.*, **10**, 751-761, 1989.

Realmuto, V. J., A. J. Sutton, and T. Elias, 1997: Multispectral imaging of sulfur dioxide plumes from the East Rift Zone of Kilauea volcano, Hawaii. *J. Geophys. Res.*, **102**, 15057-15072.

Schneider, D. J., and Rose, W. I., Observations of the 1989-1990 Redoubt volcano eruption clouds using AVHRR satellite imagery. In: Volcanic ash and aviation safety: Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety. *U. S. Geological Survey Bulletin 2047*, 405-418, 1994.

Wright, R., L. Flynn, H. Garbeil, A. Harris, and E. Pilger: 2002: Automated volcanic eruption detection using MODIS. *Remote Sensing of Environment*, **82**, 135-155.

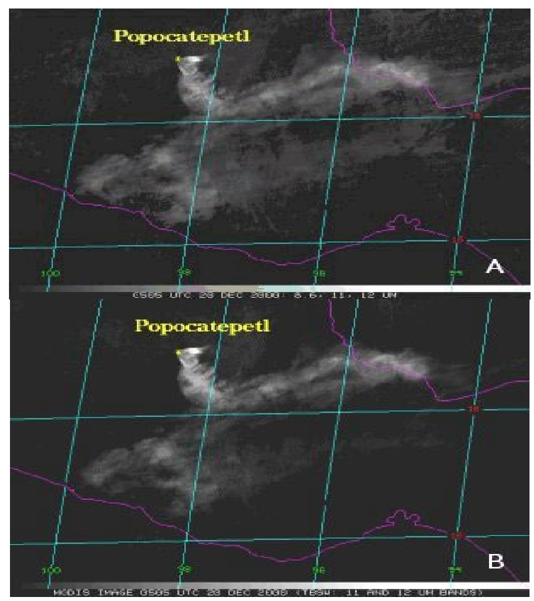


Figure 1. *Comparison of MODIS LVAP (A), and TBSW (B) images at 0505 UTC, 20 December 2000.*

Figure 2. *VAAC analysis near the time of MODIS image in Figure 1, based on GOES imagery.*

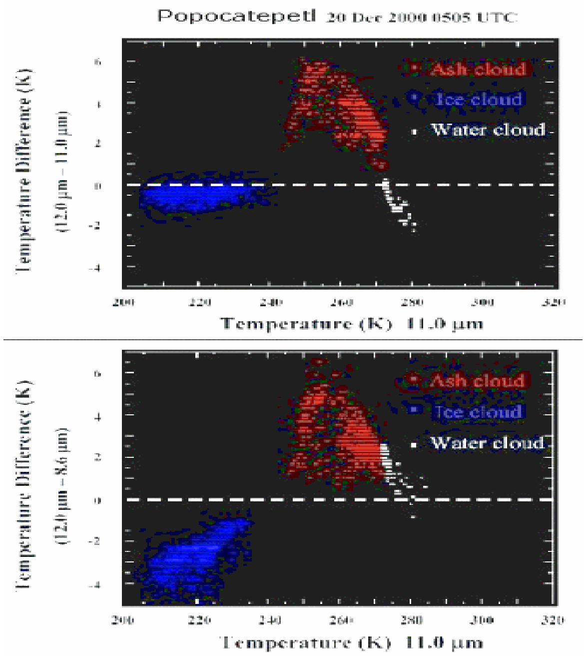


Figure 3. *Scatter plots showing BTDs for Bands 32-31 (top) and Bands 32 – 29 (bottom) at 0505 UTC, 20 December 2000.*

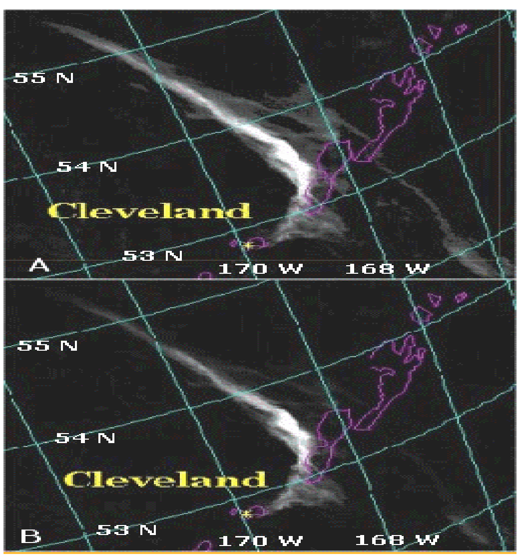


Figure 4. *Comparison of MODIS LVAP (A) With TBSW (B) at 2310 UTC, 19 February 2001.*

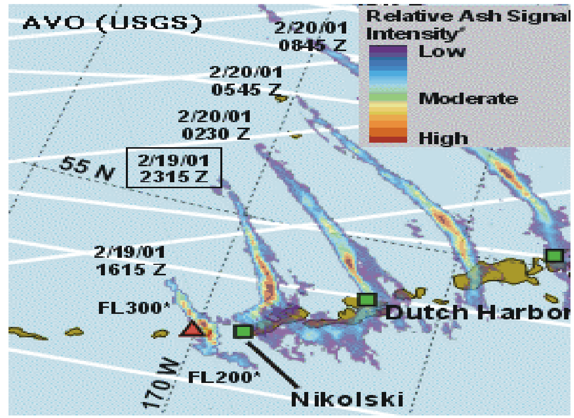


Figure 5. *Spreading of ash cloud from Cleveland Eruption on 19 February 2001 based on GOES TBSW animation. Time closest to MODIS data is outlined. (Alaska Volcano Observatory)*

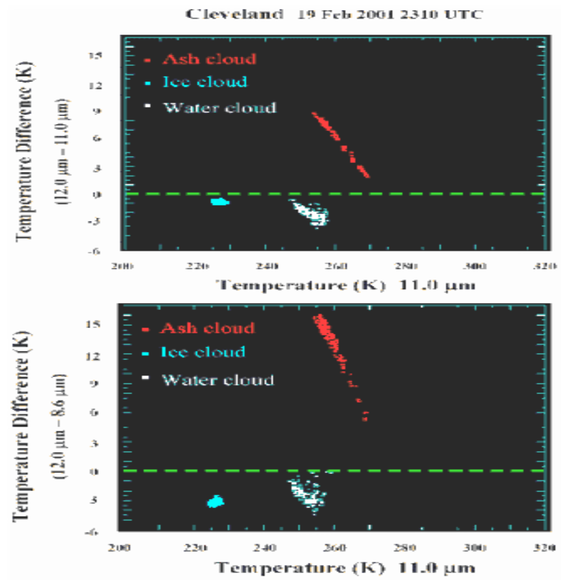


Figure 6. *Scatter plots of Bands 32 – 31 (top) and Bands 32 – 29 (lower) versus Band 31 temperature for Cleveland case at 2310 UTC, 19 February 2001.*

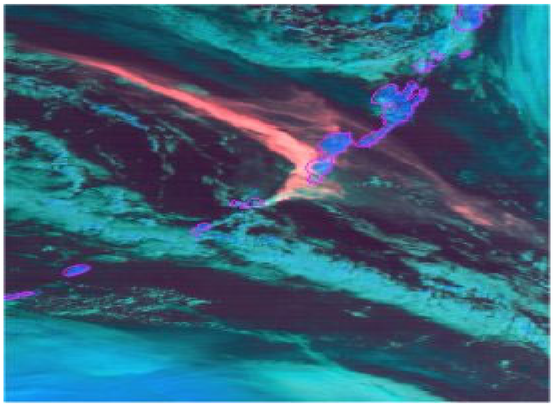


Figure 7. *Red-Green-Blue composite showing ash coverage from MODIS LVAP as red, Band 6 (1.6 μm) as green, and Band 1 (0.6 μm visible) as blue.*

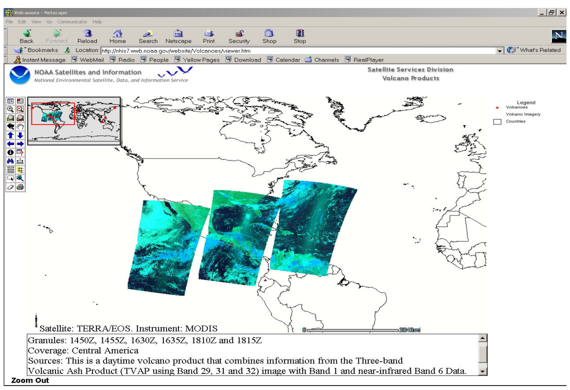


Figure 8. *Geospatial web site display of LVAP RGB composite imagery covering Central American region, delineated above.*

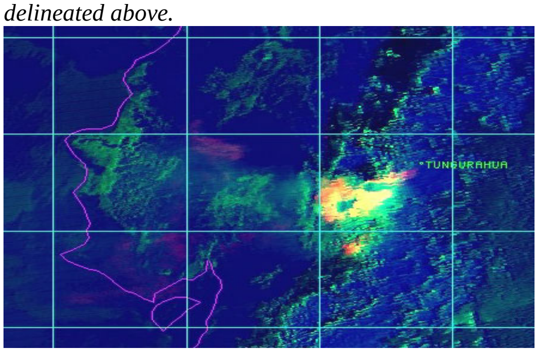


Figure 9*. MODIS AQUA LVAP RGB composite Aug. 31, 2003 1910 UTC.*

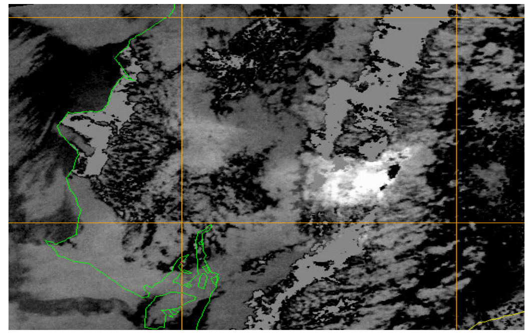


Figure 10. *AVHRR "split window", ch.4 – ch.5 Aug. 31, 2003*
1926 UTC

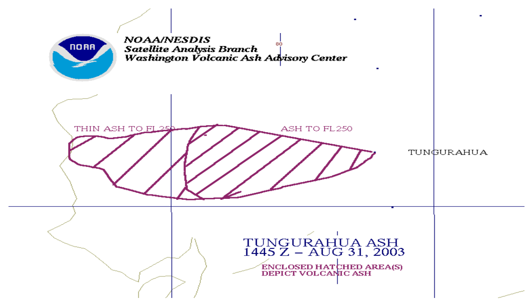


Figure 11. *W-VAAC graphical analysis from GOES imagery Aug. 31, 2003 1445 UTC*

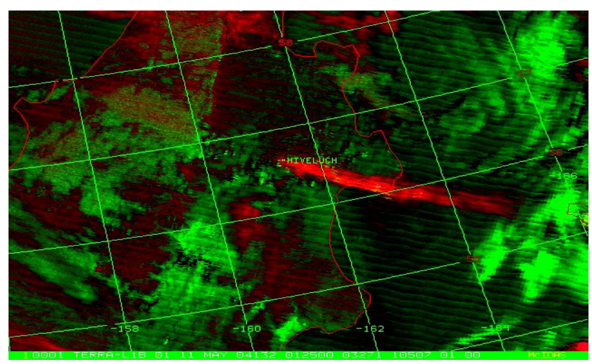


Figure 12. *LVAP detected an eruption of Sheveluch Volcano on Siberia's Kamchatka Pen-insula, May 10, 2004*

VOLCANIC ASH DISPERSION MODELING RESEARCH AT NOAA AIR RESOURCES LABORATORY

Barbara J.B. Stunder[1] and Jerome L. Heffter
NOAA Air Resources Laboratory, Silver Spring, MD, USA

ABSTRACT

The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) is conducting research, using the HYSPLIT model, to improve volcanic ash forecast guidance. In one project, preliminary results suggest an archive of trajectory forecasts and dispersion forecast patterns from hypothetical eruptions and corresponding (hypothetical) analysis dispersion patterns can be used to predict the reliability of subsequent forecasts. In another project, ensemble meteorology is used to create a prototype probabilistic forecast product. More research is needed to determine the applicability of ensemble dispersion products.

INTRODUCTION

The Hybrid-Single Particle Lagrangian Integrated Trajectories (HYSPLIT) model was developed at the NOAA Air Resources Laboratory beginning in the early 1980s (Draxler and Taylor, 1982). Draxler and Hess (1998) describe the last major upgrade and compare HYSPLIT-calculated concentrations to measurements from field experiments, calculated Cs-137 deposition to that from the 1986 Chernobyl accident, and calculated volcanic ash to satellite imagery for the Rabaul, September, 1994 eruption. Results from recent model upgrades (see http://www.arl.noaa.gov/ready/hynew.html) are compared against a database of tracer measurements from field experiments, the "Data Archive of Tracer Experiments and Meteorology" (DATEM - see http://www.arl.noaa.gov/datem/). HYSPLIT was implemented at NCEP in 1998 (see http://www.nws.noaa.gov/om/tpb/458.htm) for radiological applications. The planned NOAA National Centers for Environmental Prediction (NCEP) installation of ARL's current version of HYSPLIT will include the ability to run HYSPLIT for volcanic ash transport and dispersion forecasting and produce output in the same format as VAFTAD.

Evaluation of volcanic ash dispersion forecasts includes two main components: the dispersion model and the meteorological forecast. To evaluate the dispersion model, model calculations using analysis meteorology are compared to volcanic ash observations, typically satellite analyses. To evaluate the meteorological forecast, the model calculations using forecast and analysis meteorology are compared. Current research at ARL is focused on the meteorological component, to provide more useful volcanic ash dispersion guidance products. Two ongoing projects will be described: one to assess the reliability of a forecast, the other to assess the possible use of ensemble dispersion forecasts.

FORECAST PATTERN RELIABILITY

The reliability of a forecast pattern is based on past patterns with similar meteorological situations. We hypothesize that forecasts are more reliable in some situations and less reliable in other situations. Forecasters aware of this differentiation may be able to better interpret forecast model output and thereby assign a degree of reliability to the forecast. Seven volcanoes were chosen for this study, in or near areas of responsibility of the Volcanic Ash Advisory Centers (VAACs) located at Washington and Anchorage.

Area	Volcano
1. Alaska	Augustine
2. N. Atlantic	Hekla
3. Mexico	Popocatepetl
4. NW United States	Rainier
5. Kamchatka	Sheveluch

[1]Corresponding author: Barbara.Stunder@noaa.gov, NOAA Air Resources Laboratory (R/ARL), 1315 East-West Highway, Silver Spring, MD, 20910, USA

6. Caribbean	Soufrierre Hills
7. South America	Tungurahua

A daily archived database is being created for hypothetical eruptions of each volcano listed above. The data include: a forecast trajectory, a forecast pattern, and an "offset" forecast pattern. The offset forecast pattern is the mean of the 8 forecast patterns using meteorology offset by one degree of latitude and longitude surrounding the volcano (Draxler, 2003), and the forecast pattern from the volcano without offset meteorology. All forecasts are run out to +18 hours. For reference, an analysis pattern is run using analysis meteorology for the days corresponding to the forecasts. In summary, the archived database contains, for each volcano, on each day, a trajectory, a forecast pattern, an offset forecast pattern, and an analysis pattern.

When corresponding forecast and analysis patterns are compared (Fig. 1), a forecast region that overlaps an analysis region is called a "hit", a forecast region that extends beyond an analysis region is called "excess", and the region of the analysis that was not forecast is called a "miss". For the aviation community, some degree of an excess region (false alarms) may be acceptable, but even a small degree of a miss region may be dangerous to aircraft safety

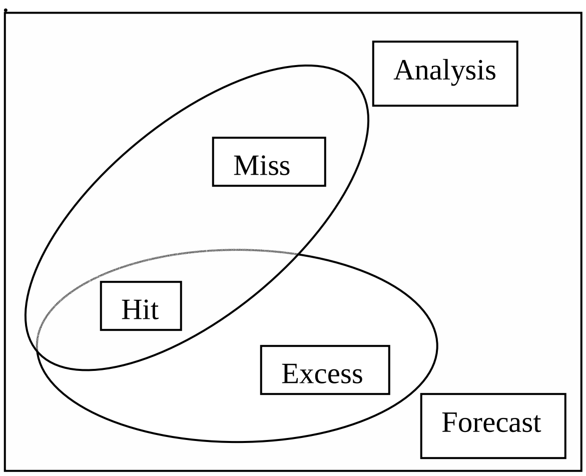


Figure. 1. Illustration of terminology with a forecast and analysis pattern: hit, miss, and excess.

The meteorological conditions for each forecast are categorized by the trajectory quadrant, trajectory distance, and the ratio of the offset forecast pattern area to the forecast pattern area, the "offset excess ratio" (Fig.2).

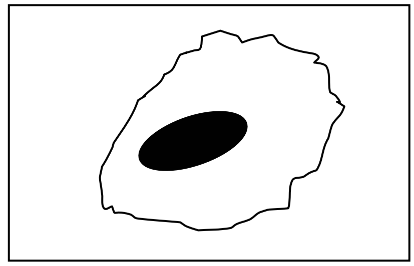


Figure 2: Offset excess ratio is the ratio of the forecast pattern area (solid oval) to offset forecast pattern area (irregular shape).

When an operational forecast is run, the database is searched for cases with meteorological conditions (trajectory quadrant and distance, and offset excess ratio) closely matching those for the forecast. A FOPARE (FOrecast PAattern REliability) chart that displays the percent of excess, hits, and misses for the matching cases, and their mean, can be created (Fig. 3). Preliminary results suggest that FOPARE charts with a small proportion of misses (<30%, 100% - 70%) and a small proportion of excesses (<30%) indicate the forecast is "reliable". When the misses are greater than 30% the forecast should be used with caution, since a significant percent of the ash pattern may extend beyond the forecast pattern. The above thresholds for misses and excesses have yet to be verified for operational use.

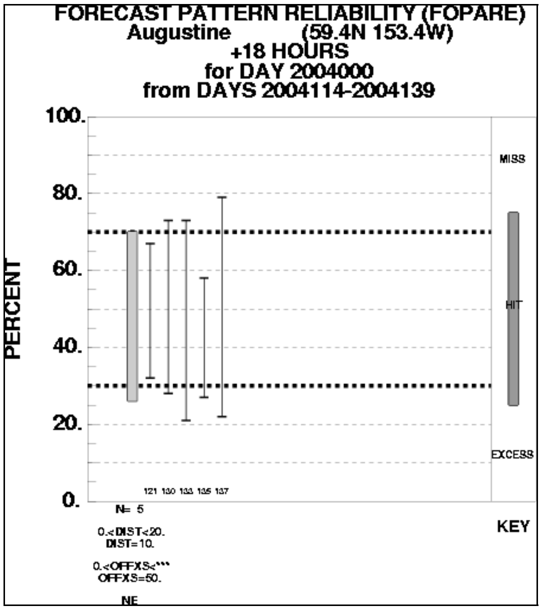


Figure 3. Example FOPARE chart.

ENSEMBLE DISPERSION FORECASTS

Uncertainties with volcanic ash dispersion forecasts have not been quantified. Servranckx and Chen (2004) describe some of the uncertainty as arising from uncertainties in the source term, meteorology, and transport and dispersion parameterizations. Current models, such as VAFTAD, and the planned NCEP implementation of HYSPLIT, use pre-determined ash particle specifications and vertical distributions, a given 3-dimensional meteorology dataset, certain transport and dispersion algorithms, and for real-time forecasting, an estimate of the eruption column height and eruption duration. A collection of dispersion forecasts using a range of realistic inputs and/or model algorithms/parameterizations, can be called an "ensemble" to show the range of forecast possibilities and the corresponding probabilistic forecast.

As an example, if the eruption column height is determined to be in a range between 20,000 ft and 25,000 ft, the model can be run for both heights, i.e. a 2-member ensemble. If the results are similar, then knowing the exact height is not important. If the results are different, perhaps because wind speeds vary significantly from 20,000 ft and 25,000 ft, the forecaster would need to use both model outputs to produce a forecast. The combined forecast product would then account for the uncertainty in the eruption column height.

Another dispersion ensemble can be created from the NCEP ensemble global meteorology forecast, which is based on an estimate of the uncertainty in the meteorological analyses (Szunyogh and Toth, 2002). For each of the 10 NCEP ensemble members, the model is run with a different analysis, which leads to different meteorological forecasts.

To illustrate an ensemble dispersion forecast, based on the NCEP ensemble meteorology, we chose a hypothetical 40,000 ft (about 12,200 m) eruption of Pavlof, Alaska, at 00 UTC 21 May 2004. Figure 4 shows the forecast pattern 18 hours after the eruption, for the layer from the surface to about FL550. The concentrations shown (units per cubic meter), spanning four orders of magnitude, are with respect to the mass (one unit) in the initial eruption column. In an operational setting, the mass of an eruption is not known so one unit is typically assumed.

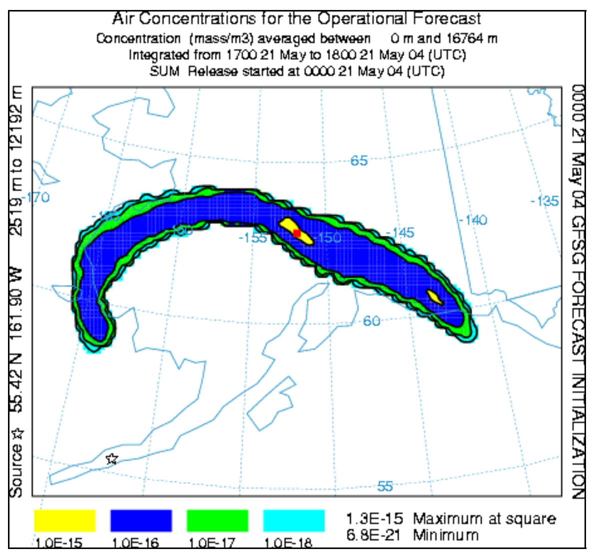


Figure 4. HYSPLIT 18-h forecast using operational NCEP GFS meteorology for a hypothetical 40,000 ft eruption of Pavlof at 00 UTC 21 May 2004.

To illustrate the differences in the meteorology, trajectories were computed using the ensemble members' meteorology beginning at the time of the hypothetical eruption (Fig. 5). At 18 hours downwind from Pavlof, the trajectory endpoints span about 400 km in the crosswind and alongwind directions.

The individual dispersion forecast patterns based on the ensemble members (not shown) are generally similar to that of the operational forecast (Fig. 4), but show differences as suggested by the ensemble trajectories (Fig. 5). Calculating the mean dispersion forecast (Fig. 6) from the ensemble member forecasts shows a larger area of ash than the operational forecast.

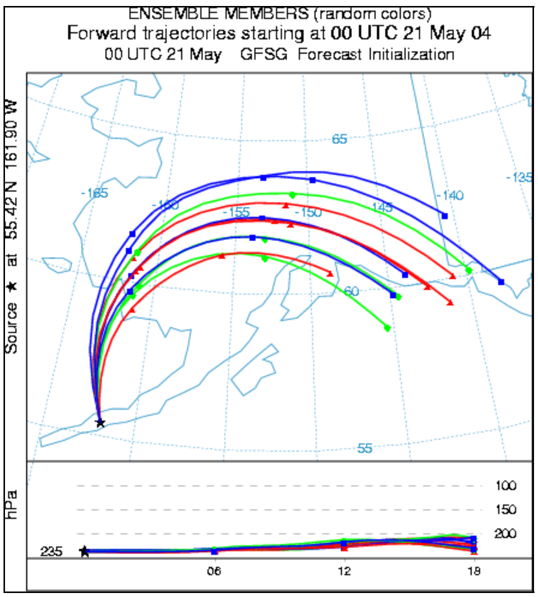


Figure 5. The ensemble of 18-hour duration HYSPLIT trajectories from Pavlof, beginning at 00 UTC 21 May 2004.

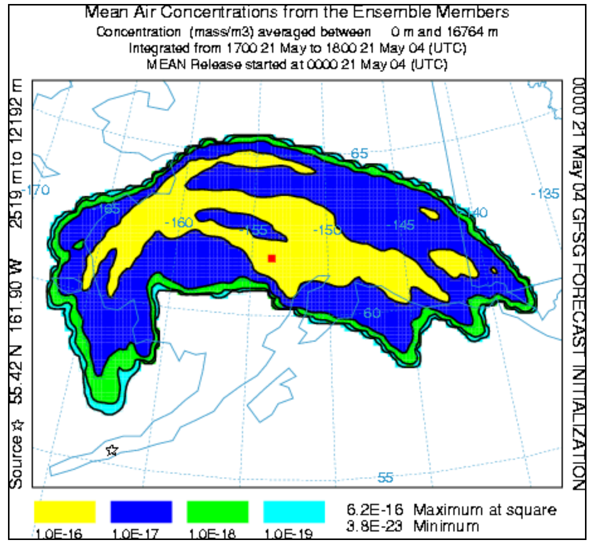


Figure 6. Mean dispersion forecast from the ensemble member dispersion forecasts.

Statistics other than the mean may also be computed from the ensemble member dispersion forecasts (Draxler, 2003). For example, the probability that the ash concentration exceeds 1.0×10^{-17} (arbitrarily chosen) is shown in Figure 7. The area with probability greater than 0%, as expected, is similar to the area with ensemble mean concentrations greater than 1.0×10^{-17} (Fig. 6). The area with probability greater than 25% is a small region. We do not have enough data yet to determine the usefulness of a product similar to this, or how a forecaster would use it. To speculate, a forecaster receiving a product such as Figure 7 might then develop a forecast that ash is likely in the area around the 25% probability area, but is possible in the area with non-zero probabilities. Forecasts such as this are somewhat analogous to current weather forecasts with probability of precipitation.

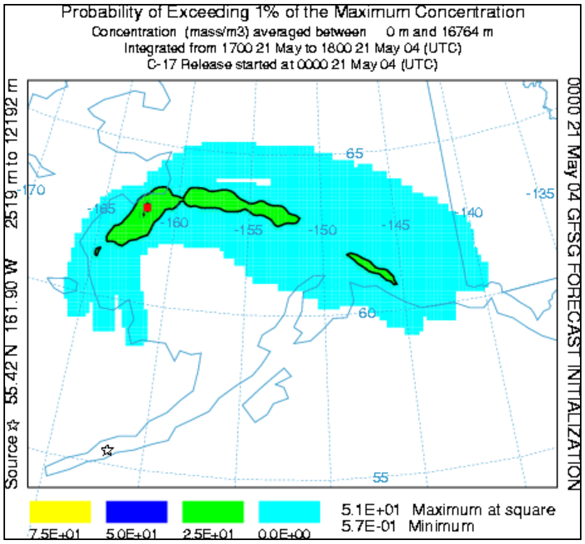


Figure 7. Forecast probability that ash concentrations are greater then 1.0E^{-17}.

Figure 8 shows the actual, but hypothetical, dispersion pattern based on analysis meteorology. Comparison to the operational forecast (Fig. 4) shows a generally similar pattern, but the analysis pattern is slightly farther north, within the ensemble mean pattern (Fig. 6). This suggests that, for this case, though the forecast was good (similar to that with analysis meteorology), use of the ensemble dispersion information may have provided additional useful information.

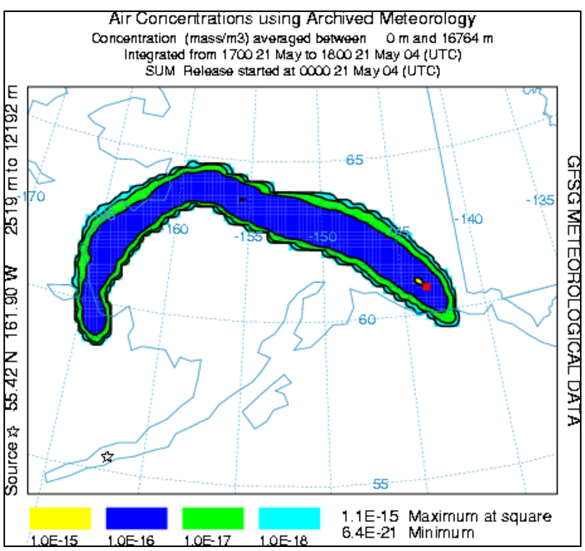


Figure 8. HYSPLIT analysis using analysis GFS meteorology corresponding to the forecast in Fig. 4.

Further research is needed beyond this case study in the dispersion application of the NCEP ensemble meteorology. More traditional use of the NCEP ensembles, such as 500 hPa height contours and quantitative precipitation forecasts, has focused on the mid- to long-range forecasts, i.e. greater than about 3 days. Use for short-term forecasts, as done here, needs to be assessed.

SUMMARY

Dispersion modeling research projects using the HYSPLIT model are being conducted at NOAA to provide more useful volcanic ash forecast guidance. In one project, the goal is to provide a qualitative assessment of the reliability of a forecast. In another project, the applicability of the NCEP ensemble meteorology forecast to improve dispersion forecasts is being studied. Results of both projects may lead to additional information of use to the forecaster.

REFERENCES

Draxler, R.R., 2003: Evaluation of an ensemble dispersion calculation, J. Applied Meteorology, 42, 308-317.

Draxler, R.R. and G.D. Hess, 1998: An Overview of the Hysplit_4 Modeling System for Trajectories, Dispersion, and Deposition, Aust. Met. Mag., 47, 295-308.

Draxler, R.R. and A.D. Taylor, 1982: Horizontal dispersion parameters for long-range transport modeling, J. of Applied Meteorology, 21, 367-372.

Heffter, J.L., 1996: Volcanic ash model verification using a Klyuchevskoi eruption. Geophy. Res. Letters, 23-12, 1489-1492.

Heffter, J.L. and B.J.B. Stunder, 1993: Volcanic ash forecast transport and dispersion (VAFTAD) model, Weather and Forecasting, 8, 533-541.

Servranckx, R. and P. Chen, 2004: Modeling volcanic ash transport and dispersion: Expectations and reality, 2nd International Conference on Volcanic Ash and Aviation Safety, Alexandria, VA, this volume.

Szunyogh, I., and Z. Toth, 2002: The effect of increased horizontal resolution on the NCEP global ensemble mean forecasts. Mon. Wea. Rev., 130, 1125-1143

OPERATIONAL VOLCANIC ASH PLUME PREDICTION MODEL PUFF AT THE JAPAN AIRLINES

H. L. Tanaka (Geoenvironmental Sciences, University of Tsukuba, Tsukuba 305-8572 Japan), Saburo Onodera (Japan Airlines, Tokyo Japan), and DAISUKE NOHARA (Meteorological Research Institute, Tsukuba Japan)

1. Introduction

Volcanic ash cloud floating and traveling in the air is a great concern to airline pilots. If a commercial jet aircraft encounters ash cloud, the damage could be serious enough to cause an engine failure (Hobbs et al., 1991; Casadevall, 1994; Onodera, 1997). In order to avoid serious accidents of commercial aircrafts, real-time volcanic plume prediction models have been developed by some agencies.

A 3-D turbulent diffusion model was developed by Armienti and Macedonio (1988) using an observed upper air wind data and applied to stronboli eruption of Mt. St. Helens in 1980. Glaze and Self (1991) constructed a turbulent diffusion model considering the vertical wind shear and applied to Usu volcano in 1977 to see distributions of ash fall. Hurst and Turner (1999) developed a 3-D turbulent diffusion model called ASHFALL to predict volcanic ash fall for operational use. In this model, the regional distribution of upper air wind is prepared by RAMS (Regional Atmospheric Modeling System). Turner and Hurst (2001) further combined HYPACT (Hybrid Particle and Concentration Transport Model) with RAMS to improve the model. Heffter and Stunder (1993) developed a transport dispersion model called VAFTAD (Volcanic Ash Forecast Transport and Dispersion) to predict ash plume floating in the air.

A group of worldwide volcanic ash advisory services was organized to form volcanic ash advisory centers (VAACs) by nine organizations under the auspice of the International Civil Aviation Treaty (ICAO). The Tokyo VAAC is one of the nine VAACs, which was established in April 1997 at the Tokyo Aviation Weather Service Center. The Tokyo VAAC operates the Lagrangian and Eulerian models to forecast the position of the volcanic ash clouds (Tokyo Aviation Weather Service Center, 2001).

In parallel with those activities, a real-time volcanic ash plume tracking model called PUFF was developed for the purpose of real-time aviation safety in northeastern Pacific rim including Alaska volcanoes (Tanaka, 1991; Kienle et al., 1991; Dean et al., 1993; Tanaka, 1994; Searcy et al. 1998). It is noted that the PUFF model is the earliest ash tracking model applied for the aviation safety purpose in a real-time operation (Tanaka et al., 1993; Akasofu and Tanaka, 1993). The model is operational under the Alaska Volcano Observatory (AVO) at the Geophysical Institute of the University of Alaska Fairbanks (GI/UAF) since the eruption of Redoubt volcano in 1990. The PUFF model at the University of Tsukuba was applied to the actual eruption of Usu volcano on 31 March 2000 in Hokkaido (Endoh et al., 2001; Tanaka and Yamamoto, 2002) and Miyake-jima Volcano on August 18 2000.

The research product of the PUFF prediction system, including the model simulation and animation graphics of the simulation results, was transplanted to Japan Airlines with the assistance by the Japan Weather Association (JWA). This report describes the latest improvements installed in the PUFF model operational at the Japan Airlines.

2. Description of the model

The volcanic plume prediction model PUFF was constructed in 1991 and reported in detail by Tanaka (1994) and Searcy et al. (1998) as an application of pollutant dispersion models. The model is based on the three-dimensional (3-D) Lagrangian form of the transport-diffusion equation. In the Lagrangian framework, a realization of the stochastic process of plume particles may be described by a random walk process (e.g., Chatfield, 1975). Here, the diffusion is simulated by a sufficiently large number of random variables $r_i(t)$, $i=1 \sim M$, representing position vectors of M particles from the source S of the volcanic crater. The diffusion is superimposed on convective transport and gravitational fallout.

With a discrete time increment, (t=5 minutes), the Lagrangian form of the governing equation may be written as

$$\begin{cases} r_i(0) = S, & i = 1 \sim M,\ for\ t = 0, \\ r_i(t+\Delta t) = r_i(t) + V\Delta t + D\Delta t + G\Delta t, & i = 1 \sim M,\ for\ t > 0, \end{cases} \quad (1)$$

where $r_i(t)$ is a position vector of an i-th particle at time t, V is the local wind velocity to transport the particle, D is a vector containing three Gaussian random numbers for diffusion, and G is the gravitational fallout speed approximated by Stokes Law.

For the computation of convective transport, the wind velocity $V=(u,v,w)$ is obtained from the global Grid Point Values (GPV) provided by Japan Meteorological Agency (JMA). The gridded data are first interpolated in time onto the model's time steps of every 5 minute. A cubic spline method (see Burden et al., 1981) is used to interpolate the wind data from 6 hour interval to the model's time step. Then, the wind velocity at an arbitrary spatial point is evaluated using the 3-D cubic-splines from the nearby gridded data.

The diffusion of the ash particles $D=(c_h, c_h, c_v)$ is parameterized by the random walk process, where the horizontal and vertical diffusion speeds c_h, c_v may be related to the horizontal and vertical diffusion coefficients K_h, K_v. We have repeated diffusion tests with various values of diffusion coefficients, and the resulting dispersals are compared with satellite images of actual dispersals for several volcanic eruptions in the past (Yamagata, 1993; Yamamoto 2000; 2002). With these diffusion tests, we find that the appropriate horizontal and vertical diffusion coefficients are K_h=150 and K_v=1.5 ($m^2\ s^{-1}$), respectively. Note that the values may be different for different volcanoes and for different weather conditions.

The gravitational settling is based on Stokes Law as a function of the particle size r. The fallout velocity $G=(0,0,-v_t)$ is approximated by the terminal speed v_t of plume particles below:

$$\frac{v_t}{v_o} = \frac{r_o}{r}\left[\left\{\left(\frac{r}{r_o}\right)^2 + \frac{1}{4}\right\}^{\frac{1}{2}} - \frac{1}{2}\right]^{\frac{3}{2}} \quad (2)$$

where v_0 (=1.0 m/s) is a reference velocity, and r_0 (=150 μm) is the particle size that separates the inertial range and viscosity range. In the viscosity range, the frictional force of the particle is proportional to v_t, so the terminal velocity becomes a function of r^2. Whereas, in the inertial range, the frictional force is proportional to v_t^2, so the terminal velocity becomes a function of $r^{1/2}$. In the present formulation, the terminal velocity v_t shifts smoothly from the former to the latter separated by r_0.

The actual eruption contains large fragments up to few meters in size as well as fine ash over a continuous particle size to less than 1 μm. Large particles settle out within a short time, so the particle size spectrum shifts toward the smaller particles as time proceeds. Because we are interested in the particles which can travel for several hours, we have assumed that the initial particle size distribution obeys a logarithmic Gaussian distribution centered at 100 μm with its standard deviation 1.0. Thus, about 95% of particles are supposed to have their size between 1 μm and 1 cm. In practice, the particles larger than 1 cm drop quickly within a few time steps of the simulation. The particles less than 100 μm can travel far from the source providing important information of the plume dispersion.

Sufficiently large numbers of particles are contained within the initial vertical column above the crater of the erupting volcano. During the 5 min of a time step, the particles are released constantly in time from the crater in the model. A simple buoyancy model is considered with initial upward motion w_0 and a constant damping rate λ (=1/60s). When the equilibrium plume height z_2 is given, the initial speed w_0 may be evaluated from z_2, and the vertical plume distribution z may be calculated from the following form:

$$Z = Z_2 - \frac{\omega_o}{\lambda} e^{-\lambda t} \quad (3)$$

Random numbers are generated uniformly in time t for the time step of 5 min, which produces dense plume particles near the top of the plume. The gravitational fallout and convective transport during the 5 min are calculated for a given time t superimposed on the vertical distribution to generate the plume source $S=(x,y,z)$.

In a case of a short-time explosive eruption puff, the ash particles are generated only for the initial time of the time integration. When the eruption continues for certain period of time, the model generates new particles over the same vertical column for every time step during the specified eruption period. For a steady eruption, the particle number tends to increase in the model atmosphere before the plume particles have dropped or crossed the vertical wall of the model domain. Therefore, the number of particles released at every time step is adjusted in order to draw optimal statistical information from the model products. For this reason, we set the number of the particles released for a time step as 100 in this study. Although it is possible to increase the number toward the limit of the computer capability, the time integration will then be considerably slower, which is a disadvantage for the urgent case. An excessive complication and sophistication are not recommended in the application to the real-time operational prediction.

3. Results

Figure 1 illustrates an example of the ash plume distribution simulated for a hypothetical eruption of Etna Volcano. The simulation started from 21:00 UTC, 28 July 2004, and the ash distribution is for 9 hours after the beginning of the eruption. Plume height in feet is designated by different colors. The model simulation takes about 2 min and the graphics takes about 3 min using the SUN Workstation Ultra 60. After the 5 min of the computation time, we can observe the 3-D animation of the ash plume dispersal during the first 10 hours of the volcanic eruption.

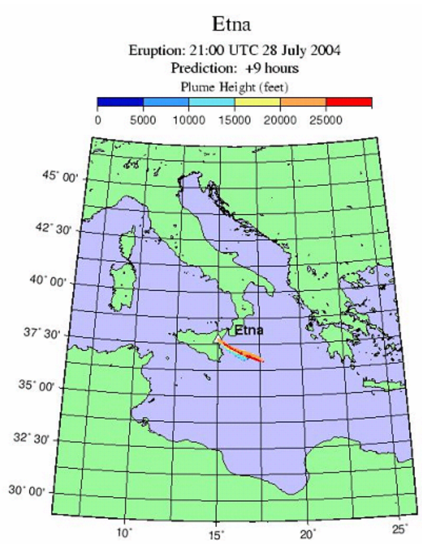


Figure 1. An example of the ash plume distribution simulated for a hypothetical eruption of Etna Volcano. The simulation started from 21:00 UTC, 28 July 2004, and the plot is for 9 hours after the eruption.

The 5 min is the critical time for the aviation safety purpose. The model simulation can be repeated many times whenever a new information, such as the accurate plume height, is reported. The model is applicable to any volcano in the world, and is routinely running for hypothetical eruptions of Sakura-jima, Usu Volcano, Miyake-jima, Mt. Asama, Mt. Fuji in Japan, Redoubt volcano, Augustine volcano in Alaska, and Etna volcano in Italy. Those PUFF model simulations may be seen at the following web site.
(http://air.geo.tsukuba.ac.jp/puff/index.html)

4. Concluding Summary

Volcanic ash cloud floating and traveling in the air is a dangerous object for commercial and non-commercial aircrafts. In order to avoid encounters with ash cloud, a real-time volcanic plume prediction model, called PUFF, has been developed in 1991 and reported by Tanaka (1994) and Searcy et al. (1998) for Alaska volcanoes. The performance of the ash tracking accuracy has been checked whenever actual eruptions occur in the world. The demonstration to real eruptions of Usu volcano and Miyake-jima are reported to assess the performance of the model for tracking the airborne ash clouds for the aviation safety purpose (Tanaka and Yamamoto, 2002). The PUFF model has been updated, and the latest version as described in this report is installed at the flight operation system in the Japan Airlines.

Since the establishment of ICAO's VAACs, volcanic plume tracking becomes operational in the world, providing useful information to aviation industry. Along with the VAACs, we need further to improve the accuracy of the PUFF model by accumulating experience in the flight operations and by establishing timely notification system to pilots with much user-friendly graphic interface.

Acknowledgments

The authors are grateful to the support rendered by Drs. S. Akasofu, K. Dean, J. Dehn of the University of Alaska. Thanks are extended to Mr. S. Shimoda and Ms. S. Yamagata of JWA for their technical support. The authors appreciate Ms. K. Honda for her technical assistance. This research was supported by the IARC/NASDA research project: Modeling the dynamics of volcanic eruption cloud, and by Asahi Breweries Foundation.

References

Akasofu, S.-I. and H. L. Tanaka, Urgent issue of developing volcanic ash tracking model, *Kagaku Asahi*, **5**, 121-124 (in Japanese), 1993.

Armienti, P. and G. Macedonio, A numerical model for simulation of tephra transport and deposition: Application to May 18, 1980, Mount St. Helens eruption, *J. Geophys. Res.*, **93**, 6463-6476, 1988.

Burden, R. L., J. D. Faires, and A. C. Reynolds, *Numerical analysis*, Prindle, Weber and Schmidt, 598 pp, 1981.

Casadevall, T. L., The 1989-1990 eruption of Redoubt volcano, Alaska: Impacts on aircraft operations, *J. Volcanol. Geotherm. Res.*, **62**, 301-316, 1994.

Chatfield, C., *The analysis of time series: An introduction*, Chapman and Hall, 286 pp, 1975.

Dean, K. G., S. I. Akasofu, and H. L. Tanaka, Volcanic hazards and aviation safety: Developing techniques in Alaska, *FAA Aviation Safety Journal*, Vol. 3, No. 1, 11-15, 1993.

Endoh, K., M. Ohno, M. Kunikita, M. Morohoshi, M. Suzuki, Y. Nishimura, D. Nagai, T. Chiba, and I. Tohno, Pheatomagmatic explosions of the 2000 eruption of Usu volcano, *Natural Science Reports, Nihon University*, **36**, 65-73 (in Japanese), 2001.

Glaze, L. S. and S. Self, Ashfall dispersal for the 16 September 1986, eruption of Lascar, Chile, calculated by a turbulent diffusion model, *Geophys. Res. Let.*, **18**, 1237-1240, 1991.

Heffter, J. L. and B. J. B. Stunder, Volcanic ash forecast transport and dispersion (VAFTAD) model, *Computer Techniques*, **8**, 533-541, 1993.

Hobbs, P. V., L. F. Radke, J. H. Lyons, R. J. Ferek, D. J. Coffman, and T. J. Casadevall, Airborne measurements of particle and gas emissions from the 1990 volcanic eruption of Mount Redoubt, *J. Geophys. Res.*, **96**, 18735-18752, 1991.

Hurst, A. W. and R. Turner, Performance of the program ASHFALL for forecasting ashfall during the 1995 and 1996 eruptions of Ruapehu volcano, New Zealand, *J. Geol. and Geophys.*, **42**, 615-622, 1999.

Kienle, J., A. W. Woods, S. A. Estes, K. Ahlnaes, K. G. Dean, and H. L. Tanaka, Satellite and slow-scan television observations of the rise and dispersion of ash-rich eruption clouds from Redoubt volcano, Alaska, *EOS*, Vol. 72, 2, 748-750, 1991.

Onodera, S., Volcanic activity and flight operations, *Aviation Meteorological Notes*, **45**, 13-30, 1997.

Searcy, C., K. Dean, and B. Stringer, PUFF: A volcanic ash tracking and prediction model, *J. Volc. and Geophys. Res.*, **80**, 1-16, 1998.

Suck, S. H., E. C. Upchurch, and J. R. Brock, Dust transport in Maricopa county, Arizona, *Atmos. Environ.*, **12**, 2265-2271, 1978.

Tanaka, H. L., Development of a prediction scheme for the volcanic ash fall from Redoubt volcano, First Int'l. Symp. on Volcanic Ash and Aviation Safety, Seattle, Washington., U.S. Geological Survey Circular 1065: 58, 1991.

Tanaka, H. L., K. G. Dean, and S. I. Akasofu, Predicting the movement of volcanic ash clouds, *EOS*, Vol. 74, No .20, 231-231, 1993.

Tanaka, H. L., Development of a prediction scheme for volcanic ash fall from Redoubt volcano, Alaska, Proc. First International Symposium on Volcanic Ash and Aviation Safety. U.S. Geological Survey, Bulletin 2047, 283-291, 1994.

Tanaka, H.L., and K. Yamamoto, Numerical Simulations of volcanic plume dispersal from Usu volcano in Japan on 31 March 2000. *Earth, Planets and Space,* **54**, 743-752, 2002.

Tokyo Aviation Weather Service Center, Volcanic ash advisory service, Japan Meteorological Agency, *Geophys. Maga. Ser. 2*, Vol. 4, No. 1-4, 2001.

Turner, R. and T. Hurst, Factors influencing volcanic ash dispersal from the 1995 and 1996 eruptions of Mount Ruapehu, New Zealand, *J. Appl. Meteor.*, **40**, 56-69, 2001.

Yamagata, S., *Development of volcanic plume prediction scheme for aviation safety,* Graduation Thesis, Natural Science, University of Tsukuba, 136 pp, 1993.

Yamamoto. K., *Numerical experiment of the volcanic ash cloud dispersion and the justification by satellite image,* Graduation Thesis, Natural Science, University of Tsukuba, 87 pp, 2000.

Yamamoto, K., *Numerical experiments and the assessment for the probability of the volcanic ash dispersal*, Master thesis, Graduate School of Life and Environmental Sciences, University of Tsukuba, 70 pp, 2002.

DETECTING ASH CLOUDS IN TROPICAL ATMOSPHERES

I.M. Watson, W.I. Rose, G.J.S. Bluth.
Dept. of Geological Mining Engineering and Sciences, Michigan
Technological University, Houghton, MI, 49931, USA

Abstract

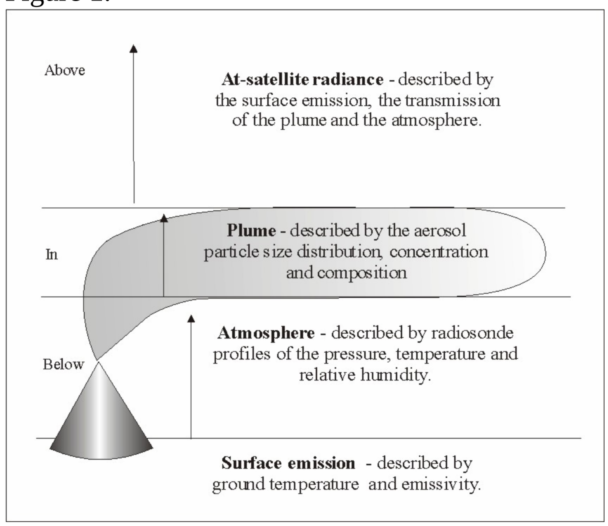
Current mapping and retrieval algorithms applied to volcanic ash are susceptible to interference from atmospheric water vapor. Whilst this interference is well documented and understood in an operational context, quantification of the effect has remained elusive. A forward model has been developed that calculates the effects water vapor has on the 'split-window' ash signal using a combination of a Mie-scattering code embedded in a MODTRAN-based atmosphere (Watson et al., in prep). Initial results from the model suggest a brightness temperature difference 'cost' of 1-3 degrees K when considering an ash cloud from a Northern latitude in a tropical atmosphere.

There is a strong dependence of the effect of water vapor on the optical depth of the cloud: thicker, higher clouds, transmitting less of the contribution of radiance from the underlying surface are less strongly affected than thinner, lower clouds where the surface contribution is more significant. This discovery has important ramifications in terms of ash cloud detection and tracking. (1) Initial stages of eruptive activity are relatively independent of atmospheric conditions, and (2) ash clouds in tropical atmospheres will become less detectable much more quickly as the water vapor signal swamps the negative brightness temperature difference signal.

Theory

A forward model has been developed (Watson et al., in prep.) that embeds a Mie-scattering aerosol model within a MODTRAN atmosphere. The model facilitates investigation of the sensitivity to key parameters that are typically either assumed or acquired from data external to the satellite image. These parameters can include (1) the volcanic ash's chemical composition and particle size distribution (defined by its effective radius, variance and total number of particles) (2) the atmosphere's temperature, pressure and relative humidity profile as a function of height (3) the ash clouds height and depth and (4) the underlying surface's temperature and emissivity (figure 1).

Figure 1.



Radiative transfer is treated by the model in three stages; (1) the ground-leaving radiance (defined by the ground temperature and emissivity) is passed through the atmosphere to the base of the plume. The atmospheric contribution to the upwelling radiance is added to yield the radiance at the cloud base; (2) this radiance is transmitted through the cloud, using both the transmission of the atmosphere (MODTRAN-derived) and the plume (Mie model derived) and again atmospheric upwelling radiance is added to yield the cloud-top radiance; (3) finally, the cloud top radiance is the then transmitted through the portion of the vertical path above the plume and again path-added upwelling radiance from the atmosphere added to yield the at-satellite radiance. This model was tested against a single layer MODTRAN model (without the presence of volcanic aerosol in the 'in' layer) in order to validate the three-layer assumption.

Methodology

The model can be used to determine the effects of water vapor on current detection (Prata 1989 a and b) and retrieval algorithms (Wen and Rose, 1994; Rose et al., 1995, 2000, 2001 and 2003; Yu and Rose 2003) and validate previous atmospheric correction attempts (Yu et al., 2002).

Figure 2.

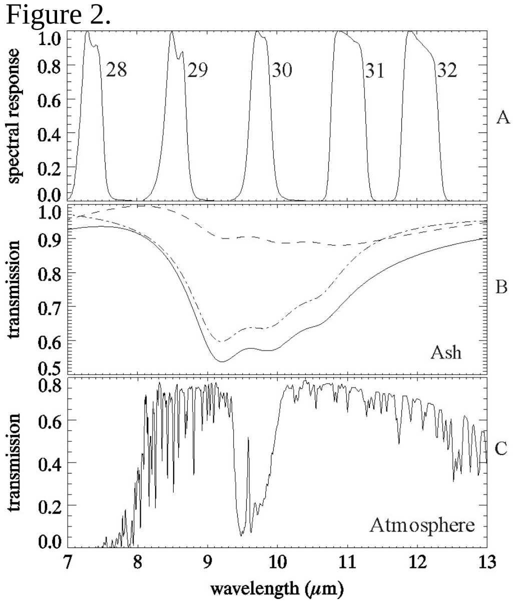


Figure 2. (after Watson et al., 2004) (A) the spectral response functions of the MODIS instrument (B signature of andesitic ash and (C) an example atmospheric transmission spectrum

The forward model is operated through a graphical user interface, allowing the user to input the ash, cloud and atmospheric data into the model. The model then calculates the at-satellite radiance for the given parameters. Separate transmission spectra for just andesitic ash and a clear atmosphere can be seen in figure 2.

The split window algorithm calculates the brightness temperature difference channels 31 and 32 of the Moderate Resolution Imaging Spectroradiometer (MODIS), which are analogous to channels 4 and 5 of the Advanced Very High Resolution Radiometer (AVHRR) and the Geostationary Operational Environmental Satellite (GOES). It can be seen from figure 2 that between 11 and 12 μm the slopes of the two transmission spectra are in opposition. Therein lies the answer to how the split window algorithm is affected by water vapor; if the two spectra are convolved (multiplied together) the ash's spectral signature, what we are using to detect the presence of ash, is washed out by water vapor. The more water vapor is added the more the ash signal is hidden.

Example results were derived using a Northern latitude and tropical atmosphere for comparison. At-satellite radiances were derived for both cold, dry and warm, wet atmospheres. In both cases 2.0 μm andesite ash particles in a lognormal distribution (with a variance of 0.74) were used to represent loading of the atmosphere at a height of 10 km and a cloud thickness of 1 km. Preliminary results are shown below.

Results

All other things being equal (including ground temperature and emissivity) the presence of water vapor reduces the positive slope of the at-satellite radiance spectrum. This effect can be more strongly seen if the radiance value is converted to brightness temperature using the Planck function (figure 3.). Here, the wavelength range is reduced to highlight the area between 10 and 13 μm that the split window retrieval uses to locate ash – the brightness temperature difference (BTD) algorithm (Prata et al., 1989 a and b; Wen and Rose, 1994). In this example the change in BTD is about 1.8 K. This has a significant effect on the detectability of volcanic ash as much of the fringes of typical volcanic ash clouds have BTD values of this order or less.

Figure 3.

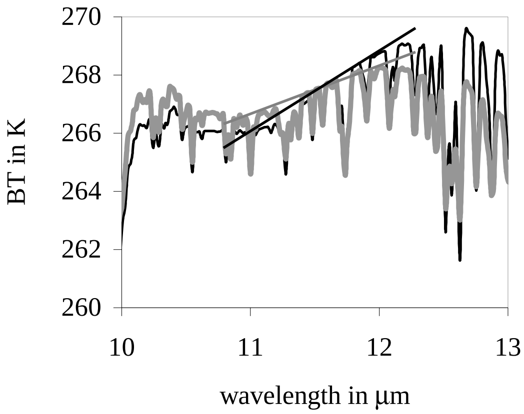


Figure 3. Brightness temperature (BT) spectra for 2.0 µm andesitic ash in a wet (grey line) and dry (black line) atmosphere. Note again the change in gradient between 11 and 12 µm for the two examples, as indicated by the straight lines.

It is possible to show how significant a ~ 2K effect on the detection of volcanic ash by taking a known northern latitude eruption and ‘moving it’ to the tropics (figure 4). Such an example has been calculated for the September 1992 Mt. Spurr eruption (Watson et al., in prep). Figure 4 shows the Spurr eruption cloud captured by AVHRR at 1700 UT on 17th September 1992 (see Schneider et al., 1995 for more details) in (a) an atmosphere that represents, as accurately as possible, the Aleutian atmosphere into which the cloud was injected and (b) a tropical atmosphere above Guadeloupe that causes a 2K suppression of the brightness temperature difference signal. What is immediately apparent is that the are of the detectable part of the cloud is dramatically reduced (by the order of 50 %). A 2 K cost is by no means extreme (3.5 K has been observed in some model runs) and, can clearly be seen to remove significant fringes from the cloud when using zero as a BTD cut off.

Figure 4.

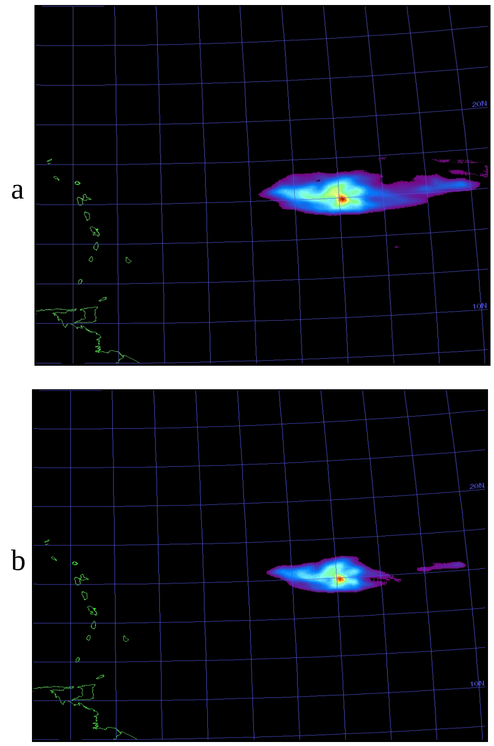


Figure 4. Example ash map indicating the change in area for the September 1992 Mt. Spurr eruption cloud (above the Caribbean volcanic arc) with enough water vapor in the atmosphere to change the BTD by (a) 0 and (b) -2 K respectively.

Preliminary conclusions

Forward modeling can be used to quantitatively determine the effects of different water vapor concentrations on the ‘split-window’ signal. Water vapor more strongly affects clouds that are optically thinner as relative proportions of signal from the underlying ground (and water vapor) increase. Lower (optically thick) clouds with larger particles (per constant volume) will be more strongly affected than higher clouds with smaller particles. Clouds with larger particles (of equivalent mass/volume) will be more strongly affected than clouds with smaller particles. Thus, water vapor effects are a complex function of water vapor content, cloud height, cloud opacity and particle size and *must* be treated as such. The 'cost' in BTD varies from -0.8 (atypical) to 3.5 K and usually ranges from +1 to +3 K in clouds of optical depth 0.2 to 0.9. Cloud areas and tonnages can be reduced to 10% or less of their high latitude analogues (Watson et al., in prep).

References

Prata, A.J., Infrared radiative transfer calculations for volcanic ash clouds, *1989a Geophysical Research Letters, Vol. 16, pp. 1293-1296*

Prata, A.J., Observations of volcanic ash clouds in the 10-12 m window using AVHRR/2 data, *1989b, International Journal of Remote Sensing, Vol. 10, pp. 751-761*

Rose, W I, D. J. Delene, D. J. Schneider, G. J. S. Bluth, A. J. Krueger, I. Sprod, C. McKee, H. L. Davies and G. G. J. Ernst, 1995, Ice in the 1994 Rabaul eruption cloud: implications for volcano hazard and atmospheric effects, *Nature, 375: 477-479.*

Rose, W I, G J S Bluth and G G J Ernst, 2000, Integrating retrievals of volcanic cloud characteristics from satellite remote sensors--a summary, *Philosophical Transactions of Royal Society, Series A, vol. 358 no 1770, pp. 1585-1606.*

Rose, W I, G J S Bluth, D J Schneider, G G J Ernst, C M Riley and R G McGimsey 2001, Observations of 1992 Crater Peak/Spurr Volcanic Clouds in their first few days of atmospheric residence, *Journal of Geology, 109: 677-694.*

Rose, W I, Y Gu, I M Watson, T Yu, GJS Bluth, A J Prata, A J Krueger, N Krotkov, S Carn, M D Fromm, D E Hunton, G G J Ernst, A A Viggiano, T M Miller, J O Ballentin, J M Reeves, J C Wilson, B E Anderson D Flittner, 2003, The February-March 2000 eruption of Hekla, Iceland from a satellite perspective, *AGU Geophysical Monograph 139: Volcanism and the Earth's Atmosphere, ed by A Robock and C Oppenheimer, pp. 107-132. ISBN 0-87590-998-1*

Schneider, D. J., W. I. Rose and L. Kelley, 1995, Tracking of 1992 eruption clouds from Crater Peak/Spurr Volcano using AVHRR, *U. S. Geol. Surv. Bull. 2139 (Spurr Eruption, edited by T. Keith), 27-36.*

Watson, I.M., Realmuto, V.J., Rose.,W.I., Bluth G.J.S., Forward modeling of volcanic cloud transmissions through different atmospheres, *in preparation for Journal of Geophysical Research – Atmospheres*

Watson, I.M., Realmuto, V.J., Rose, W.I., Prata, A.J., Bluth, G.J.S., Gu, Y., C. E. Bader, Yu, T., 2004 Thermal infrared remote sensing of volcanic emissions using the Moderate Resolution Imaging Spectroradiometer (MODIS), *Journal of Volcanology and Geothermal Research, Vol. 135, pp. 75-89*

Wen, S and W I Rose, 1994, Retrieval of Particle sizes and masses in volcanic clouds using AVHRR bands 4 and 5, *Journal of Geophysical Research, 99:5421- 5431.*

Yu, T W I Rose and A J Prata, 2002, Atmospheric correction for satellite-based volcanic ash mapping and retrievals using "split window" IR data from GOES and AVHRR, *Journal of Geophysical Research, 106: No D16, 10.1029.*

Yu, T and W I Rose, 2000, Retrieval of sulfate and silicate ash masses in young (1-4 days old) eruption clouds using multiband infrared HIRS/2 data, *AGU Monograph 116 --Remote Sensing of Active Volcanism, ed by P Mouginis-Mark, J Crisp and J Fink, pp. 87-100.*

ERUPTION CLOUD ECHO MEASURED WITH C-BAND WEATHER RADAR

Yoshihiro Sawada
Faculty of Science, Hokkaido University, Sapporo, Japan

Abstract
Careful inspections of radar echo-data in Japan showed that eruption clouds by fairly smaller sized eruptions can be registered with C-band weather radars. Aggregation of fine ash particles and water-coated ash particles inside eruption clouds are considered as the reason of detection.

Introduction
C-band weather radars are commonly operated for weather observation in many countries having active volcanoes, and eruption clouds by strong volcanic eruptions have been registered as radar echoes. However, almost no observation is reported for smaller eruption cloud. Radar data of C-band weather radars in Japan were inspected and several echoes were obtained (Sawada, 2003b). The reason of detection is considered.

Report of Eruption Cloud with Weather Radar
According to the database of Smithsonian Institution during a period since 1970 through 2003, observations of eruption clouds as echoes with weather radars are reported. In addition to the data, the author inspected and gathered radar data in Japan obtained with weather radars of Japan Meteorological Agency (JMA). Results in papers are inspected, too. The volcanoes of which eruption clouds were detected as radar echoes counted 13 with 23 eruptions as shown in Table 1.
Wavelength of C-band radar (wavelength of 5 cm) is basically too long to detect fine ash particle (mm-μm in size) of eruption cloud. In general, it is considered that major portion of eruption cloud composed with accumulated large sized particles, high distribution-density of particles and high content of water/ ice particles can be detected as echoes. Actually, the big eruption columns such as 1980 Mount St. Helens, 1991 Pinatubo and 1992 Spurr were well detected, and major extents & top altitudes were well monitored with time (Smithsonian Institution Web site, Harris et al.,1981 and Oswald et al.,1996). Doppler radar system can measure movements of ash/ water particles, and is very effective to monitor small eruption clouds. Small & not so dense ash plumes lower than 5 km in heights from Popocatepetl, Mexico were well detected (Table 1).

Observation Result in Japan
ECE (Eruption Cloud Echo) by Large-Sized Eruption
JMA operates 29 C-band weather radars in Japan; 20 stations with wavelength of 5.7cm, power of 250 - 300 kW & detection range of 300 km, and 9 airport stations with power of 200 kW & detection range of 100 km.
Eruption clouds higher than 9 km by four strong eruptions of 1973 Tyatya, 1977 Usu, 1986 Izu-Oshima and 2000 Miyake-jima were obtained as clear ECEs by the radars (Table 1).
<u>1973 July 14 Tyatya Eruption</u>
ECEs were observed with Kushiro radar (ca. 220 km SW of the volcano). Eruptions simultaneously occurred from two craters (Abdurakmanov et al., 1999) and the double ECEs were clearly monitored (Photo 1, Japan Meteorological Agency, 1974)).
<u>1977 August 7, 8 & 9 Usu Eruption</u>
ECEs were observed with radars of Sapporo (ca. 70 km NE of the volcano) and Hakodate (ca. 80 km SSW). Analysis of PPI (Plan-Position Indicator) and RHI

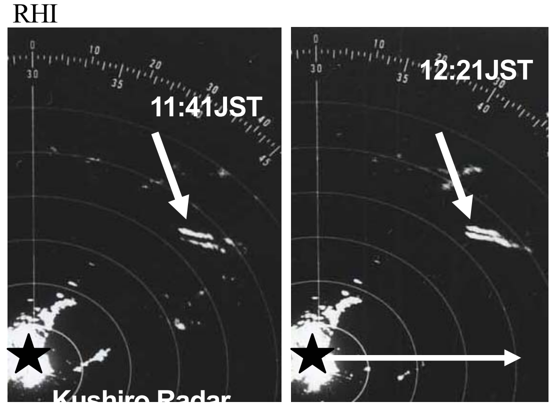


Photo 1 Double eruption cloud echoes (white arrows) of July 14, 1973 Tyatya Eruption tracked with Kushiro weather radar (Japan Meteorological Agency, 1974)

Table 1. List of volcanoes of which eruption clouds were detected with radars during 1970 - 2003
*: Visual Measurement; ** : Doppler Radar; *** : X-band Radar

Observation Date	Volcano	Max. Height of Eruption Cloud
1970 May 5	Hekla, Iceland	15 (1) km
1973 July 14, 17, 18	Tyatya (Kunashir)	9 (2)
1976 Jan. 23	Augustine, Alaska	14 (1)
1977 Aug. 7, 8, 9	Usu, Hokkaido	9.7 (3)
1980 May 8, June, July	Mt St. Helens (Washington)	>25 (4)
1981 Apr. 9	Hekla (Iceland)	6.6 (1)
1981 May 15	Pagan (Mariana Islands)	18 - 20 (1)
1984 July 7	Sakura-jima (Kyushu)	2.1* (5)
1986 Nov. 21	Izu-Oshima (Izu Islands)	10 - 12 (6)
1991 Jan. 17	Hekla (Iceland)	11.5 (1)
1991 June 12, July 27, Aug. 5 - 11	Pinatubo (Philippines)	16.5 (1)(7)
1991 June 3, 8, 12	Unzen (Kyushu)	6.5 (8)(9)
1992 June 27, Aug. 18 - 21, Sep. 17	Spurr (Alaska)	18 (1)
1992 Aug. 20, 21, Sep.	Pinatubo (Philippines)	9 (1)
1992 Feb. 5	Unzen (Kyushu)	Not obs.* (8)
1993 May 21	Unzen*** (Kyushu)	4* (10)
1996 July 16	Sakura-jima** (Kyushu)	0.6* (11)
1996 Dec. 14	Sakura-jima (Kyushu)	Not obs.* (12)
1998 Feb. 11, Sep. 8, 22, Oct. 17	Popocatepetl** (Mexico)	4* (1)
1999 Mar. 11, 18, Apr. 4, 11	Popocatepetl** (Mexico)	Not obs.* (1)
2000 Feb. 26 – 27	Hekla (Iceland)	12* (13)
2000 Mar. 31	Usu (Hokkaido)	3.5* (14)
2000 Aug. 10, 18, 29	Miyake-jima (Izu Isls.)	16 - 17* (15)

(1) Smithsonian Institution, (2) JMA (1974), (3) JMA (1980), (4) Harris et al. (1981), (5) Uehara et al. (1985), (6) Seis. & Volc. Dep. (1987), Takano (1987), (7) Oswalt et al. (1996), (8) Niina (1992), Fukuoka DMO (1996), (9) Tanegashima WS (1992), (10) Arao et al. (1996), (11) Fukui et al. (1997), (12) Tanegashima WS (1998), (13) Lacasse et al. (2004), (14) by the courtesy of Sapporo DMO, Sawada (2003b), (15) by the courtesy of Tokyo DMO, Sawada (2003b) Where, JMA: Japan Meteorological Agency, Seis. & Volc. Dep.: Seismological and Volcanological Department, DMO: District Meteorological Observatory and WS: Weather Station.

(Range Height Indicator) data showed horizontal moving velocities and approximate vertical profiles of eruption columns, respectively (Japan Meteorological Agency, 1980).

1986 November 21 Izu-Oshima Eruption

ECEs were observed with 4 radars; Fuji (wavelength of 10.4 cm & detection range of 500 km, ca. 100 km NW of the volcano, operated by 1999), Tokyo (ca. 110 km NNE), Haneda airport (ca. 100 km NNE) (Seismological and Volcanological Department, 1987) and Nagoya (ca. 220 km WNW) (Takano, 1987). Extent of the ECE v.s. that with satellite image was under the ratio of one : several tens (Sawada, 2003a).

2000 August 18 Miyake-jima Eruption

ECEs were tracked with Shizuoka radar (ca. 145 km NW of this volcano) (by the courtesy of Tokyo District Meteorological Observatory, Sawada、 2003b).

ECE by Small-Sized Eruption

7 ECEs by small eruptions with cloud-top lower than 4 km were detected in Japan (Table 1), while 2 ECEs of 1993 Unzen & 1996 July Sakura-jima are with X-band and Doppler radars, respectively.

Sakura-jima (South of Kyushu)

Kagoshima airport radar (ca. 25km NNE of the volcano) detected ECE on July 7, 1984 as shown in Fig. 1 (Uehara et al., 1985). Its cloud top was 2.1km and extent of ECE was about 3 km x 3km over the crater.

Weak & small ECEs were obtained on December 14, 1996 with Tanegashima radar (ca. 102 km SSE of the

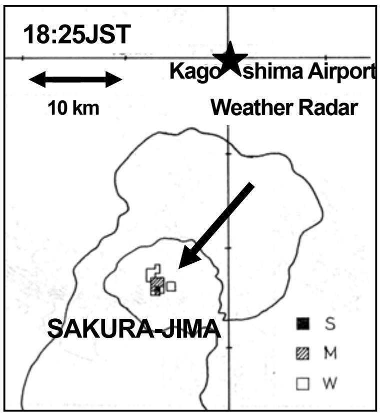


Fig. 1 Eruption cloud echo (solid arrow) of Sakura-jima eruption on July 7, 1984 obtained with Kagoshima airport weather radar (Uehara et al., 1985 (modified))

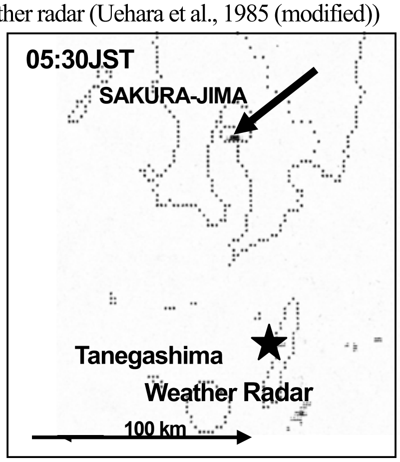


Fig. 2. Eruption cloud echo (solid arrow) of Sakura-jima eruption on December 14, 1996 with Tanegashima radar (Tanegashima Weather Station, 1998 (modified))

volcano) (Fig. 2). The eruption occurred before dawn, and its cloud-top was not observed due to darkness. However, the size of eruption was at ordinary level (Tanegashima Weather Station, 1998).

Unzen (SW of Kyushu)

ECEs accompanied by pyroclastic flows on June 3 & 8, 1991 and by eruptions with lapilli-ejections on June 12 were obtained with Fukuoka radar (about 80 km N of the volcano). ECEs in February, 1992 were very weak ones. (Niina, 1992, Fukuoka District Meteorological Observatory, 1996). The ECEs on June 8 were also registered with Tanegashima weather radar (ca. 235 km SSE) of the volcano (Tanegashima Weather Station, 1992). The ECEs on June 3 drifted eastward and could be tracked across the Ariake Inland Sea reaching over Kumamoto City, ca. 36km ENE of the volcano (Fig. 3).

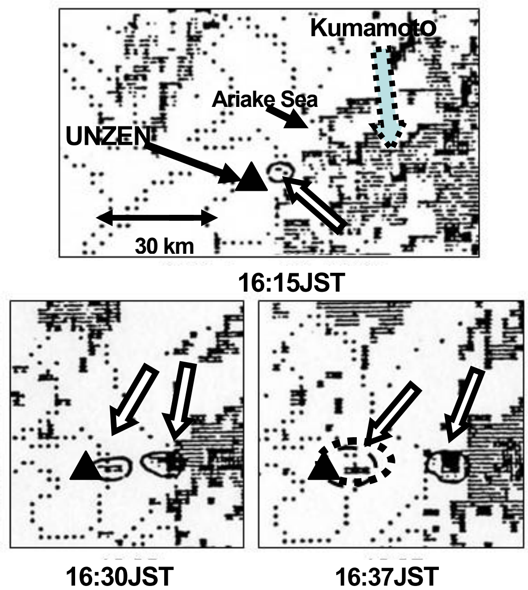


Fig. 3. Eruption cloud echoes of pyroclastic flows (white arrows) at Unzen on June 3, 1991 tracked with Fukuoka weather radar (Niina, 1992, Fukuoka District Meteorological Observatory, 1996 (modified))

Usu (SW of Hokkaido)

Phreatomagmatic eruptions occurred with 3.5 km high eruption clouds on March 31, 2000. Only possible small echoes (one-two pixels) moving eastward were detected twice on the day with Hakodate weather radar (ca. 70 km S of the volcano) (by the courtesy of Sapporo District Meteorological Observatory, Sawada, 2003b).

Discussion

Why can C-band weather radar observe ECEs of small volcanic eruptions ?

Cloud top of June 8, 1991 Unzen ECE with RHI was 6.5 km and radar reflection from the upper ECE was weaker than that from the lower (Niina, 1992). He considered that weaker reflection was due to fall out of ash particles from the upper cloud, while those fallen particles accumulated at the lower ECE causes stronger radar reflections.

Arao et al. (1996) observed about 4 km tall ash clouds accompanied by pyroclastic flows with X-band radar (wavelength of 3.2 cm) at Unzen on May 21 1993. The radar reflection from the upper ECE was stronger than that from the lower. They discussed that ash particles in the upper cloud were aggregated and were coated with water due to cooling of water-vapor under high humidity in eruption cloud & upper surrounding air. At the lower cloud, fallen ash particles dispersed due to low humidity conditions in and outside the ECE. They showed that radar reflections from water-coated particles increase compared with those from dry particles.

ECEs of February, 2000 Hekla Eruption were very well and for long time tracked with C-band radar, and the effects with high contents of water or ice particles are discussed for the reason (Lacasse et al., 2004).

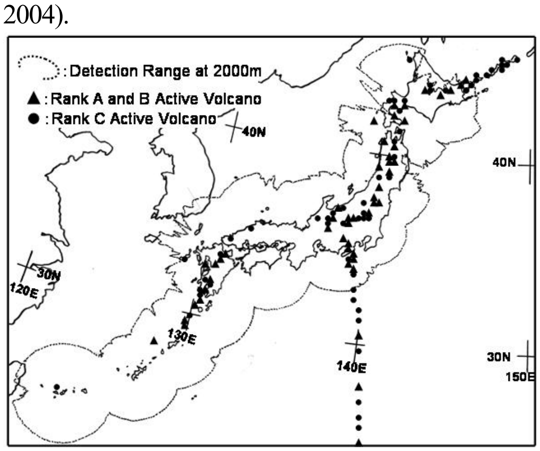


Fig. 4. Overlay of the detection range at 2000m of JMA's weather radar network and active volcanoes in Japan. (after instruction data of Japan Meteorological Agency)

Small and possibly thin ECEs of ash clouds by pyroclastic flows at Unzen on June 3, 1991 could be tracked at east-side around Kumamoto city , about 34 km from the volcano (Fig. 3). There were rain clouds in the area, and high humidity may cause water-coatings & aggregation of fine ash particles in the small ECEs.

In addition to water vapor content in eruption clouds, high water contents due to phreatomagmatic eruptions, existence of underground water, and high humidity conditions of surrounding air may accelerate to generate water-coated ash particles and to aggregate ash particles in eruption clouds. These eruption clouds will be detected and tracked with C-band weather radars.

Conclusion

Not only ECEs by large-sized eruptions, but also by small volcanic eruptions could be detected by C-band weather radars. It is considered that water coatings and aggregations of ash particles enabled to be detected as ECEs. However, it is hard to discriminate ECEs from rain clouds.

The detection range of JMA's radar network can cover most of active volcanoes in Japan (Fig. 4). Recently, airport weather radars are being reinstalled as doppler type systems. By the network, it is expected to observe ECEs by not only radars near volcanoes but also those far from eruption sites. Detection capability of ECEs by the network is up to the strength of eruption, weather condition and topographical condition between radar sites and volcanoes, but further high detection rate is expected with the combinations of weather radars. It will be possible to detect ECEs of eruption clouds higher than 5 km except insular volcanoes in the ocean with JMA's C-band weather radar network under good conditions.

Acknowledgement

The author gratefully acknowledges to the personnel at radar observatories of Japan Meteorological Agency for providing of the radar data for this research work.

References

Abdurakmanov, A. I. and Steinberg, G. S. (1999): Tyatya volcano – Morphology and geological structure of the volcano. Institute of Volcanology and Geodynamics Russian Academy of Natural Science, 1-20

Arao, K., Iwasaki, H., Fukui, K., Hayakawa, Y. and Takeda, T. (1996): A case study of structure and evolution of the ash cloud derived from Unzen pyroclastic flow using radar data. Bulletin of Volcanological Society of Japan, v. 41, 149-158 (in Japanese with English abstract and captions)

Fukuoka District Meteorological Observatory (1996): Pyroclastic flow on June 8, 1991 of Unzen observed with weather radar. Memoirs of Fukuoka Meteorological Observatory, v. 51, 71-75 (in Japanese)

Fukui, K., Mori, T. and Churei, M. (1997): Observation of volcanic plume from Sakura-jima with doppler radar. Abstract of Session of Meteorological Society of Japan, v. 71, 226 (in Japanese)

Harris, D. M., Rose W. I. Jr., Roe R. and Thompson M. R. (1981): Radar observations of ash eruptions at Mount St. Helens volcano, Washington. The 1980 Eruptions of Mount St. Helens, Washington: U. S. Geological Survey Professional Paper, v. 1250, 323-333

Japan Meteorological Agency (1974): Volcanic activities after the 1973 June 17 Earthquake off Nemuro Peninsula. Technical Report of Japan Meteorological Agency, v. 87, 3, 17-18 & 101-102 (in Japanese)

Japan Meteorological Agency (1980): The 1977 August – 1978 December Eruption of Usu. Technical Report of Japan Meteorological Agency, v. 99, 7-14 & 193 (in Japanese)

Lacasse, C., Karlsdottir, S., Larsen, G., Soosalu, H., Rose, W. I., and Ernst, G. G. J. (2004): Weather radar observations of the Hekla 2000 eruption cloud, Iceland. Bulletin of Volcanology, v. 66, 457 – 473

Niina, Y. (1992): Radar echoes obtained by Fukuoka weather radar, of eruption clouds with pyroclastic flows at Fugen-dake, Unzen. Radar-Kansoku-Gijutsu-Shiryou of Japan Meteorological Agency, v. 41, 41-52 (in Japanese)

Oswalt, J. S., Nichols W. and O'hara J. F. (1996): Meteorological observations of the 1991 Mount Pinatubo Eruption. Fire and Mud: Newhall, C. G. and Punongbayang R. S. edt., Philippine Institute of Volcanology and Seismology and University of Washington Press, 625-636

Sawada, Y. (2003a): Study on observation and analysis of eruption cloud with imagery of Geostationary Meteorological Satellite (HIMAWARI). Journal of Meteorological Research of Japan Meteorological Agency, v. 55, 57-152 (in Japanese with English abstract and captions)

Sawada, Y. (2003b): Eruption cloud echo observed with JMA's C-band weather radar. Sokko-jihou of Japan Meteorological Agency, v. 70, 119-169 (in Japanese)

Seismological and Volcanological Department (1987): The 1986 Eruption of Izu-Oshima. Special Report Series of Natural Disasters of Japan Meteorological Agency, v. 1 in 1987, 90-91 & 148-152 (in Japanese)

Smithsonian Institution Website: http://www. volcano. si.edu (accessed 2004-07-17)

Takano, S. (1987): Recent Radar Observations (84)－Echoes by the Izu-Oshima Eruption Clouds. Geophysical Notes of Tokyo District Meteorological Observatory, v. 88, 1 (in Japanese)

Tanegashima Weather Station (1992): Echoes by the large pyroclastic flows of Fugen-dake, Unzen (1991 June 8). Radar-Gijutu-Uchiawasekai- Shiryou of Japan Meteorological Agency in 1991, 74 & 77 (in Japanese)

Tanegashima Weather Station (1998): Radar echoes possibly by eruptions of Sakura-jima. Radar-Gijutsu-Uchiawasekai-Shiryou of Japan Meteorological Agency in 1997, 27-28 (in Japanese)

Uehara, M., Taira, T. and Fukunaga, S. (1985): Weather radar system at Kagoshima airport station. Radar-Kansoku-Gijutsu-Shiryou of Japan Meteorological Agency, v. 34, 28-32 (in Japanese)

THE INTERNATIONAL AIRWAYS VOLCANO WATCH (IAVW)

Raul Romero
International Civil Aviation Organization, Montreal, Canada

1. INTRODUCTION

The definition of the IAVW is included in ICAO Annex 3 — *Meteorological Service for International Air Navigation* to the Convention on International Civil Aviation and reads as follows:

International airways volcano watch (IAVW). International arrangements for monitoring and providing warnings to aircraft of volcanic ash in the atmosphere.

[Note: The IAVW is based on the cooperation of aviation and non-aviation operational units using information derived from observing sources and networks that are provided by States. The watch is coordinated by ICAO with the cooperation of other concerned international organizations.]

2. HISTORICAL BACKGROUND

The IAVW was first established in 1987 with an amendment to Annex 3, which introduced a requirement for the international dissemination of information on volcanic ash to aircraft. This information was included in SIGMETs and NOTAMs. This amendment was developed with the assistance of the former Volcanic Ash Warnings Study Group (VAWSG), which had been created in 1982. For the initial detection and notification of a volcanic eruption and/or volcanic ash cloud, ICAO sought and received the cooperation of a number of other international organizations that administer vulcanological observatories, aircraft reports and satellite data. The responsibility for the issuance of SIGMETs and NOTAMs lay with the meteorological watch offices (MWOs) and aeronautical control centres (ACCs) through their NOTAM Offices (NOFs), respectively, both of which are designated by States to provide service for a flight information region (FIR).

It was clear from the outset that many MWOs, not having necessary tools, would have difficulty in providing accurate forecasts of volcanic ash extent and trajectory for the SIGMET and particularly for the required twelve hours, i.e. six to eight hours beyond the usual period of validity of SIGMETs. Steps were taken by ICAO, therefore, to designate, on advice from WMO, centres having the capability to provide advisory information on volcanic ash to the MOWs. At the conjoint ICAO/WMO Communications/Meteorology/Operations (COM/MET/OPS) Divisional Meeting (1990), it was agreed that information on forecast trajectory covering 12 hours beyond the validity period of a SIGMET should be included in an "outlook". Information to assist MWOs in preparing SIGMETs for volcanic ash, and especially the "outlook", was to be provided by designated meteorological centres, which henceforth were known as volcanic ash advisory centres (VAACs). The designation of VAACs was accomplished one by one, as Provider States concerned agreed to accept the responsibility. The designations are reflected in the relevant ICAO regional air navigation plans. Due to the fact that the development of the IAVW involved coordination with other international organizations not hitherto linked to civil aviation, the operational procedures were largely based upon experience, and were tested as guidance material first before being included as formal ICAO Annex provisions.

Recent developments of the IAVW include the introduction of a new format for volcanic ash advisories and templates for SIGMETs for volcanic ash for data link purposes in 2001 (Appendix A). During the ICAO MET Divisional Meeting (2002), in order to face the problem of the lack of implementation (e.g. SIGMETs are not issued by certain States), a set of measures were recommended, including the review of the ICAO regional SIGMET guides. A requirement was also introduced for maintenance of a 24-hour watch by the VAACs. In view of flight safety considerations, the requirement for information from selected State volcano observatories was introduced in ICAO provisions in order for the ACCs MWOs and the VAACs to receive from these selected observatories messages on volcanic activity. All the provisions endorsed by the MET Divisional Meeting (2002) will become applicable in November 2004 as part of Amendment 73 to Annex 3.

In order to assist States exposed to volcanic eruptions, specific special implementation projects on the issuance of SIGMETs with emphasis on volcanic ash have been undertaken by ICAO in a number of ICAO Regions during recent years. Special implementation projects involved visits to States; in each State visited the ICAO expert met with officials from three areas involved in the implementation of the IAVW; ATS authorities/providers; MET authorities/providers and vulcanological agencies. In some of the States, representatives from the airlines were also available during the meetings. These projects were considered very successful by the States concerned and ICAO, and resulted in noticeable improvements in the local procedures.

The MET Divisional Meeting (2002), recognizing the need for a reliable operation of the IAVW and its impact in flight safety, recommended the establishment of an operations group in order to coordinate and oversee the development of the IAVW. In 2003, the International Airways Volcano Watch Operations Group (IAVWOPSG) was established; it held its first meeting in Bangkok, Thailand, in March 2004. It formulated twenty-eight conclusions and five decisions related to the operation and development of the IAVW.

3. OPERATION OF THE IAVW

The IAVW comprises an observing part to detect volcanic eruptions and volcanic ash and a warning part concerned with the issuance of volcanic ash advisory information in both alphanumerical and graphical format, SIGMETs, NOTAMs (and the special series NOTAM called ASHTAM designed specifically for volcanic eruptions/ash). This section deals with the recent developments of the IAVW.

3.1 Observing component of the IAVW

The observing part depends upon initial notification of volcanic eruptions/ash cloud to MWOs, ACCs and/or VAACs by vulcanological agencies, meteorological observing networks, United Nations Disaster Relief Organization field officers, national networks such as police, military, border guards, forestry personnel etc; pilot reports and satellite data. Substantial efforts have been made to ensure that personnel from the foregoing organized networks understand that if they see or learn of a volcanic eruption in their area they are to inform the nearest civil aviation or meteorological contact point. These contact points and channels of communication are organized nationally in those States having active volcanoes in the FIRs for which they are responsible. Ultimately, the notification of a volcanic eruption/ash cloud has to reach the ACCs, MWOs and VAACs to permit the issuance of the necessary advisory information, SIGMETs and NOTAMs.

3.2 Ground-based observations

The ground-based observing part of the IAVW, which used to be dependent on voluntary cooperation, is by no means 100 per cent effective. In this regard, the MET Divisional Meeting (2002) was informed that difficulties were being experienced by some vulcanological agencies in obtaining the necessary funding for sending messages on volcanic activity to ACCs, MWOs and the VAACs in their region. These additional funds most often involved staffing and communications costs. In order to face this issue, the requirement for information from selected State volcano observatories is being introduced in ICAO provisions. This requirement means that the role of the volcano observatories, which are the front line of alert of the IAVW, will be formalized.

3.3 Observations from air-reports

The provision of special air reports on volcanic eruptions/ash cloud by pilots is in general operating well, and on many occasions such reports have provided the initial notification of an eruption. However, at the IAVWOPSG/1 Meeting it was recognized that there are still certain areas where further work is necessary. With regard to the implementation of the existing provisions concerning the reporting, recording and post-flight reporting of aircraft observations related to volcanic activity, there is a reluctance by some airlines in providing the special air report of volcanic activity form. According to the *Procedures for Air Navigation Services — Air Traffic Management* (PANS-ATM, Doc 4444), special air-reports containing volcanic activity shall be recorded on the special air-report on volcanic activity form. Information contained in this form is considered of particular importance to the successful operation of the VAACs due to the fact that the details related to the eruption can be deducted from the report. Therefore, the IAVWOPSG/1 concluded that airlines should be encouraged by ICAO to adhere to the existing provisions regarding the reporting, recording and post-flight reporting of aircraft observations of volcanic activity.

3.4 Space-based observations

The space-based component using satellite data is critical for the VAACs in assessing the existence and extent of volcanic ash cloud, and in detecting the initial eruption. The space-based observations have the potential for the largest scope for improvement in the future. The MET Divisional Meeting (2002) had noted with satisfaction the work being done in some States in order to improve satellite-based techniques for the detection of volcanic eruptions and volcanic ash clouds. The additional capabilities that would assist future research offered by the second-generation of METEOSAT satellites launched by EUMETSAT was also noted. The MET Divisional Meeting (2002) called for WMO to encourage VAAC Provider States to continue and, if possible, to accelerate research on the detection of volcanic ash. During the Third International Workshop on Volcanic Ash (organized by Meteo-France in 2003, in cooperation with WMO and ICAO) the latest developments on the detection of volcanic eruptions and volcanic ash by remote sensing techniques were discussed. In this regard the METEOSAT second generation satellites and the potential use of the moderate resolution imaging spectroradiometer (MODIS) and the ground-based infrared detection (G-bIRD) were highlighted. During the same workshop all parties involved in the IAVW were encouraged to continue to develop modelling technologies with the enhancement of various models.

3.2 Warning component of the IAVW

3.2.1 Areas of responsibilities of the VAACs

Each Provider State of the VAACs undertook responsibility for an area for which they generally had access to high-resolution satellite information. There are some exceptions to this, but on the whole, this was the basic principle to which most Provider States adhered. For obvious reasons, the main international air routes were covered first which still left some areas of the world uncovered. In the evolving air navigation systems, the emphasis will be on “major traffic flows” from one “homogenous area” to another, and so-called “free flight”, which in theory, at least, will permit aircraft to flight plan off air routes for any flight level and routing which is considered economically attractive. It will be necessary, therefore, to ensure that the “major traffic flows” are adequately covered and eventually, most areas of the globe, in order to protect future “free flight” operations off air routes. In the actual concept of “organized tracks” the VAACs are providing adequate coverage, however, this may not be the case for the evolving ATM systems. In this regard, in response to a conclusion by the IAVWOPSG/1 Meeting, VAACs Toulouse and Washington agreed to extend their areas of responsibility in order for the IAVW to reach a quasi-global coverage. The current VAAC areas of responsibility are given in Figure 1.

3.2.2 Advisory information in graphical format

The alphanumerical and graphical formats for volcanic ash advisory information have existed for a few years. All VAACs issue volcanic ash advisory messages, but not all VAACs have implemented graphical advisories. The IAVWOPSG is currently developing a future format for graphical volcanic ash advisories to be issued by VAACs. The issuance of advisory messages in alphanumeric format continues to be essential for all VAACs because it provides a reliable means of addressing individual “offices or units” via the ICAO Aeronautical Fixed Telecommunication Network

(AFTN); graphical advisories cannot be disseminated over the AFTN. Graphical advisories are disseminated on the International Satellite Communication System (ISCS) 1 and 2 and the Satellite Distribution System for Information Relating to Air Navigation (SADIS) satellite broadcasts; however, their reception cannot be guaranteed.

3.2.3 Distribution of NOTAMS for volcanic ash

The distribution of NOTAMs for volcanic ash and ASHTAMs on the SADIS and ISCS broadcasts, was tested in July 2001. The test was successful and proved that it is, in principle, possible to route these types of messages to SADIS provided that a WMO abbreviated header is added thereto. However, in an operational environment, adding such dummy headers is not feasible and the NOTAMs will have to be processed as they are. The IAVWOPSG had agreed that ASHTAMs and NOTAMs for volcanic ash be required for uplink on the ISCS and SADIS; and that a draft amendment to Annex 15 — *Aeronautical Information Services* be developed.

3.2.4 Advisory information for airlines

Advisory information is also disseminated to airlines through an AFTN address provided specifically for this purpose. The introduction of this requirement was based on the fact that, in many cases, the first warning of the existence of an ash cloud came from the volcanic ash advisory message.

4. EFFECTS OF RECENT VOLCANIC ERUPTIONS

There has been no respite in the recent past from the occurrence of violent volcanic eruptions producing ash cloud that warranted the issuance of advisories, SIGMETs and/or NOTAMs. Since the Pinatubo eruption in 1991, the volcanoes that have caused the most difficulty for civil aviation were probably Soufriere Hills in Montserrat, Popocatepetl and Colima in Mexico, Sakurajima and Suwanosejima in Japan, Etna in Italy, Tungurahua and El Reventador in Ecuador, Sheveluch, Karimsky, Klyuchevskoi, Cleveland and Anatahan in the North Pacific Ocean and Semeru, Ruang, Dukono and Ulawun in Indonesia, some of them continue to be active. There have, however, been numerous other eruptions that have caused temporary problems, especially over the North Pacific; and there have been few weeks when the IAVW has not been activated at least somewhere in the world.

In addition to its potential to cause a major aircraft accident, the consideration of the economic cost of volcanic ash to international civil aviation is staggering. This involves numerous complete engines changes, engine overhauls, different aircraft repairs, loss of revenue due to the aircraft down-time, cost of rerouting and delays, clearance from airports and damages to equipment and buildings on the ground. On average, various estimates made calculated the costs to aviation to be well in excess of US$ 250 million between 1982 and 2000.

5. SPECIFIC PROBLEMS TO BE ADDRESSED

The following are the main issues, to be addressed within the IAVW:

- lack of sufficiently reliable and timely notification of volcanic eruptions to ACCs, MWOs and VAACS;
- communication difficulties between observing sources and ACCs, MWOs and VAACs and also between the ACCs/MWOs/VAACs themselves; and
- extension of VAAC coverage over all future “major international air traffic flows” and, eventually, all areas to support “free flight” or “dynamic aircraft routing”.

6. GUIDANCE MATERIAL

Extensive guidance has been prepared by ICAO to assist States and Users. Two documents were published by ICAO, in close cooperation with the IAVW, during the last few years. One is the *Handbook on the International Airways Volcano Watch (IAVW)* (Doc 9766) in 2000, updated in 2004, and the other is the *Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds* (Doc 9691) published in 2001.

The handbook on the IAVW is an operational publication for the daily use by operational staff in the ACCs, NOFs, MWOs, VAACs and contains information regarding active volcanoes, VAACs and their responsibilities, useful websites, IAVW procedures and finally it provides the IAVW contact list. The handbook is available and kept up-to-date at the ICAO website: http://www.icao.int/anb/iavwopsg .

The main purpose of the manual is to assist States and international organizations involved in the IAVW by gathering together in one document information on the problem of volcanic ash, and to provide guidance regarding what each of the parties in the IAVW is expected to do and why. Currently ICAO, with the assistance of the IAVWOPSG, is in the process of updating the manual. It is expected that the new edition will be available in early 2005.

Additionally, ICAO produced training aids designed to support the implementation of the Standards and Recommended Practices (SARPs) related to volcanic ash. They consist of a video entitled Volcanic Ash Avoidance, and a poster entitled *Warning — if you inadvertently enter a volcanic ash cloud*.

Finally, as an example of excellent international cooperation, the *World map of volcanoes and principal aeronautical features* was issued in 1995. This world map was published by the USGS in a conjoint effort with Jeppesen Sanderson, Inc., ICAO, various US federal agencies, international organizations and individual experts involved in volcanic ash issues.

7. FUTURE DEVELOPMENTS

The most urgent issue for the IAVW in the interest of air safety is how to ensure the reliable and timely notification of volcanic eruptions. In this regard, ICAO is working closely with WMO regarding the infrasonics and seismic network established by the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) to support the verification procedures. The idea is to study the feasibility by

IAVW of gaining real-time access to the CTBTO infrasonic and seismic networks to detect volcanic eruption "signatures". ICAO has been exchanging letters with the CTBTO Secretariat in this regard for the last year in support of the IAVW and in the interests of air safety. Currently the CTBTO is undertaking an assessment on the usefulness of seismic and infrasonic data from the CTBTO observing networks to the IAVW; it is expected that the final report will be sent to ICAO during the next few months.

Recently during a meeting of a working group of the WMO Commission of Basic Systems, it was indicated by the CTBTO that a potential existed as far as the use of the CTBTO network for IAVW was concerned; however, the results were preliminary with a number of unknowns.

8. CLOSING REMARKS

It can be said that, given the safety and economic implications of volcanic ash to aircraft operations, it is necessary to maintain the IAVW in much the same way that the aerodrome fire services are maintained; in constant readiness but with the fervent hope that it rarely has to be used.

APPENDIX 5. TECHNICAL SPECIFICATIONS FOR SIGMET AND AIRMET MESSAGES AND SPECIAL AIR-REPORTS

(See Chapter 7 of this Annex)

Table A5-1. Template for SIGMET and AIRMET messages and special air-reports

Key: M = inclusion mandatory, part of every message
C = inclusion conditional, included whenever applicable
= = a double line indicates that the text following it should be placed on the subsequent line

Note.— The ranges and resolutions for the numerical elements included in SIGMET/AIRMET messages and in special air-reports are shown in Table A5-2 of this appendix.

Element as specified in Chapters 5 and 7	*Detailed content*	*Template(s)*				*Examples*
		SIGMET	*SIGMET SST1*	*AIRMET*	*SPECIAL AIR-REPORT2*	
Location indicator of FIR/CTA (M)3	ICAO location indicator of the ATS unit serving the FIR or CTA to which the SIGMET/ AIRMET refers (M)	nnnn			—	YUCC4 YUDD4
Identification (M)	Message identification and sequence number5 (M)	SIGMET [nn]n	SIGMET SST [nn]n	AIRMET [nn]n	ARS	SIGMET 5 SIGMET A3 SIGMET SST 1 AIRMET 2 ARS
Validity period (M)	Date-time groups indicating the period of validity in UTC (M)	VALID nnnnnn/nnnnnn			6	VALID 221215/221600 VALID 101520/101800 VALID 251600/252200
Location indicator of MWO (M)	Location indicator of MWO originating the message with a separating hyphen (M)	nnnn				YUDO4 YUSO4
Name of the FIR/ CTA *or* aircraft identification (M)	Name of the FIR/ CTA7 for which the SIGMET/AIRMET is issued *or* aircraft radiotelephony call sign (M)	nnnnnnnnnn FIR[/UIR] *or* *nnnnnnnnnn CTA*		*nnnnnnnnnn FIR[/n]*	*nnnnnn*	*AMSWELL FIR*4 SHANLON FIR/UIR4 AMSWELL FIR/24 SHANLON FIR4 VA812
IF THE SIGMET IS TO BE CANCELLED SEE FOR DETAILS AT THE END OF THE TEMPLATE						
Phenomenon (M)8	Description of phenomenon causing the issuance of SIGMET/AIRMET (C)	OBSC9 TS [GR10] EMBD12 TS [GR] FRQ13 TS [GR] SQL14 TS [GR]	MOD TURB11 SEV TURB ISOL15 CB16 OCNL18 CB FRQ13 CB GR	*SFC WSPD nn[n]KMH (SFC WSPD nn[n]KT)* *SFC VIS nnnnM (nn)*17 ISOL15 TS[GR]10 OCNL18 TS[GR] MT OBSC	TS TSGR SEV TURB SEV ICE SEV MTW	SEV TURB FRQ TS OBSC TS GR EMD TS GR TC GLORIA VA ERUPTION MT ASHVAL LOC S15 E073 VA CLD

		TC nnnnnnnnnn SEV TURB11 SEV ICE19 SEV ICE (FZRA)20 SEV MTW21 HVY DS HVY SS VA[ERUPTION] [MT nnnnnnnnnn] [LOC Nnn[nn] *or* Snn[nn] Ennn[nn] *or* Wnnn[nn]] VA CLD	VA[ERUPTION] [MT nnnnnnnnnn] [LOC Nnn[nn] or Snn[nn] Ennn[nn] *or* *Wnnn[nn]] VA CLD*	BKN CLD nnn/[ABV]nnnnM (BKN CLD nnn/[ABV]nnnnFT) OVC CLD nnn/[ABV]nnnnM (OVC CLD nnn/[ABV]nnnnFT) ISOL15 CB16 OCNL18 CB FRQ13 CB ISOL15 TCU16 OCNL18 TCU16 FRQ13 TCU MOD TURB11 MOD ICE19 MOD MTW21	HVY SS VA CLD [FL nnn/nnn] VA [MT nnnnnnnnnn] MOD TURB11 GR10 CB16	MOD TURB MOD MTW ISOL CB BKN CLD 120/900M (BKN CLD 400/3000FT) OVC CLD 270/ABV3000M (OVC CLD 900/ABV10000FT) SEV ICE
Observed or forecast phenomenon (M)	Indication whether the information is observed and expected to continue, *or* forecast (M)	OBS [AT nnnnZ] FCST OBS [AT nnnnZ] AND FCST			OBS AT nnnnZ —	OBS AT 1210Z OBS OBS AND FCST OBS AT 2245Z
Location (C)	Location (referring to latitude and longitude (in degrees and minutes) *or* locations or geographic features well known internationally)	[N OF, NE OF, E OF, SE OF, S OF, SW OF, W OF, NW OF] [Nnn[nn]][Wnnn[nn]] or [N OF, NE OF, E OF, SE OF, S OF, SW OF, W OF, NW OF] [Nnn[nn]][Ennn[nn]] or [N OF, NE OF, E OF, SE OF, S OF, SW OF, W OF, NW OF] [Snn[nn]][Wnnn[nn]] or [N OF, NE OF, E OF, SE OF, S OF, SW OF, W OF, NW OF] [Snn[nn]][Ennn[nn]] or [N OF, NE OF, E OF, SE OF, S OF, SW OF, W OF, NW OF] nnnnnnnnnnnn			NnnnnWnnnnn or NnnnnWnnnnn or SnnnnWnnnnn or SnnnnEnnnnn	S OF N54 N OF N50 N2020 W07005 YUSB4 N2706 W07306 N48 E010
Level (C)	Flight level *and* extent22(C)	FLnnn *or* FLnnn/nnn *or* TOP FLnnn *or* [TOP] ABV FLnnn *or*[TOP] BLW FLnnn *or*23 CB TOP [ABV] FLnnn WI nnnKM OF CENTRE (CB TOP [ABV] FLnnn WI nnnNM OF CENTRE) or CB TOP [BLW] FLnnn WI nnnKM OF CENTRE (CB TOP [BLW] FLnnn WI nnnNM OF CENTRE) *or*24 FLnnn/nnn [APRX nnnKM BY nnnKM] [Nnn[nn] *or* Snn[nn]Wnnn[nn] *or* Ennn[nn] TO Nnn[nn] *or* Snn[nn]Wnnn[nn] *or* Ennn[nn] [TO Nnn[nn] *or* Snn[nn]Wnnn[nn] *or* Ennn[nn]] [TO Nnn[nn] *or* Snn[nn]Wnnn[nn] *or* Ennn[nn]] (FLnnn/nnn [APRX nnnNM BY nnnNM] [Nnn[nn] *or* Snn[nn]Wnnn[nn] *or* Ennn[nn] TO Nnn[nn] *or* Snn[nn]Wnnn[nn] *or* Ennn[nn] [TO Nnn[nn] *or* Snn[nn]Wnnn[nn] *or* Ennn[nn]] [TO Nnn[nn] *or* Snn[nn]Wnnn[nn] *or* Ennn[nn]])			FLnnn	FL180 FL050/080 TOP FL390 BLW FL200 TOP ABV FL100 FL310/450 CB TOP FL500 WI 270KM OF CENTRE (CB TOP FL500 WI 150NM OF CENTRE) FL310/350 APRX 220KM BY 35KM FL390

<table>
<tr><td></td><td></td><td colspan="3"></td><td colspan="2"></td><td></td></tr>
<tr><td>Movement or expected movement (C)</td><td>Movement or expected movement with reference to one of the eight points of compass, or stationary (C)</td><td colspan="3">MOV N [nnKMH] or MOV NE [nnKMH] or MOV E [nnKMH] or
MOV SE [nnKMH] or MOV S [nnKMH] or MOV SW [nnKMH] or
MOV W [nnKMH] or MOVNW[nnKMH] or
(MOV N [nnKT] or MOV NE [nnKT] or MOV E [nnKT] or MOV SE [nnKT] or MOVS[nnKT] or MOV SW [nnKT] or MOV W [nnKT] or MOV NW [nnKT]) or
STNR</td><td colspan="2">—</td><td>MOV E 40KMH
(MOV E 20KT)
MOV SE
STNR</td></tr>
<tr><td>Changes in intensity (C)</td><td>Expected changes in intensity (C)</td><td colspan="3">INTSF or WKN or NC</td><td colspan="2">—</td><td>WKN</td></tr>
<tr><td>Forecast position (C)22</td><td>Forecast position of volcanic ash cloud or the centre of the TC at the end of the validity period of the SIGMET message (C)</td><td colspan="3">FCST nnnnZ TC CENTRE
Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]
or
FCST nnnnZ VA CLD
Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]
TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]
[TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]]
[TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]]</td><td>—</td><td>—</td><td>FCST 2200Z TC CENTRE N2740 W07345

FCST 1700Z VA CLD S15 E075 TO S15 E081 TO S17 E083 TO S18 E079 TO S15 E75</td></tr>
<tr><td>Outlook22 (C)</td><td>Outlook providing information beyond the period of validity of the trajectory of the volcanic ash cloud and positions of the tropical cyclone centre (C)</td><td colspan="3">OTLK nnnnnn TC CENTRE
Nnnnn or SnnnnWnnnnn or Ennnnn
nnnnnn TC CENTRE
Nnnnn or SnnnnWnnnnn or Ennnnn
or
OTLK nnnnn VA CLD APRX
[Flnnn/nnn]25 Nnn[nn] or Snn[nn] Wnnn[nn] or Ennn[nn]
TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]
TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]
[TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]]
[TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]]
nnnnnn VA CLD APRX
Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]
TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]
TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]
[TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]]
[TO Nnn[nn] or Snn[nn]Wnnn[nn] or Ennn[nn]]</td><td colspan="2"></td><td>OTLK 260400 TC CENTRE N28030 W07430 261000 TC CENTRE N3100 W07600

OTLK 212300 VA CLD APRX S16 E078 TO S17 E084 TO S18 E089 TO S19 E081 TO S16 E078 220300 VA CLD APRX S17 E81 TO S18 E86 TO S20 E92 TO S21 E84 TO S17 E81</td></tr>
<tr><td colspan="8">OR</td></tr>
<tr><td>Cancellation of SIGMET/ AIRMET26 (C)</td><td>Cancellation of SIGMET/AIRMET referring to its identification</td><td>CNL SIGMET [nn]n nnnnnn/nnnnnn</td><td>CNL SIGMET SST [nn]n nnnnnn/nnnnnn</td><td>CNL AIRMET [nn]n nnnnnn/nnnnnn</td><td colspan="2">—</td><td>CNL SIGMET 2 101200/10160026

CNL SIGMET SST 1 212330/22013026

CNL AIRMET 151520/ 15180026</td></tr>
</table>

Notes.–

1. Only for transonic and supersonic flights.
2. Automated special air-reports also include information on wind and temperature which does not need to be uplinked to other aircraft in flight.
3. In cases where the airspace is divided into a flight information region (FIR) and an upper flight information region (UIR), the SIGMET is identified by the location indicator of the air traffic services unit serving the FIR; nevertheless, the SIGMET message applies to the whole airspace within the lateral limits of the FIR, i.e. to the FIR and to the UIR. The particular areas and/or flight levels affected by the meteorological phenomena causing the issuance of the SIGMET are given in the text of the message.
4. Fictitious location.
5. Corresponding with the number of SIGMET/AIRMET messages issued for the FIR/CTA since 0001 UTC on the day concerned.
6. Special air-reports are to be uplinked for 60 minutes after their issuance.
7. Or a sub-area thereof in the case of AIRMET messages.
8. Only one of the weather phenomena listed should be selected and included in each SIGMET.

9. Obscured (OBSC) indicates that the thunderstorm (including, if necessary, cumulonimbus cloud which is not accompanied by a thunderstorm) is obscured by haze or smoke or cannot be readily seen due to darkness.

10. Hail (GR) may be used as a further description of the thunderstorm as necessary.

11. Severe and moderate turbulence (TURB) refers only to: low-level turbulence associated with strong surface winds; rotor streaming; or turbulence whether in cloud or not in cloud (CAT) near to jet streams. Turbulence is not required to be used in connection with convective clouds. Turbulence is considered:

   a) severe whenever the turbulence index is between 15 and 27 (i.e. the peak value of the eddy dissipation rate (EDR) exceeds 0.5); and
   b) moderate whenever the turbulence index is between 6 and 14 (i.e. the peak value of the eddy dissipation rate (EDR) exceeds 0.3 while not exceeding 0.5).

12. Embedded (EMBD) indicates that the thunderstorm (including cumulonimbus cloud which is not accompanied by a thunderstorm) is embedded within cloud layers and cannot be readily recognized.

13. Frequent (FRQ) indicates an area of thunderstorms within which there is little or no separation between adjacent thunderstorms with a maximum spatial coverage greater than 75 per cent of the area affected, or forecast to be affected, by the phenomenon (at a fixed time or during the period of validity).

14. Squall line (SQL) indicates thunderstorm along a line with little or no space between individual clouds.

15. Isolated (ISOL) indicates an area of individual cumulonimbus and/or thunderstorms with a maximum spatial coverage less than 50 per cent of the area affected, or forecast to be affected, by the phenomenon (at a fixed time or during the period of validity).

16. The use of cumulonimbus, CB, is restricted to AIRMETs and SIGMETs related to SST flight during transonic and supersonic cruise; the use of towering cumulus, TCU, is restricted to AIRMETs.

17. The weather phenomenon causing the reduction in visibility in brackets; choose one from the following list: DZ, RA, SN, SG, PL, IC, GR, GS, FG, BR, SA, DU, HZ, FU, VA, PO, SQ, FC, DS or SS.

18. Occasional (OCNL) indicates an area of well-separated cumulonimbus and/or thunderstorms with a maximum spatial coverage between 50 and 75 per cent of the area affected, or forecast to be affected, by the phenomenon (at a fixed time or during the period of validity).

19. Severe and moderate icing (ICE) refers to severe icing in other than convective clouds.

20. Freezing rain (FZRA) refers to severe icing conditions caused by freezing rain.

21. A mountain wave (MTW) is considered:

   a) severe whenever an accompanying downdraft of 3.0 m/s (600 ft/min) or more and/or severe turbulence is observed or forecast;
   b) moderate whenever an accompanying downdraft of 1.75–3.0 m/s (350–600 ft/min) and/or moderate turbulence is observed or forecast.

22 Only for SIGMET messages for volcanic ash cloud and tropical cyclones.

23. Only for SIGMET messages for tropical cyclones.

24. Only for SIGMET messages for volcanic ash.

25. Up to four layers (or levels) to be included in the SIGMET outlook for volcanic ash.

26. End of the message (as the SIGMET/AIRMET message is being cancelled).

General Note.— Severe or moderate icing and severe or moderate turbulence (SEV ICE, MOD ICE, SEV TURB, MOD TURB) associated with thunderstorms, cumulonimbus clouds or tropical cyclones should not be included.

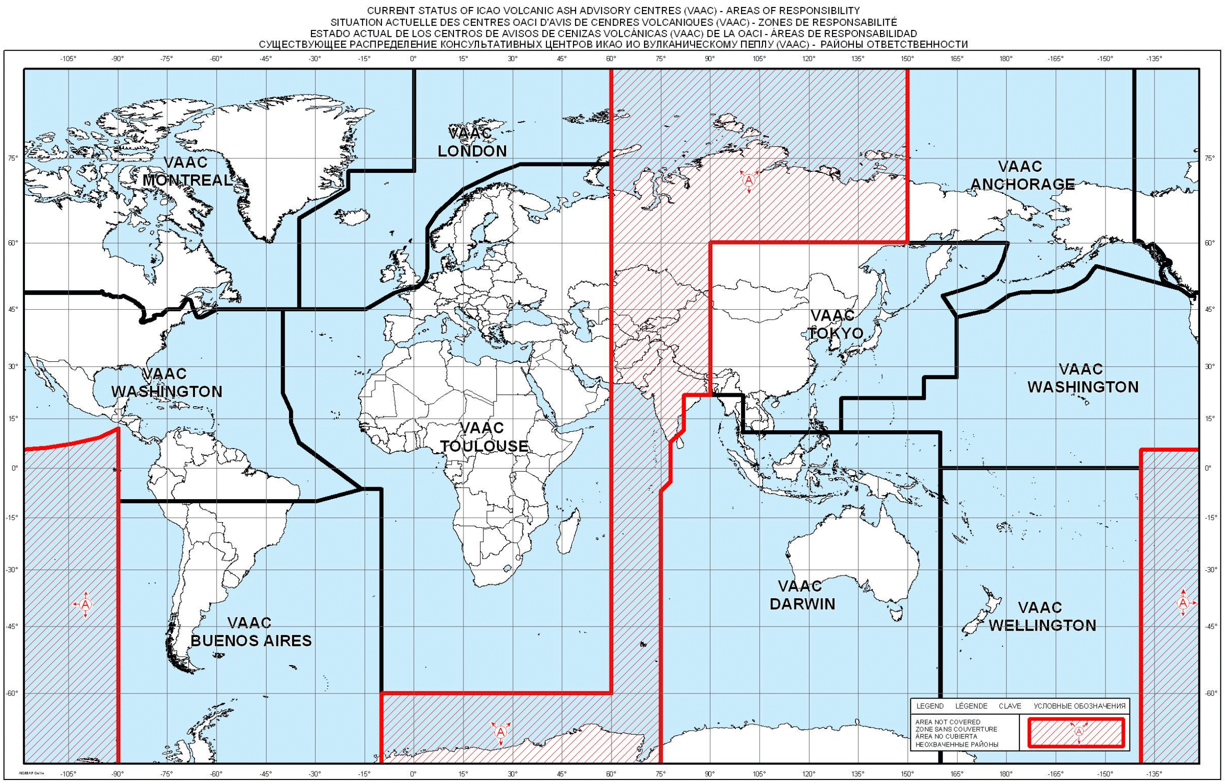
ADVISORY MESSAGE FOR VA

VOLCANIC ASH ADVISORY
ISSUED: 20000402/0700Z
VAAC: TOKYO
VOLCANO: USUZAN 805-03
LOCATION: N4230E14048
AREA: JAPAN
SUMMIT ELEVATION: 732M
ADVISORY NUMBER: 2000/432
INFORMATION SOURCE: GMS JMA
AVIATION COLOUR CODE: RED
ERUPTION DETAILS: ERUPTED 20000402/0614Z ERUPTION OBS ASH TO ABV FL300
OBS ASH DATE/TIME: 02/0645Z
OBS ASH CLD: FL150/350 N4230E14048-N4300E14130-N4246E14230-N4232E14150-N4230E14048
SFC/FL150 MOV NE 25KT FL150/350 MOV E 30KT
FCST ASH CLD + 6 HR: 02/1245Z SFC/FL200 N4230E14048-N4232E14150-N4238E14300-N4246 E14230
FL200/350 N4230E14048-N4232E14150N4238E14300-N4246E14230
FL350/600 NO ASH EXP
FCST ASH CLD + 12 HR: 02/1845Z SFC/FL300 N4230E14048-N4232E14150-N4238E14300-
N4246E14230 FL300/600 NO ASH EXP
FCST ASH CLD + 18 HR: 03/0045Z SFC/FL600 NO ASH EXP
NEXT ADVISORY: 20000402/1300Z
REMARKS: ASH CLD CAN NO LONGER BE DETECTED ON SATELLITE IMAGE

SIGMET FOR VA

YUDD SIGMET 2 VALID 211100/211700 YUSO-
SHANLON FIR/UIR VA ERUPTION MT ASHVAL LOC E S1500 E07348 VA CLD OBS AT 1100Z
FL310/450 APRX 220KM BY 35KM S1500 E07348E TO S1530 E07642 MOV ESE 65KMH FCST 1700Z VA
CLD APRX S1506 E07500 TO S1518 E08112 TO S1712 E08330 TO S1824 E07836
OTLK 212300Z VA CLD APRX S1600 E07806 TO S1642 E08412 TO S1824 E08900 TO S1906 E08100
220500Z VA CLD APRX S1700 E08100 TO S1812 E08636 TO S2000 E09224 TO S2130 E08418

FIGURE 1


CURRENT STATUS OF ICAO VOLCANIC ASH ADVISORY CENTRES (VAAC) - AREAS OF RESPONSIBILITY
SITUATION ACTUELLE DES CENTRES OACI D'AVIS DE CENDRES VOLCANIQUES (VAAC) - ZONES DE RESPONSABILITÉ
ESTADO ACTUAL DE LOS CENTROS DE AVISOS DE CENIZAS VOLCÁNICAS (VAAC) DE LA OACI - ÁREAS DE RESPONSABILIDAD
СУЩЕСТВУЮЩЕЕ РАСПРЕДЕЛЕНИЕ КОНСУЛЬТАТИВНЫХ ЦЕНТРОВ ИКАО ИО ВУЛКАНИЧЕСКОМУ ПЕПЛУ (VAAC) - РАЙОНЫ ОТВЕТСТВЕННОСТИ
VAAC MONTREAL
VAAC LONDON
VAAC ANCHORAGE
VAAC TOKYO
VAAC WASHINGTON
VAAC TOULOUSE
VAAC WASHINGTON
VAAC DARWIN
VAAC BUENOS AIRES
VAAC WELLINGTON
LEGEND LÉGENDE CLAVE УСЛОВНЫЕ ОБОЗНАЧЕНИЯ
AREA NOT COVERED
ZONE SANS COUVERTURE
ÁREA NO CUBIERTA
НЕОХВАЧЕННЫЕ РАЙОНЫ

THE WORLD METEOROLOGICAL ORGANIZATION (WMO) ACTIVITIES RELATED TO VOLCANIC ASH

Mr. Saad Benarafa, World Meteorological Organization,
Geneva, Switzerland

ABSTRACT

This paper provides the main thrusts of the World Meteorological Organization (WMO) activities related to volcanic ash. The WMO Emergency Response Activities (ERA) Programme objectives are presented and the involvement of the WMO designated Regional Specialized Meteorological Centers (RSMCs) is highlighted. The excellent cooperation with the International Civil Aviation Organization (ICAO) regarding the international airways volcano watch is also highlighted

The World Meteorological Organization (WMO) is one of the various stakeholders involved in volcanic ash and aviation safety. The WMO Emergency Response Activities (ERA) Programme is being implemented to assist National Meteorological and Hydrological Services (NMHSs), other relevant agencies of WMO Member countries and international organizations to respond effectively to environmental emergencies related to large-scale transboundary air pollution, caused in particular by major nuclear accidents, volcanic eruptions, and land fires. This programme is implemented through the provision of specialized Global Data Processing and Forecasting System products by 29 designated WMO Regional Specialized Meteorological Centers (RSMCs). This programme also includes the development and implementation of procedures for the provision and exchange of specific observational data, and related training support for users. The WMO Fourteenth Congress (Cg-XIV) held in May 2003, decided to expand the ERA Programme to include, in particular, chemical accidents.

Through the ERA Programme under the auspices of the World Weather Watch and the Global Atmospheric Watch Programme (GAW) being implemented under the Atmospheric Research and Environment Programme (AREP), WMO will continue to support its Members to develop the appropriate environmental prediction tools to prepare and strengthen their capability to advise Member countries relevant national authorities when required. In this regard , the "ensemble" approach for predicting the atmospheric transport and dispersion of tracers is being explored for emergency response applications and WMO constituent bodies are encouraging RSMCs to further develop and test new technologies such as ensemble methods, new products to satisfy growing requirements and the use of the Internet for the information exchange.

In line with its excellent cooperation with ICAO regarding aviation safety, WMO has been actively participating in activities undertaken by the ICAO International Airways Volcano Watch Operations Group (IAVWOPSG). In this context, ICAO has been benefiting from results of the specialized atmospheric transport modeling of airborne volcanic ash conducted under WMO auspices. Products generated from transport models are essential for supporting the operations of the International Airways Volcano Watch Programme

In response to Recommendation 1/18 of the Conjoint WMO CAeM Session/ICAO/Meteorology Divisional Meeting (2002), related to the completion of the assessment of the usefulness of seismic and infrasonic data from the Comprehensive Test Ban Treaty Organization (CTBTO) monitoring networks detecting explosive volcanic eruptions, a report on this assessment, that will not include a definitive conclusion, is expected to be sent by CTBTO to ICAO and WMO in the near future. If the assessment concludes that the provision of CTBT data is of use to the IAVW and thus worth implementing operationally, it would be necessary to prepare a “road map”, which would lead to the implementation of operational arrangements between CTBTO, ICAO and WMO.

NOAA'S NWS VOLCANIC ASH PROGRAM: CURRENT STATUS AND PLANS FOR THE FUTURE

Christopher S. Strager, NWS Alaska Region Headquarters, Anchorage, AK, USA
Jeffrey M. Osiensky, NWS Alaska Aviation Weather Unit, Anchorage AK, USA
Gary L. Hufford, NWS Alaska Region Headquarters, Anchorage, AK, USA

Operationally, the National Oceanic and Atmospheric Administration (NOAA) plays an important role in the worldwide volcanic ash network through the operation of two of the world's nine Volcanic Ash Advisory Centers (VAACs) and four Meteorological Watch Offices (MWO). The operational responsibilities of these two VAACs are defined in the International Civil Aviation Organization (ICAO) Annex 3. The Washington VAAC is jointly managed by the National Environmental Satellite, Data and Information Service (NESDIS) Satellite Analysis Branch and the National Weather Service's (NWS) National Centers for Environmental Prediction (NCEP). The Anchorage VAAC is managed by the NWS' Alaska Aviation Weather Unit. Together, these centers are responsible for providing volcanic ash advisories and ash dispersion forecasts for a wide area ranging from the Pacific Ocean eastward over the U.S and much of the Atlantic Ocean. Research and development efforts in support of those operations include (but are not limited to) assets from NOAA's NCEP, NESDIS, Forecast Systems Laboratory, Air Research Laboratory and U.S. Geological Survey. With regards to policy, NOAA's Volcanic Ash Program has a responsibility to meet both U.S. and international customers' needs by ensuring product content, dissemination and coordination procedures remain consistent and compatible with ICAO standards. This presentation will examine NOAA's NWS Volcanic Ash Program, discussing the current status and future plans in the areas of operations, research/development, and policy development.

VOLCANIC ASH IMPACT ON INTERNATIONAL AIRPORT OF MEXICO CITY (AICM), DUE TO EMISSIONS OF POPOCATEPETL VOLCANO

Humberto Rodríguez, DMTA of SENEAM, México, D. F. México.

ABSTRACT

Since 1995, the CAPMA of SENEAM, which is the main office of the Aviation Weather Service in Mexico, has been issued SIGMETS of volcanic ash. At present, most of the SIGMETS were issued due to emissions of Popocatepetl volcano. Since that time Popocatepetl volcano has had several erupted events some of them have threatened the safety of the aviation . In this work we are going to comment two important eruptions: (1) The event occurred on June 30, 1997, where the AICM was closed for about 10 hours and (2) The July 19, 2003 event. The collaboration from VAAC of Washington, CENAPRED in Mexico City and The Air Traffic Service (ATS) of SENEAM has been essential to alert the pilots and flight dispatchers about volcanic ash plumes. However, we still have lack of tools and techniques to track more efficiently the volcanic ash plumes.

INTRODUCTION

Since December 21, 1994, Popocatepetl volcano started another eruptive stage. This obligated authorities of Civil Aviation, AICM (Aeropuerto Internacional de la Ciudad de Mexico - International Airport of Mexico City), and SENEAM (Servicios a la Navegación en el Espacio Aéreo Mexicano), among others entities, to restrict flight operations around 10 NM from volcano crater. Also, a contingency plan was issued to prevent and minimize the threat of volcanic ash plumes. The CAPMA (Centro de Análisis y Pronósticos Meteorológicos Aeronáuticos - Analysis and Forecasting Meteorological Center for Aviation) of SENEAM, which is the main meteorological office of the Aviation Weather Service in Mexico was designated the responsible to gather information of volcanic activity an also responsible to issue the volcanic ash SIGMETS. The CAPMA receives information and reports from CENAPRED (Centro Nacional de Prevención de Desastres - National Center for Disaster Prevention), Weather Observers, Controllers, Pilots, Civil Protection and VAAC of Washington. The coordination between the VAAC of Washington and CAPMA is so important and it has been improved since we had the June 30, 1997 event. CAPMA of SENEAM has a procedure, which is followed carefully when a volcanic ash plume is reported. This is important because we can alert with more opportunity to airlines and pilots. In this work we try to discuss two cases related with volcanic ash that have impacted the AICM and emphasize the roll of aeronautic meteorology in the prevention of these phenomena. Also, to show the economic impact they caused to aeronautical operations in Mexico.

POPOCATEPETL VOLCANO FEATURES

- It is located about 35NM (64.8km) southeast of International Airport of Mexico City. See Fig. 1.
- It has an age of 700,000 years (CENAPRED, 1995)
- Its geographical position is: 19.0°N and 98.6ºW
- Popocatepetl means "Smoking Mountain"
- Elevation: 5,465 m (17,930 ft).

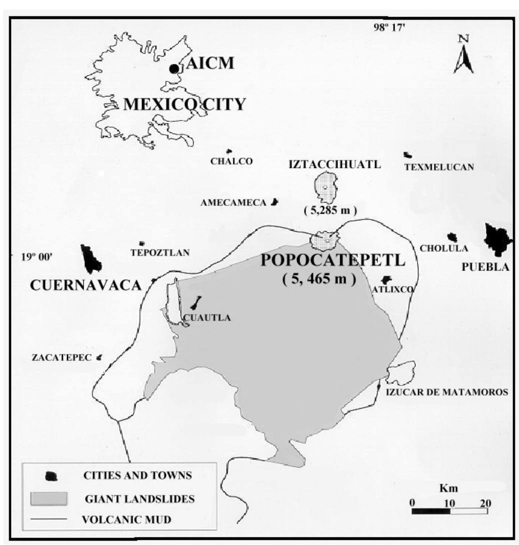


Fig. 1: Location of Popocatepetl volcano (source: CENAPRED).

AICM FEATURES

- About 830 operations take place daily.
- In 2003 about 21 million passengers used the AICM.
- It is located in the Northeast Mexico City area, at 35NM northwest of Popocatepetl volcano.
- Elevation: 2,229m (7,316 ft).
- Geographical location: 19°25'N and 99°05'W.

THE JUNE 30, 1997 CASE

Popocatepetl volcano is so close to Mexico City and consequently close to the "Benito Juarez" International Airport of Mexico City (AICM). This means the constant threat of volcanic ash plumes due to summer circulation which has a East/Southeast (E/SE) wind component in the low and middle levels of the atmosphere, between May to October months of each year.

There are no records in the history of AICM that indicate the volcanic ash has impacted the Airport of Mexico City like the case we are going to discuss. As we pointed before, Popocatepetl volcano started with some important activity at the end of 1994. During the years of 1995 to 1996 occurred some considerable eruptions. However, in the evening of June 30, 1997 a big one was present. At 19:26 hrs. LT (0026 UTC), the crew of AVIACSA airline reported that a large volcanic ash plume from Popocatepetl was moving to Mexico City. This was the first report received in the CAPMA of SENEAM. Few minutes later, at 19:30 hrs. LT (0030 UTC), a report from CENAPRED, confirmed the eruption indicating the ash column reached, in few minutes, a high of 8km from volcano crater (De la Cruz-Reyna and Quaas, 1997). That means the ash column reached an altitude of more than 40,000 ft.

According to sounding of Mexico City of July 01, 1997 at 0000 UTC, at middle levels we had winds with a component of the east with 20knots (kt), meanwhile in upper levels (25,000 to 40,000 ft), the winds had a direction from southeast with an intensity of 15 kt. This sounding showed a deep layer of 7km of moisture (around 4.7km thickness). The weather reports (METAR) from AICM indicated a ceiling conditions of broken of low clouds, overcast of middle clouds and light rain. These weather conditions presented to observers a difficulty to evaluate what was going on that evening. On the other hand, the convective clouds covering Popocatepetl volcano did not allow us to observe the ash plume in the GOES-8 satellite infrared imagery. The ash started to fall around 0110 UTC over the AICM and ending at 0645 UTC. We recognize that this surprised event caused some confusing among the personal who work at the AICM because it was the first time we had an event like this. The Local Security committee of AICM determined to close the airport at 21:20 hrs. LT (0220 UTC).

The Air Traffic Services of SENEAM prepared 10 airports as alternative airports to receive the deflected flights. The AICM was closed for about 10 hours. At 07:13 hrs. LT (1213 UTC) of July 1, 1997 the International Airport of Mexico City started operations using the 05R runway. To clean up the runways was a difficult mater, we had to use brooms to sweep the dust and particles of volcanic ash from the runways surface. The aeronautical operations of AICM were recovering gradually. At 16:13 hrs LT (2113 UTC), the runway 05L was opened to air traffic (DGAC, 1997).

This event caused a lot of damage and losses to aeronautical industry in Mexico. Table 1, shows us the economic impact that emissions of Popocatepetl volcano caused on June 30, 1997. The experience left by this eruption was taking into account and it has allowed us to improve our contingency plans in order to face with more efficiency episodes like these, that can happen again at any time.

Table 1: Economic Impact at AICM, June 30, 1997.

CONCEPT	AMOUNT	LOSSES ($USD)
WINDSHIELD DAMAGED	22	132,000.00
ENGINE DAMAGED	3	2,588,417.00
PASSENGERS AFFECTED	19, 000	
DELAYS	15,957 minutes	515,781.00
LOSSES DUE TO AFFECTED PASSENGERS		588,643.00
AIRLINE LOSSES		1,351,994.00
CANCELED FLIGHTS	205	
DELAY FLIGHTS	284	
DEFLECTED FLIGHTS	19	
AIRPORT CLOSED	10 HRS.	

Source: DGAC, SCT, 1997.

THE JULY 19, 2003 CASE

In this case, as the previous one, the trade winds were the cause of volcanic ash plume moves to Mexico City. That day of July 19, 2003, CENAPRED reported the event started at 09:20 hrs LT (1420 UTC) with a dense volcanic ash column which reached an altitude of more than 28,000 ft (CENAPRED, 2003).

The sounding of Mexico City (MEX) of July 19, 2003 at 1200 UTC, showed a wind profile with an east component almost in all levels with 10 to 15 kt speed. Because of this circulation the ash plume was forced to move to central and south areas of Mexico City. Fortunately, with this situation the AICM was less affected than the event of June 30, 1997. This pattern of wind was determinant to carry out the volcanic ash, mainly to Mexico City. The volcanic ash arrived AICM at 13:25hrs. LT (1825UTC). In other scenery, with a wind pattern like shown by the sounding of MEX at 1200Z of July 20, 2003, the impact on AICM had been devastate due to the wind direction, it was from the southeast, in the middle and upper levels of the atmosphere, with an intensity of 15kt. Fortunately this circulation occurred the next day of the event, so that, no ash emission occurred

The weather observations (METAR) of MEX reported, almost for five hours, from 191825Z to 192203Z, light volcanic ash fallen on AICM. Even with this condition, the visibility was ranging between 5 to 6 statute miles. Also, these weather reports indicated the ash plume was moving westward . In comparison with the June 1997 case, in this event the AICM was working nearly in normal conditions. The International Airport of Mexico City was closed only for 6 minutes, between 191832Z to 191838Z (ATS of SENEAM records, 2003). The airline with more delays was AEROMAR (Lydia Robles, 2004, personal communication). Table 2 shows the economic impact caused by the eruption of Popocatepetl volcano. No damage to windshield and engine of aircrafts were reported.

Table 2: Economic impact at AICM, July 19, 2003.

CONCEPT	**AMOUNT**	**LOSSES ($USD)**
PASSENGERS AFFECTED	380	
DELAYS	70 minutes	
AIRLINE LOSSES		19,250.00
CANCELED FLIGHTS	1	
DELAY FLIGHTS	2	
AIRPORT CLOSED	6 minutes	

Source: Airlines and ATS of SENEAM, 2004

CONCLUSIONS

We have learned a lot from the experiences left by these two cases. After this events we have to improve and verify our procedures and contingency plans to prevent as possible, the threat and effects of volcanic ash plumes. Some of the most important conclusions are pointed below:

- The aviation safety must be our first priority.
- Alert Pilots and Airlines, as soon as possible, about volcanic ash plumes to mitigate negative impacts like those discussed here.
- The communication and coordination between CAPMA and VAAC of Washington, CENAPRED, ATS, and DGAC have been improved significantly, since the June 30, 1997 event.
- Maintain a permanent volcano watch.
- Improve our contingency plans.
- Continuos training for operational meteorologists.
- The need of appropriate equipment such as: Wind profiler, Doppler Weather Radar, Software to analyze satellite data, etc.

ACKNOWLEDGMENTS

I would like to thank the USGS, NOAA, OFCM among others entities for their support to participate in the 2nd. International Conference on Volcanic Ash and Aviation Safety. Also, to thanks Authorities of SENEAM who gave me the permission to attend this important meeting. And finally, thanks to Grace Swanson, from VAAC of Washington, who is the person we have received a great collaboration in this matter.

REFERENCES

CENAPRED, 1995, 2003, SG.

De la Cruz-Reyna, Servando y Roberto Quaas, 1997: Resumen de la Erupción del Volcán Popocatepetl del día 30 de Junio de 1997. CENAPRED, Agosto de 1997.

DGAC, SCT Informe, 1997: Volcán Popocatepetl.

Robles, Lydia. 2004, Personal communication, Aeromar.

SENEAM, ATS records, Julio 19, 2003, ACC MEX..

THE DARWIN VAAC VOLCANIC ASH WORKSTATION

Rodney Potts[1], Mey Manickam[1], Andrew Tupper[2] and Jason Davey[2]
[1] Bureau of Meteorology Research Centre, Melbourne, Australia
[2] Bureau of Meteorology, Darwin Regional Office, Australia

Introduction

The Darwin VAAC has been operating since March 1993 providing advice on volcanic ash for the aviation industry in accordance with arrangements established as part of the ICAO IAVW (ICAO, 2001). The Volcanic Ash Advisories (VAA's) are based on an initial report of an eruption, an analysis of satellite data to identify and track the ash cloud, and a forecast of the movement of the ash derived from upper level winds and an atmospheric dispersion model. The VAA message is prepared in the agreed format and disseminated to the aviation industry. This process must be completed in a timely manner so that aircraft likely to be affected by the ash cloud can take appropriate avoidance measures.

There are a number of complex issues in the preparation of warnings relating to volcanic ash. There are numerous volcanoes in the Darwin area of responsibility and most are remote and not routinely monitored. As a result, advice of volcanic eruptions or ash clouds may be delayed. Current satellite data has proved of considerable value for detection of volcanic eruptions and the detection and tracking of ash clouds and there have been improvements in the utilisation of these data to support the volcanic ash warning service. However, the discrimination of volcanic ash from water/ ice clouds and delineation of the observed ash boundary remains problematic with current data and processing techniques. This necessitates intensive manual analyses of satellite data with resultant time and resource implications. Ash dispersion models provide useful guidance on the expected movement of an ash cloud but there are uncertainties in the wind field in the underlying atmospheric model and the source term for initialising the dispersion model. Moreover, the concentration of ash that presents a risk to aircraft, either for safety reasons or maintenance impacts, is not well known. Hence delineation of the forecast 'threat area' is also problematic. Finally the preparation of the VAA can be manually intensive and during busy operational periods this can cause undue pressure for operational staff. All these factors cause delays and increase the potential for errors in the provision of advice that is of critical importance to aircraft operating in regions where there are active volcanoes.

With these issues in mind there is ongoing effort in the Bureau that is designed to improve the efficacy of the advisory service that is provided. This includes improvements in the use of satellite data for detecting volcanic eruptions and ash clouds, improvements in the utilization of the volcanic ash dispersion model and streamlining the warning preparation process. In this paper we briefly examine the operational uncertainties, using the Indonesian Ruang eruption of 25 September 2002 as a case study, and then describe efforts directed at using available guidance in a more integrated and streamlined way for preparation of the volcanic ash advisory and a corresponding graphical product.

Ruang Volcano Eruption of 25 September 2002

The Ruang volcano is located in the Sangihe Islands of Indonesia at 2.28°N 125.425°E and around 0345 UTC, 25 September 2002, the volcano erupted to a height of approximately 20 km in clear conditions. The evolution of the ash plume was observed in hourly GMS5 satellite data and other satellite data (Tupper etal, 2004). Winds over the volcano at the time of the eruption were from the east in the layer up to 18 km and most of the ash plume moved to the west. A thin layer of ash and SO_2 in the layer 18-20 km did move to the east but for the purposes of this discussion is not considered further.

Fig.1a shows the IR1 (BT_{11}) image from GMS5 at 1230UTC and Fig. 1b shows the corresponding IR1-IR2 (BT_{11}-BT_{12}) channel difference image, with negative differences in orange and red indicating the possible presence of ash. It was possible to track the boundary of the ash cloud up to this time from a loop of the hourly visible, IR1 and IR1-IR2 images and Fig 1a also shows a manually analysed boundary for the ash plume. Discriminating ash from water/ice clouds and defining its boundary as it disperses can be difficult in visible and IR imagery, and although the IR1-IR2 image may show a well-defined ash signature it does not identify the full extent of the ash as shown in Fig 1. For this event the IR1-IR2 data showed the presence of ash for around 40 hours following the eruption but delineation of the ash boundary, or threat area, became problematic after just 9 hours. When there is active convection in the area and extensive water/ice cloud present, uncertainties in delineating the analysed threat area increase greatly.

Guidance on the dispersion of volcanic ash clouds is provided by the Hysplit dispersion model (Draxler and Hess, 1998) and Fig.2 shows model output for the Ruang eruption for the same time as that shown in Fig 1. This figure shows the integrated concentration from the surface to 18 km. Comparison of the boundary shown in Fig. 1a with that in Fig. 2 shows general agreement but the extent of the analysed ash is significantly greater. Such differences can arise because the forecast wind field from the underlying NWP model is not representative. There are also uncertainties in the source term for initialising the dispersion model, including

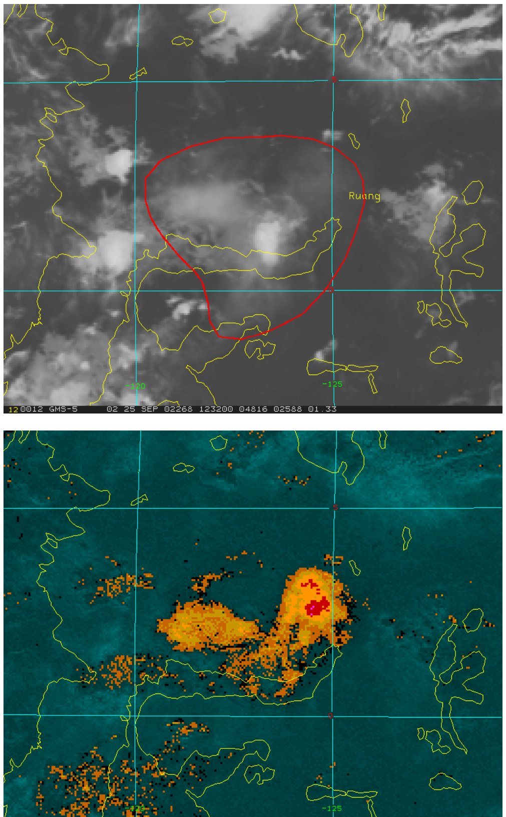


Figure 1. GMS-5 satellite imagery for 1230 UTC, 25 Sep 2002, showing Ruang eruption cloud. (a) IR1 image with manually analysed boundary of ash plume, and (b) image of brightness temperature difference (IR1-IR2) with blue indicating positive differences and orange/red indicating negative differences.

the height of the eruption plume and the mass distribution. Many dispersion models assume a line source but in reality there is horizontal spreading of the plume in the early stages due to internal dynamics of the eruption. This will contribute to greater spreading of the plume than models predict. Finally the nominal ash concentration that presents a risk to aircraft is not well known. These issues lead to uncertainties in delineating the forecast threat area.

These uncertainties mean that the forecaster must use satellite data and dispersion model output in an integrated way to provide the best assessment of the analysed and forecast ash boundary or threat area.

The Darwin Volcanic Ash Warning Preparation System (VAWS)

The Volcanic Ash Warning Preparation System (VAWS) has been developed to enable more integrated use of available satellite data and dispersion model output and to streamline the generation of the text and corresponding graphical volcanic ash products. The system also provides a stable framework that should simplify the operational implementation of improved analysis and prediction components that are underway.

The VAWS interface includes a map window that shows coastlines and all volcanoes in the region, a table for the display of relevant volcano details, a layer manager and a toolbar, as illustrated in Fig 3. Full roam and zoom capabilities are available in the map window and the user can select the volcano of interest, using the

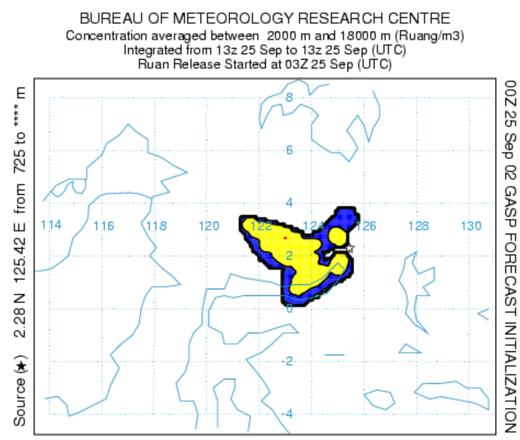


Figure 2. Hysplit dispersion model forecast for 1300 UTC, 25 September 2002 based on eruption at 0345 UTC.

mouse or a text based search, and add the volcano to the volcano table. The operator defines the analysed and forecast threat areas for 0 hr, +6 hr, +12 hr and +18 hr using the mouse and the VAA products are then generated in a two-step process. The operator selects the ‘Advisory’ icon on the toolbar and this generates a text dialogue that shows all the required fields for the VAA. Most fields are filled automatically using details derived from the graphical interface and the few remaining fields, such as the information source, are completed manually. The output products are then previewed and submitted for dissemination. The products include the VAA in text format and a corresponding graphical product (Fig 4) that was developed in liaison with regional aviation industry representatives. The output products are archived together with system files that store relevant information for each advisory and for the system status.

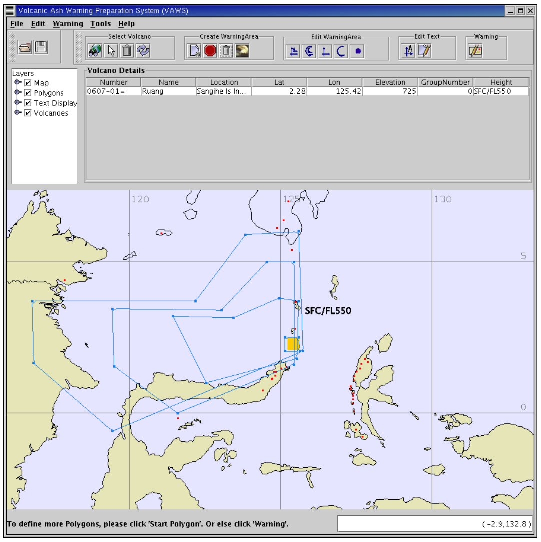


Figure 3. Graphical interface for Volcanic Ash Warning Preparation System.

In the development of the user interface several design criteria have been adhered to. These include platform independence; a responsive graphical interface; the need to integrate the system within the Bureau's operational infrastructure (Kelly, etal, 2004); the ability to display satellite data, NWP data and output from the

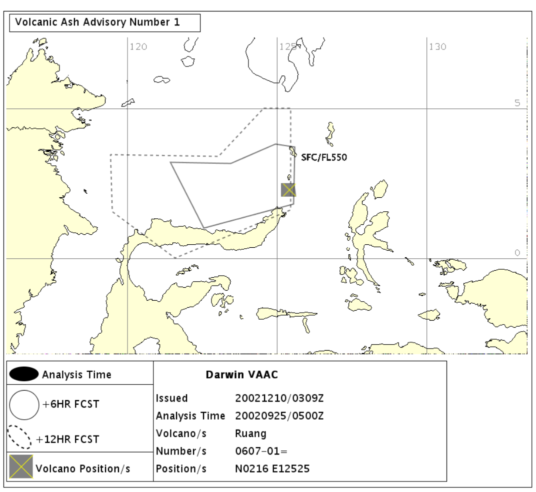


Figure 4. Volcanic Ash Advisory graphical product.

ash dispersion model using a concept of layers; and, the need to archive relevant information for training purposes and for ongoing research and development.

In the first stage of development the focus has been to streamline the preparation of the VAA message and to generate a corresponding graphical product. Future operational implementations of the VAWS system will allow for the display of satellite data and dispersion model output within the graphical interface and work on this is well advanced.

Operational Experiences

Operational use of the stage-one system started in December 2003 and over 200 VAA's have been generated and disseminated in the period up to 1 June 2004 with a text and graphical product for each. Following feedback from operational forecasters a number of upgrades have been provided to improve system operation and functionality. The system has streamlined the preparation of the VAA message, reduced the potential for errors, and feedback from forecasters has been positive. Feedback from the aviation industry on the format of the graphical product has also been positive. It is consistent with the text product and satisfies the need, expressed by flight planning personnel and pilots, for a concise and simple product that shows the variation of the ash boundary with time. The simple format also means the product remains legible when faxed to pilots at briefing stations that may have limited facilities.

Conclusions

The Volcanic Ash Advisories (VAA's) issued by the Darwin VAAC are based on an initial report or detection of a volcanic eruption or ash cloud, an analysis of satellite data to identify and track the ash cloud, and a forecast of the movement of the ash derived from upper level winds and an atmospheric dispersion model. Uncertainties in delineating the analyzed and forecast ash boundary or threat area, requires intensive manual analysis and integrated use of available guidance by the forecaster when generating output products for the aviation industry. This process, together with preparation of the VAA, can be time consuming with resultant delays and potential for errors.

The Volcanic Ash Warning Preparation System (VAWS) is a person-machine user interface that has been developed to streamline preparation of the VAA text product and automatically generate a corresponding graphical product. It enables satellite data and dispersion model outputs to be used in a more integrated way to delineate the analysed and forecast threat areas. The system should also provide a stable framework that simplifies the operational implementation of improved analysis and prediction components that will be developed in the future. The system has been in operational use since December 2003 and feedback from forecasters and the aviation industry has been positive.

References

Draxler, R.R. and G.D. Hess, 1998: An Overview of the Hysplit_4 Modeling System for Trajectories, Dispersion, and Deposition, Aust. Met. Mag., 47, 295-308.

ICAO, 2001: Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds. ICAO Doc 9691-AN/954, First Edition-2001.

Kelly J., A.Donaldson, C.Ryan, J.Bally, J. Wilson and R. Potts, 2004: The Australian Bureau of Meteorology's next generation forecasting system. 20th IIPS Conference, AMS.

Tupper A., S. Carn, J. Davey, Y. Kamada, R.J. Potts, F. Prata and M. Tokuno, 2004: An evaluation of volcanic cloud detection techniques during significant eruptions in the western 'Ring of Fire'. Remote Sensing of Environment, 91, 27-46.

SHARED SITUATIONAL AWARENESS AND COLLABORATION THROUGH THE USE OF THE VOLCANIC ASH COLLABORATION TOOL (VACT)

Jeffrey M. Osiensky, NWS Alaska Aviation Weather Unit, Anchorage, AK, USA
Greg Pratt, NOAA Forecast Systems Laboratory, Boulder, CO, USA
David J. Schneider, USGS Alaska Volcano Observatory, Anchorage, AK, USA
Lynn Sherretz, NOAA Forecast Systems Laboratory, Boulder, CO, USA

There are approximately 100 historically active volcanoes located in an area stretching from Alaska to the Northern Kurile Islands. Many of these volcanoes are located within close proximity to the major North Pacific (NOPAC) jet routes that traverse the Pacific Ocean. Aircraft flying at speeds of 500 mph or greater coupled with the close proximity of these historically active volcanoes to the jet routes, creates a potentially serious hazard to aviation with potentially rapid ash encounters. This situation requires a highly accurate and rapid response in volcanic ash plume forecasting to the aviation community. Several groups are responsible for monitoring and forecasting volcanic ash in the North Pacific area. It is imperative that all agencies speak with “one voice” with regard to plume height, aerial extent and movement. In order to facilitate real-time collaboration during North Pacific eruptions, a pilot project was instituted in 2003 to develop the Volcanic Ash Collaboration Tool (VACT). The VACT consists of workstations located at the Anchorage VAAC, the Anchorage Center Weather Service Unit, and the USGS Alaska Volcano Observatory, with shared access to satellite and meteorological data. The VACT allows for shared situational awareness by providing common views of the data sources, and by allowing all groups to view, enhance and annotate graphical data. The project team is continuing to define requirements for the system with implementation through rapid software updates. This presentation will provide an overview of the VACT, demonstrate some of its current and future capabilities, and propose how a system such as this could enhance collaboration between international agencies.

PERSPECTIVES ON OPERATIONAL VOLCANIC ASH WARNINGS

James Travers, Hordur Thordarson

Meteorological Service of New Zealand (MetService), Wellington, New Zealand

ABSTRACT

MetService is directly involved in many aspects of volcanic ash warnings for a large part of the South Pacific Ocean and for New Zealand, and has a long history of involvement with the International Airways Volcano Watch (IAVW). MetService operates the Wellington VAAC and is the operational co-ordinator of the New Zealand domestic Volcanic Ash Advisory System (NZ VAAS). This is a local enhancement of the Wellington Volcanic Ash Advisory Centre (VAAC). MetService personnel have actively participated in the work of the ICAO ASIA/PAC Working Group on Volcanic Ash and successor groups. MetService undertakes a National Meteorological Service (NMS) role under contract to the New Zealand Government. It also provides a wide range of commercial services to the media, the general public, industry and to aviation. As a service provider in these roles, combined with a long and active involvement with ICAO and WMO, there have been lessons learned over many years and perspectives gained. This paper offers some of these perspectives in terms of international aspects of warning services, the structure of warning systems, development of customised services, what seems to work for users and what doesn't.

1. Introduction

The Meteorological Service of New Zealand in Wellington provides a Meteorological Watch Office (MWO) and a Volcanic Ash Advisory Centre (VAAC). As such we provide SIGMETs and Volcanic Ash Advisory (VAA) messages. Work is ongoing to improve these messages and warnings by increasing the quality of the information used to generate these messages, understanding the limitations associated with such information and gaining an understanding of user needs.

The Wellington VAAC area covers much of the Southwest Pacific Ocean. The area encompasses our own FIR along with parts of the FIR areas of Honiara, Nauru, Nadi and Tahiti. This, along with the fact that parts of our VAAC area are remote and some of the volcanoes are not monitored, presents a challenge that we work hard to face. High quality information about volcanic activity is available within New Zealand but it is sometimes difficult to obtain such information from the outer reaches of our VAAC area.

The VAA format, VA SIGMETs, our operational experience via a real example and lessons we have learned from interaction with the aviation industry will be discussed.

2. The Volcanic Ash Advisory format and VA SIGMETs.

It is fair to say that there is some ambiguity regarding the role of the VAA and it's content. In some cases the VAA seems to be used as a volcanic ash warning for aviation, thus extending its role beyond what was originally envisaged. Warnings for aviation, whether they pertain to severe icing, turbulence or volcanic ash have traditionally been disseminated as SIGMETs. MWO offices in some parts of the world do not always issue SIGMET warnings about volcanic ash. This problem has in some cases been addressed, by including information, which would normally be contained within a SIGMET, in the VAA.

The view of the MetService is that the VAA should remain a mechanism for sharing scientific information between VAA Centres and MWOs. Warnings for aviation should be contained within SIGMETs and if volcanic ash SIGMETs are not being issued for one reason or another, then steps should be taken to rectify that situation.

Also, it is our opinion that the current format can sometimes contribute to unrealistic expectations regarding the accuracy of the advisory. In many cases the ash envelope can not be specified 6,12 and 18 hours forward in time with great precision. It is easy for end users to gain the impression that if the ash envelope is specified by an area bounded by points in degrees and minutes of latitude/longitude, then this information can be trusted to the extent that flights can be planned directly adjacent to the forecast ash envelope area. This is a dangerous practice because of the uncertainties involved in forecasting the dispersion of an ash envelope. Information regarding the initial ash plume height may be missing or of poor quality and atmospheric forecast models do not always forecast winds correctly.

Given these facts the VAA format should be simplified and there should not be a demand for such precise forecasts of the ash envelope, 6,12 and 18 hours forward in time.

We should work to improve our capabilities but we should not imply that we are capable of something that we are in fact not.

2. The eruption of Lopevi in June 2003

Lopevi is one of many active volcanoes located in the Republic of Vanuatu in the Southwest Pacific. This region is important for international aviation since flight routes between the United States and Australia cross it. It lies within the Wellington VAAC area.

Vanuatu has few resources for monitoring volcanoes and timely, accurate and reliable observations can not be always be expected.

Lopevi is not monitored by seismographs and no warning or indication was received in the Wellington VAAC before the volcano actually erupted on the 8th of June 2003. An airborne observer at 5,000 feet made the initial observation and reported ash up to above 40,000 feet. "A massive rate of growth and a black/brown plume becoming white at high altitude".

This report raises the question, how did an observer at 5,000 feet estimate that the ash rose to above 40,000 feet? The actual height of the ash plume is of course a critical piece of information. This needs to be known with a fair degree of accuracy in order to be able to forecast the dispersion of the ash. Of course the height of the ash plume also needs to be known to ascertain the impact on aviation. Will it be possible to fly above the plume or must it be avoided altogether?

These can quickly become important questions from an operational point of view. Whether or not trans Pacific flights will have to be diverted or not may hinge upon the answers. One such diversion can easily cost more than $US 100,000. The cost would of course be much greater should a flight actually encounter volcanic ash, exposing passengers and crew to danger and making repairs necessary to aircraft costing tens of millions of dollars.

We were not able to verify the initial observation by using satellite imagery and we did not receive any other observations at the time. Therefore we had to base our assumptions on the initial observation being true.

During the 7 days this eruption lasted, we only received 7 direct observations and only two of these mentioned ash above 10,000 feet.

This example highlights the uncertainties and difficulties involved in forecasting ash dispersion from volcanoes in remote areas. VA advisories can sometimes give little more than rough estimates of ash envelopes. Specifying envelopes far into the future with high precision can be misleading. Computer models have achieved a high level of performance. It must however not be forgotten that when initial observations are of poor quality, then output from the models will reflect this.

It is important that end users know as much as possible about volcanic ash and its impact on aviation. They also need to understand what VA advisories are, and the limitations associated with them.

3. What could be improved?

The most important factor that contributes to being able to provide timely and accurate information about volcanic ash is close collaboration by all agencies involved. Civil aviation authorities, Geological and Meteorological services need to keep in contact in order to assure a smooth fast flow of information whenever the need arises.

If MWOs are unable to issue VA SIGMETs for some reason, then they need to be helped to do so.

Everyone needs education. Typical eruption patterns for major volcanoes, effects of volcanic ash, uncertainties involved in ash envelope forecasting, etc. need to be known by all involved.

Observations need to be improved. Advances in remote sensing need to be utilised. The importance of direct observations must not be forgotten. Reconnaissance flights by light aircraft are relatively inexpensive compared to many other means of observing volcanic ash, and should be exploited where possible.

4. The situation within New Zealand

A comprehensive system for monitoring and observing volcanoes and a system for interaction between agencies involved is in place in New Zealand. This is provided through interaction between aircraft operators, the Civil Aviation Authority of New Zealand, Airways Corporation New Zealand, the Institute of Geological and Nuclear Sciences and the Meteorological Service of New Zealand. Issues illustrated in the Lopevi case do not present problems within New Zealand.

5. Summary

Timely, simple, accurate and realistic warnings are what end users need and this is what we should strive to provide. Nothing is gained by unnecessary complication that can fuel unrealistic expectations and cause confusion.

Communications between all the agencies concerned with VA warnings need to be maintained and strengthened. Good working relationships should be developed. Advances in remote sensing must be monitored and utilised if they are to increase our ability to detect ash. A course of action that could lead to significant advances in volcanic ash forecasting is to improve monitoring, observations and contacts with people in areas outside New Zealand.

VOLCANIC CLOUD CONCEPTUAL MODELS FOR VOLCANIC ASH ADVISORY CENTRE OPERATIONS

Andrew Tupper[1], Gerald Ernst[2], Christiane Textor[3], Kisei Kinoshita[4], J. Scott Oswalt[5], Daniel Rosenfeld[6]

[1] Bureau of Meteorology, Darwin, Northern Territory, Australia, and School of Mathematical Sciences, Monash University, Victoria, Australia
[2] Geological Institute, University of Ghent, Krijgslaan, Ghent, Belgium
[3] Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France
[4] Faculty of Education, Kagoshima University, Kagoshima, Japan
[5]US Navy (retired), USA
[6]Institute of Earth Sciences, The Hebrew University of Jerusalem, Israel

Corresponding author address: A.C. Tupper, Bureau of Meteorology Northern Territory Regional Office, PO Box 40050, Casuarina NT 0811, Australia. E-mail: A.Tupper@bom.gov.au

Abstract

Volcanic Ash Advisory Centre operations are hampered by limited ground-based monitoring, imperfect remote sensing, and few reliable direct observations. These issues are fundamental and must be addressed to improve the warning service. However, it is also essential to maximise our use of the information available. A basic approach to factual uncertainty in operational meteorology is to develop conceptual models and related procedures that allow fast diagnosis of the nature of an event, the degree of risk, and the action required. The height of rise of a volcanic cloud, concentration of maximum ash, detectability of the cloud, cloud evolution and rate of ash deposition are all highly dependent on the meteorological environment. Therefore, we must consider how, given an assumed level of volcanic activity, a volcanic cloud will develop in its meteorological context. Here, we use ground and aircraft based video observations from Japan and the Philippines, remote sensing of the Pinatubo 'Volcanic Thunderstorms' using particle radius measurement techniques, and results from the Active Tracer High Resolution Atmospheric Model to discuss modes of volcanic convection, relative particle concentrations, and plume dispersal. In mid-latitude winter and summer, and active and inactive periods of the tropical monsoon, conceptual models can be developed which allow implementation of pre-defined risk management strategies, and quick remote sensing and other report interpretation during an event. The further development of these models relies on continued close co-operation between the aviation, meteorological, and geophysical communities.

Introduction

Despite the rapid advances in remote sensing and ground-based monitoring of volcanic clouds, there are still large deficiencies in our observation system. Remote sensing of eruption clouds using meteorological satellites is severely hampered by the presence of overlying cloud or of water within the eruption cloud (Rose *et al.*, 1995: Tupper *et al.*, 2004a), human ground-based height observations are often severely limited, and instrumental monitoring for aviation purposes is patchy (Tupper and Kinoshita, 2003).

This is a difficulty primarily because the International Airways Volcano Watch is designed as a reactive system; warnings are issued (and airspace is closed) based on confident observations of volcanic ash, rather than on the possibility of volcanic ash. This contrasts with, for example, tropical cyclone or mid-latitude severe storm warning systems, where often patchy observations are coupled with increasingly sophisticated conceptual models to produce credible warnings. Warnings for volcanic clouds are relatively new, and so the application of conceptual models has been rather limited to the present.

Since the 1st International Symposium on Volcanic Ash and Aviation Safety, a great deal has been added to our understanding of volcanic cloud characteristics. The main variations on the basic eruption column conceptual models (Self and Walker, 1994) are the effect of wind and moisture on the development of eruption columns and on the observability of the eruptions with remote sensing.

In this paper, we give some examples of how particular understandings of volcanic cloud behaviour could affect the warning strategy for that event.

Wind Effects

The effect of wind on eruption columns, particularly weaker eruption columns, has been covered extensively in theory and observation (Ernst *et al.*, 1994: Sparks *et al.*, 1997: Woods, 1998: Graf *et al.*, 1999). For large eruptions, Graf et al. (1999) suggest a difference in the mean height of ash of as much 7 km between different wind regimes, although these results were based on a Cartesian formulation of the model and may be overestimated. Fig. 1 shows the effect that strong winds can have on a smaller volcanic plume in a summer situation – explosions that would normally be expected to rise to moderate altitudes shear immediately and barely rise above the volcano top. Ground based gas and ash measurement stations will record anomalously high values in the path of the plume and the plume will rapidly extend a great distance away from the volcano, possibly affecting airports and nearby shipping (Kinoshita *et al.*, 2003) but posing a relatively low risk to overflying aircraft.

Figure 1 - Explosions from Sakurajima, Japan are immediately 'blown down' over Sakurajima town in a lee wave, 3 August 1999, as a typhoon passes close to the area.

Where minor explosions are known to be a consistent feature of activity at a volcano but cannot be observed due to bad weather and lack of instrumentation, a strategy can be developed which allows appropriate NOTAMs and SIGMETs to be issued well in advance, based on forecast wind variations assuming continuation of the same volcanic activity level.

Moisture Effects

The effect of moisture on plume rise has been modelled by simple models for a range of plume sizes (Woods, 1993), and by the Active Tracer High Resolution Atmospheric Model (ATHAM) model for Plinean style eruptions (Graf *et al.*, 1999). The effect is difficult to show in observations because of the other variables involved; for example, the plumes of Satsuma-Iojima in sub-tropical Japan show a pronounced seasonality in height, but it is difficult to separate wind and stability influences (Matsui *et al.*, 2004). As a generalisation, however, moist convection can be coincident with, or induced by, volcanic activity, and can transport volcanic ash to any altitude within the troposphere or lower stratosphere. In other words, a large eruption is not required for transportation of volcanic ash to cruising levels, given the appropriate meteorological conditions.

Fig. 2 shows a typical (moist) summer situation over Sakurajima. On this day, the active vent (on the right) was emitting gas, steam and ash continuously without explosions, with the result that ash-bearing cumulus was forming continuously over the vent and dissipating to the north (left of picture), leaving fine ash at cloud-top levels. Discussions with observers in Japan, Indonesia and Papua New Guinea suggest that, in this common situation, the height of volcanic ash officially reported would be the base of the cloud, since the cumulus cloud is not regarded as being volcanic.

Figure 2 - Cumulus over Sakurajima, 12 Aug 2002, 0750 UTC. After Tupper & Kinoshita (2003).

A complex picture emerges when considering an active volcano interacting with the broader environment. Fig. 3 shows the mean brightness temperature measured over the Philippines, using hourly data for three and a half months following the climactic 1991 Pinatubo eruptions. During this period, smaller eruptions, secondary explosions and 'volcanic thunderstorms' were common over the area (Oswalt *et al.*, 1996), yet not one high level ash event could be explicitly detected using the split-window algorithm (Tupper *et al.*, 2004b).

The Pinatubo area was, however, the most active source of convection in the whole region during that period, as shown by the coldest mean brightness temperature (i.e. highest average cloud tops) in Fig. 3. Analysis of the diurnal variation (Fig.4) shows further that the diurnal cycle of convection remained dominant over Pinatubo, but that the cycle was shifted significantly earlier when compared to nearby topography, due to the convection initiation from lower level explosions and the heating of the denuded area around the mountain. Knowledge of these interactions can help to set warning policy; in the absence of any other information, deep convection near an erupting volcano should be assumed to contain at least trace levels of ash.

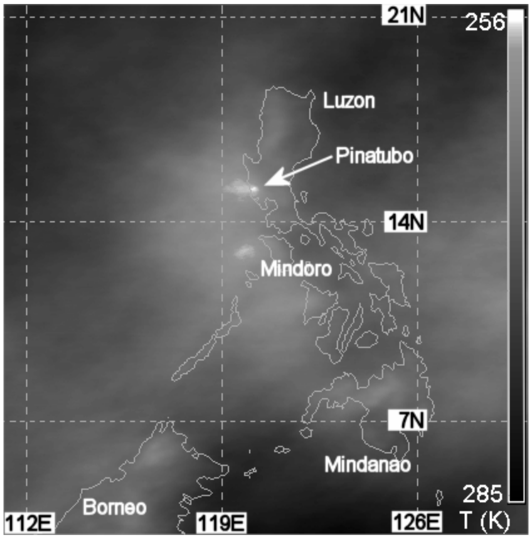


Figure 3 - Mean GMS-4 brightness temperature, 17 June - 30 Sept 1991 (excluding typhoon-cloud affected days), Philippines area.

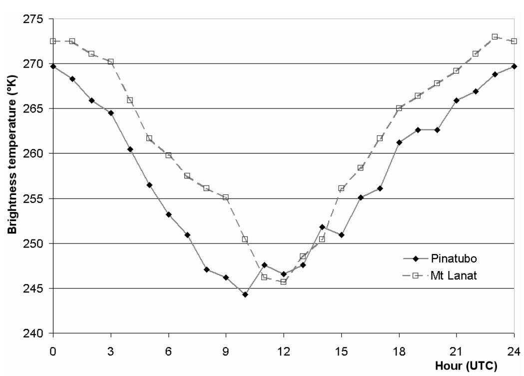


Figure 4 - Diurnal variation of mean GMS-4 brightness temperature above Mt Pinatubo (solid line) and nearby Mt Lanat area (dashed line), Luzon, 17 June - 30 Sept 1991. Values are for 20x 20 km boxes, using the same source data as Fig. 3.

Putting the volcanic activity within a large-scale meteorological framework also helps us with the warning strategy. Fig. 5 shows the situation six days after the climactic eruption at Pinatubo; at this stage, a southwest monsoon surge was affecting the Philippines, with maritime convection cloudiness at a maximum in the early morning. On this day, radar suggested Mt Pinatubo was venting to about 20,000 ft (6.1 km), but deep convection (16-17 km) was unusually strong in the Pinatubo area. Normally, in a situation so cloudy, there could be no direct evidence of the ash cloud. However, recent work has shown that ash contamination of an opaque cold cloud top can be detected by measuring the effective radius of the cloud top particles using NOAA/AVHRR data. The relative smallness of the particles is proportional to the amount of ash in the cloud, with ice-laden eruption clouds from Pinatubo having measured effective radii of around 15 µm, 'clean' cumulonimbus tops 30-35 µm or higher, and ash-contaminated cumulonimbus (with ash entrained at lower levels) in-between (Rosenfeld and Tupper, 2004). In the 21 June 1991 case of Fig. 5, cloud tops with a notably reduced effective radius of 20-25 µm were found in the high level 'return flow' extending at least 100 km southwest from the volcano (Tupper *et al.*, 2004b).

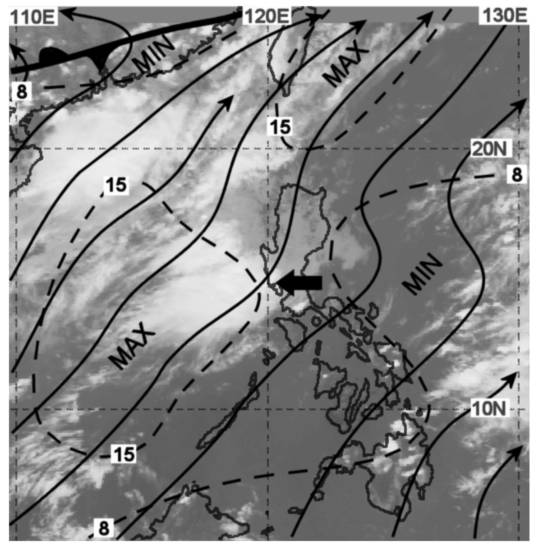


Figure 5 - 900 hPa streamline analysis overlaid on GMS-4 infrared image, 21 June 1991. The location of Mt Pinatubo, Philippines, is indicated by an arrow. Isotach values are indicated in m/s.

Warning seasonality

We now consider the effect on the International Airways Volcano Watch if assumptions about ash distribution are made on routine basis. Fig. 6 shows the consequences of the current system. There is a pronounced variation between wet season and dry season observation of ash, and therefore on the issue of volcanic ash advisories, for Semeru volcano in eastern Java, Indonesia. The increased warning incidence in the dry season is caused partially by the lack of cloud, but also by fresh dry winds causing low, long highly visible ash plumes. The actual activity at the volcano has not had any known seasonal variation over that ten-year period.

The current warning regime at Semeru is therefore focussed mainly on conditions that are relatively safe for flying. In the wet season, ash will rise higher and be hidden by extensive cumulonimbus cloud, so volcanic ash advisories are rarely able to be issued.

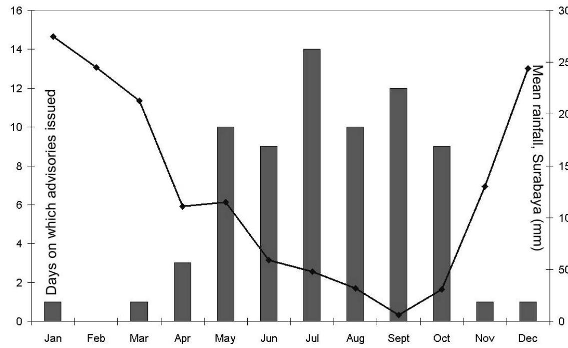


Figure 6 - Number of Volcanic Ash Advisories issued by Darwin Volcanic Ash Advisory Centre for Semeru by month (bars), against average rainfall from nearby Surabaya (black line), 1993-2003 (Davey *et al.*, 2003).

However, if the assumption of passive ash transport within cumulonimbus is made, there is a danger of substantial over-warning, as deep convection is very frequent around Indonesia's many active volcanoes. To reduce the possibility of over-warning, it will be necessary to a) define a warning threshold for ash concentrations, and b) examine ash dispersion and advection processes in the context of deep convection.

Ash removal processes

Given a warning threshold, how would we start to approach the ash dispersion problem?

Recent work with ATHAM (Textor *et al.*, 2003: Textor *et al.,* 2004a: b) has found a number of relevant results:

1) Hydrometeors are dominant in controlling many processes within the volcanic plume, even when a relatively dry lower troposphere leads to water evaporating from ash aggregates as they fall, thus giving the appearance of a dry ash cloud.
2) The collection efficiency of icy particles is sensitive to the amount of ice in the model, which is dependent upon the ambient humidity.
3) The initial size distribution of the erupted particles has a major influence on ash aggregation and sedimentation patterns.

Fig. 7 shows the mean height of particles in two size classes for a Plinean eruption, for the range of atmospheres described in Textor et al. (2003). With these ash-dominant, large eruption clouds, ice has a crucial role in the removal of particles from the atmosphere, but the small-sized particles of interest to aviation have a relatively long residence time.

Since the ash distribution over time is dependent on both the eruption and atmospheric characteristics, simulations would be necessary for a range of eruption types as well as atmospheres. More development work will be required to effectively model complex interactions such as those described for Pinatubo above.

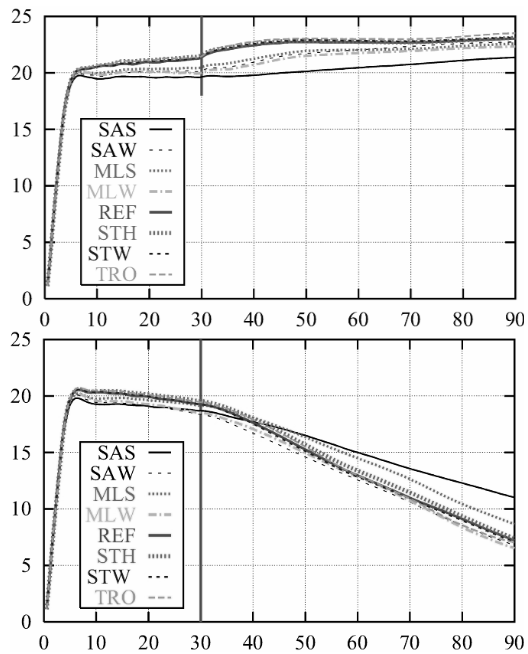


Figure 7 - Mean height (km) of small (top) and large (bottom) particle classes in Plinean style eruption clouds developing in a range of atmospheric conditions.

Conclusions

We believe that it is possible to integrate theoretical and observational knowledge of volcanic cloud interactions with the environment to develop useful conceptual models of volcanic ash cloud evolution, and then apply these models in an appropriate warning strategy. Marrying the complexity of volcanic clouds with the already challenging field of aviation meteorology is a formidable problem, but not impossible.

Basic understandings of wind, moisture, mesoscale and synoptic scale interactions can already be applied in a simple way to substantially alleviate the effect of incomplete observations. Advanced satellite techniques such as effective particle radius measurement will occasionally provide explicit evidence of ash affecting the microphysical processes in deep convection, and improve our conceptual models and warning confidence. Modelling using ATHAM-style models will eventually provide much greater insights into the processes within the cloud.

In order to make substantial progress in these areas, it is absolutely necessary to define a warning threshold of volcanic ash concentrations. The alternative will be substantial over-warning in situations where trace amounts of ash can be assumed to be present. Intensive investigation of aircraft encounters such as those described in this volume will aid these efforts.

References

Davey, J. P., A. C. Tupper, and R. J. Potts, 2003, Volcanic Cloud monitoring issues at the Darwin VAAC. *WMO/ICAO Third International Workshop on Volcanic Ash, Toulouse, France, September 29 -October 3, 2003*.

Ernst, G. G. J., J. Davis, and R. S. J. Sparks, 1994. Bifurcation of volcanic plumes in a crosswind. Bull. Volcanol., ***56***, 159-69.

Graf, H., M. Herzog, J. M. Oberhuber, and C. Textor, 1999. Effect of environmental conditions on volcanic plume rise. J. Geophys. Res., ***104***, 24309 - 20.

Kinoshita, K., C.Kanagaki, A.Tupper, and N. Iino, 2003, Observation and Analysis of Plumes and Gas from Volcanic Islands in Japan. *International Workshop on Physical Modelling of Flow and Dispersion Phenomena, 3-5 Sept. 2003*, Prato, Italy, Firenze University Press, 78-83.

Matsui, T., K. Kinoshita, S. Machida, H. Takahara, M. Yamamoto, and C. Kanagaki, 2004, Automatic long-time observation of the volcanic clouds at Satsuma-Iojima. *Volcanic eruption clouds in the Western Pacific - ground and satellite based observations and analyses*, K.Kinoshita, Ed., Kagoshima University, 74-82.

Oswalt, J. S., W. Nichols, and J. F. O'Hara, 1996, Meteorological Observations of the 1991 Mount Pinatubo Eruption. *Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines*, C. G. Newhall and R. S. Punongbayan, Eds., Philippines Institute of Volcanology and Seismology & University of Washington Press, 625-36.

Rose, W. I., D. J. Delene, D. J. Schneider, G. J. S. Bluth, A. J. Krueger, I. Sprod, C. McKee, H. L. Davies, and G. G. J. Ernst, 1995. Ice in the 1994 Rabaul eruption cloud: implications for volcano hazard and atmospheric effects. Nature, ***375***, 477-9.

Rosenfeld, D. and A. Tupper, 2004. Volcanic eruptions revealed through ash affecting satellite-inferred cloud properties, *submitted to J. Applied Meteorology*.

Self, S. and G. P. L. Walker, 1994, Ash clouds: characteristics of eruption columns. *First International Symposium on volcanic ash and aviation safety*, Seattle, Washington, US Geological Survey, 65-74.

Sparks, R. S. J., M. I. Bursik, S. N. Carey, J. E. Gilbert, L. Glaze, H. Sigurdsson, and A. W. Woods, 1997. Volcanic Plumes. Chichester: Wiley, 589 pp.

Textor, C., H. Graf, M. Herzog, and J. M. Oberhuber, 2003. Injection of gases into the stratosphere by explosive volcanic eruptions. J. Geophys. Res., ***108***, 4606 doi: 10.1029/2002JD002987.

Textor, C., H. Graf, M. Herzog, J. M. Oberhuber, W. I. Rose, and G. G. J. Ernst, 2004a. Volcanic Particle Aggregation in Explosive Eruption Columns Part I: Parameterisation of the Microphysics of Hydrometeors and Ash. submitted paper.

——, 2004b. Volcanic Particle Aggregation in Explosive Eruption Columns Part II: Numerical Experiments. submitted paper.

Tupper, A. and K. Kinoshita, 2003. Satellite, air and ground observations of volcanic clouds over islands of the Southwest Pacific. South Pacific Study, ***23***, 21-46.

Tupper, A., S. Carn, J. Davey, Y. Kamada, R. Potts, F. Prata, and M. Tokuno, 2004a. An evaluation of volcanic cloud detection techniques during recent significant eruptions in the western 'Ring of Fire'. Remote Sens. Environ., ***91***, 27-46, doi:10.1016/j.rse.2004.02.004.

Tupper, A. C., J. S. Oswalt, and D. Rosenfeld, 2004b. Satellite and radar analysis of the 'volcanic storms' following the paroxysmal eruption of Mt Pinatubo, Philippines, June-September 1991. for submission to J. Geophysical Research, under preparation.

Woods, A. W., 1993. Moist convection and the injection of volcanic ash into the atmosphere. J. Geophys. Res., ***98***, 17627-36.

——, 1998, Observations and models of volcanic eruption columns. *The Physics of Explosive Volcanic Eruptions*, J. S. Gilbert and R. S. J. Sparks, Eds., Geological Society, London, 91-114.

VOLCANIC ASH ADVISORY SUPPORT FOR THE U.S. DEPARTMENT OF DEFENSE

Richard Gonzalez and Charles Holliday
Air Force Weather Agency, Offutt AFB, Nebraska U.S.A.

ABSTRACT

The Air Force Weather Agency (AFWA) issues volcanic ash advisory products tailored for U.S. Department of Defense (DoD) support. AFWA's Meteorological Satellite Applications Branch (XOGM) monitors a variety of sources for volcanic ash plume activity, and creates both alphanumeric and graphic advisory products supporting DoD resource protection. In addition, AFWA serves as a hot backup for the Washington Volcanic Ash Advisory Center (W-VAAC).

BACKGROUND

Volcanic ash is a major concern to the DoD. Several U.S military installations stand within the shadows of active volcanoes in Asia, the Pacific, and the Mediterranean, while DoD aircraft regularly traverse regions susceptible to ash plumes from active volcanoes. Besides high altitude (>30,000 ft) transit of active volcanic chains, the DoD has localized operations in Southeast Asia, the Marianas Islands, and other regions. These areas frequently require sustained flight at much lower altitudes (<20,000 ft) near volcanoes increasing aircraft vulnerability to airborne ash.

AFWA at Offutt AFB, Nebraska provides volcanic ash advisory support for DoD customers. AFWA's XOGM issues a suite of text and graphical products tailored to DoD requirements for volcanic ash advice and forecasts. With U.S Forces operating worldwide, a standardized and consistent set of timely advisory and forecast products from one source is essential to DoD planners for both situational awareness and decision-making.

SATELLITE DATA

Satellite imagery plays a critical role in surveillance of recently active or potentially active volcanoes worldwide. In addition, it is used to verify and provide quality control for ash dispersion model forecast graphics output.

AFWA's operational global satellite database consists of five geostationary satellites providing frequent imagery refresh coverage of suspect areas. In addition, AFWA receives higher resolution global polar orbiter data over areas of interest via stored readout from two National Oceanographic and Atmospheric Administration (NOAA) and four DoD Defense Meteorological Satellite Program (DMSP) satellites.

XOGM augments the above imagery with data relayed from the Air Force MARK IVB network of tactical direct readout sites. This permits timely review of data over volcano regions at full resolution from both NOAA and DMSP satellites. In addition, the direct readout capability enables AFWA to leverage data from several older polar satellites for which stored readout is no longer possible.

XOGM uses the Satellite Image Display and Analysis System (SIDAS) to examine ash plume characteristics. This AFWA interactive graphics toolkit allows analysts to display, interrogate, and manipulate satellite imagery to maximize imagery data extraction.

SIDAS facilitates multi-spectral analysis including infrared channel differencing when meteorological cloud or darkness inhibits visual imagery inspection of ash plumes. In addition, data from other sources (conventional surface and upper air data, cloud drift winds, numerical analysis and prognosis fields) can be overlaid on the image to assist in the analysis of plume height or other features.

OTHER DATA SOURCES

Global monitoring of active volcanoes and airborne ash is an extensive task, and cannot be effectively accomplished with review of satellite imagery alone. Aircraft, surface reports, and alerts from volcano observatories often provide the first notification of an eruption.

A primary method to alert analysts to these reports is to use automated text filter capabilities to scan existing alphanumeric bulletin traffic across the DoD's Automated Weather Network (AWN). This XOGM developed software package interrogates Meteorological Aerodrome Report (METAR) observations, Pilot Reports (PIREPS), Significant Meteorological Information (SIGMET) bulletins, and civilian Volcanic Ash Advisories (VAAs). When ash is detected, the software alerts branch analysts and highlights the alphanumeric data for closer review and crosscheck with satellite imagery.

Although limited to a small number of volcanoes, AFWA leverages web cams as an additional method of monitoring. XOGM developed software provides a grid display of multiple volcano web cam sites with continuously updating animated image loops covering the last 30 min. This greatly assists the analyst in effectively managing limited time by eliminating the need to contact each web site for single image updates.

PRODUCTS

AFWA issues alphanumeric advisory and forecast graphic products when ash is detected or suspected. Bulletin updates on ash activity occur at six-hour intervals until the end of the event. As a measure of global activity for 2003, XOGM issued advisories for 450 initial eruptions from 38 volcanoes. Ongoing activity necessitated over 2,000 updates. Ash plumes below 20,000 ft accounted for 75% of the notices.

AFWA bases its forecast graphic products upon the University of Alaska, Fairbanks' volcanic ash dispersion model called PUFF (not an acronym) and wind fields from the National Weather Services' (NWS) Global Forecast System (GFS). The current PUFF graphical user interface version includes customization for AFWA by the Johns Hopkins University's Applied Physics Lab. PUFF run length is dependent upon the height of the initial ash cloud and the duration of the eruption. Low-level eruptions (<20,000 ft) have a six hour run period with forecast intervals of three hours. Maximum run lengths for higher-level eruptions may extend to 48 hours with forecast intervals of 12 hours. Forecast graphics include both animated and static products.

The animated forecast is a color graphic product with dynamic, optimized geographical boundaries to incorporate the entire ash cloud at its maximum forecasted extent. Ash is visualized using a consistent color scheme, with ash plotted in five thousand foot (Kft) bins from the surface (Sfc) to 55 Kft.

The static graphic product is a set of four-panel charts for forecast intervals extracted from the PUFF model run. This is a color graphic product with fixed geographic boundaries and ash plotted within four flight levels – Sfc-12Kft, 12-24Kft, 24-36Kft, and 36-55Kft.

In addition to actual eruption situations, AFWA also prepares forecast products in both animated and four-panel static format for hypothetical eruptions. These automated products assist DoD flight planners in route decisions near active volcanoes, particularly during exercises and contingency operations.

COMMUNICATIONS

AFWA disseminates alphanumeric ash advisories via the AWN. In addition, the bulletins are e-mailed to numerous customers who have a direct interest in the products. Air Force customers include the Tanker Airlift Control Center (Scott AFB, IL), Operational Weather Squadrons, and selected Base Weather Stations. Products are e-mailed to other DoD agencies as well, such as the Navy's Meteorological & Oceanographic Centers. For eruptions likely to directly impact DoD facilities, product submission is preceded by telephonic communication to ensure timely notification.

XOGM posts volcanic ash imagery and graphic forecast products on the Joint Air Force and Army Weather Information Network (JAAWIN) web site for ease of access for customers. JAAWIN is a web-based system which provides DoD customers access to over

800,000 products daily. These include all forms of meteorological data products – satellite, model output, radar, lightning, observations, charts, space environment, and a myriad of other products. The JAAWIN Environmental Events page features the volcanic graphic products divided into four regions around the globe – the Americas, Europe/Africa, North Pacific, and South Pacific. For each active volcano, customers have direct access to alphanumeric bulletins, satellite imagery, and both the animated and four panel PUFF graphics.

WASHINGTON VAAC BACKUP

AFWA provides backup for the W-VAAC to ensure continuity of operations during power failures, communications outages, or other contingencies. During backups, AFWA assumes the monitoring function for the W-VAAC and issues volcanic ash text and forecast graphic products on behalf of Washington. To ensure readiness, AFWA and the W-VAAC hold quarterly exercises to test the effective execution of these duties. During 2003, AFWA provided immediate "hot" backup five times due to communications difficulties.

SUMMARY

AFWA is the DoD focal point for volcanic ash advisory products including monitoring, forecasting, notification and product dissemination. This is a mission of global extent carried out 24/7 by AFWA's Meteorological Satellite Applications Branch (XOGM). These efforts ensure planners and flight crews have the information needed to ensure mission accomplishment and resource protection.

WEB ACCESS TO THE VOLCANIC ASH ADVISORY DATABASE

Paula Dunbar, National Geophysical Data Center, Boulder, CO, USA
Grace Swanson, NOAA Satellite Services Division, Camp Springs, MD, USA

Volcanic ash is a significant hazard to aviation and can also affect global climate patterns. To ensure safe navigation and monitor possible climatic impact, NOAA's Volcanic Ash Advisory Centers (VAACs) track volcanic ash eruptions and monitor surface weather observations, aircraft pilot reports, and satellite imagery for ash clouds. The NOAA Washington VAAC is part of the National Environmental Satellite, Data, and Information Service (NESDIS) and the National Weather Service (NWS). The Satellite Analysis Branch (SAB) of NESDIS and the National Centers for Environmental Prediction of the NWS share duties as the regional Washington VAAC located in Camp Springs, Maryland. The Washington VAAC area of responsibility includes the continental United States and southward through Central America, the Caribbean to 10 degrees South in South America, and the United States controlled oceanic flight information regions (FIRs). The NOAA Anchorage VAAC is part of the Alaska Aviation Weather Unit in Anchorage and is responsible for Alaska and Anchorage FIRs and a small portion of Russia north of the Kamchatka peninsula.

NOAA's VAACs issue two products after a volcanic eruption. The first product, the Volcanic Ash Advisory (VAA) statement, includes text describing current volcanic activity and ash cloud position. The second product (when appropriate), the Volcanic Ash Forecast Transport and Dispersion (VAFTAD) model, provides a forecast of ash location in the atmosphere for the next 48 hours. All of this information is provided to the Federal Aviation Administration, the U.S. Geological Survey, Meteorological Watch Offices, climate analysts, and scientists in other countries.

The VAAC system had its roots in the 1980's when the NESDIS SAB began to provide the aviation and volcanology community real-time analysis of satellite products to support response actions to volcanic ash eruptions. In 1997, the Washington VAAC joined a global network formed by the International Civil Aviation Organization to provide worldwide coverage of volcanic ash events. Since the beginning of its volcanic ash monitoring program, the NESDIS SAB has maintained an archive of Volcanic Ash Messages, VAFTAD model output, and substantiating information. The substantiating information includes surface weather observations, pilot reports, volcanic observatory reports, news media reports, and satellite imagery for each event. The National Geophysical Data Center (NGDC) has had this analog archive scanned into image format and is now making it available on the web.

The digital archive, known as the Volcanic Ash Advisory Database (VAADB), currently consists of information from over 600 folders representing different eruptive episodes. Since the Washington VAAC originally had global responsibility for volcanic ash monitoring, the VAADB includes information on over 40 volcanoes from all over the world (Figure 1). The current database includes information from 1996 to 2001. It will eventually be extended back to the 1980's and will also include advisories issued after 2001 which are already in digital format. The VAADB images are being delivered over the Web using a geospatially-enabled relational database management system using a text-based search interface (Figure 2). Users can search the database using one or more of the following search parameters:

- Volcano name
- General location by description (region or country) or latitude-longitude entry
- Beginning date of the eruption
- Type of information (advisory or substantiating),
- Type of image (VAA, VAFTAD, Ash analysis graphic, Satellite imagery, Media report, Pilot report, Volcano Observatory report, Surface Weather Observation, etc.)

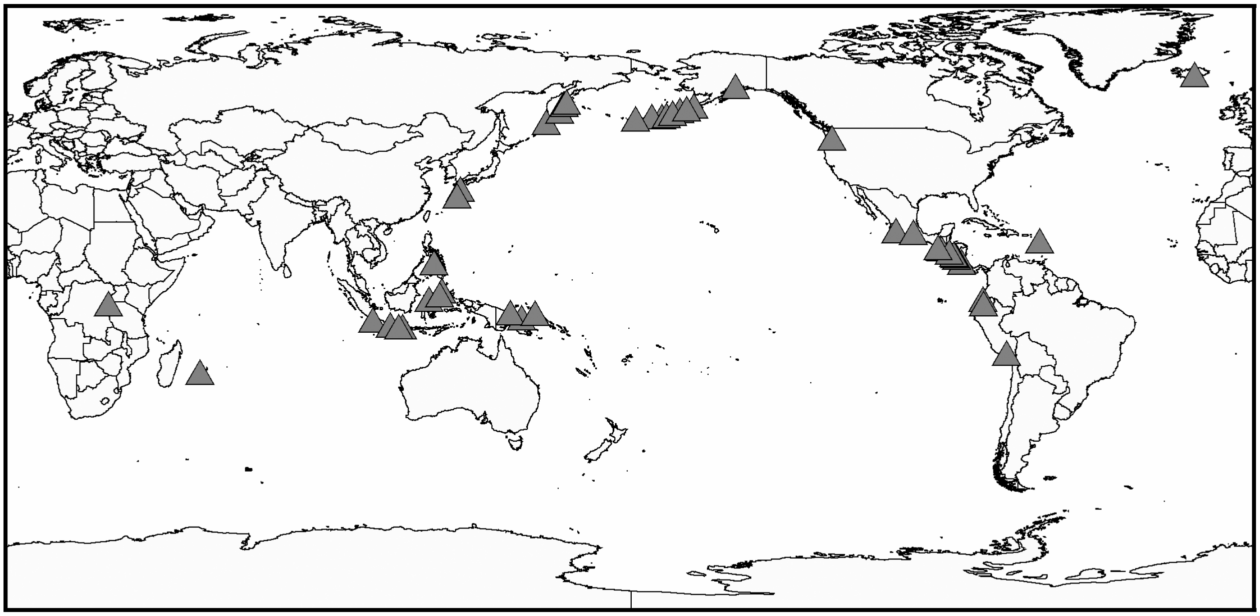


Figure 1. Volcanoes included in the Volcanic Ash Advisory Database.

Examples of the types of output and images currently available online are shown in figures 3-6. Figure 3 shows the result of searching the database for all images from Popocatepetl in Mexico. Figures 4-6 provide examples of advisory information for Popocatepetl during the March 1996 eruptive episode.

The VAADB will eventually be accessible via an interactive map interface and will be integrated into the NGDC Natural Hazards interactive map that provides Web-based GIS access to volcano, earthquake, tsunami, and auxiliary geospatial data. In addition, links will be provided to the Smithsonian's Global Volcanism Database, associated images in NGDC's natural hazards slide sets, and GOES imagery from the Comprehensive Large Array-data Stewardship System GOES active archive.

Volcanic ash modelers, climate analysts, and volcanologists will soon have web-access to a vast collection of data from past volcanic events. The VAADB website is listed below:
http://www.ngdc.noaa.gov/seg/hazard/vol_ash.html

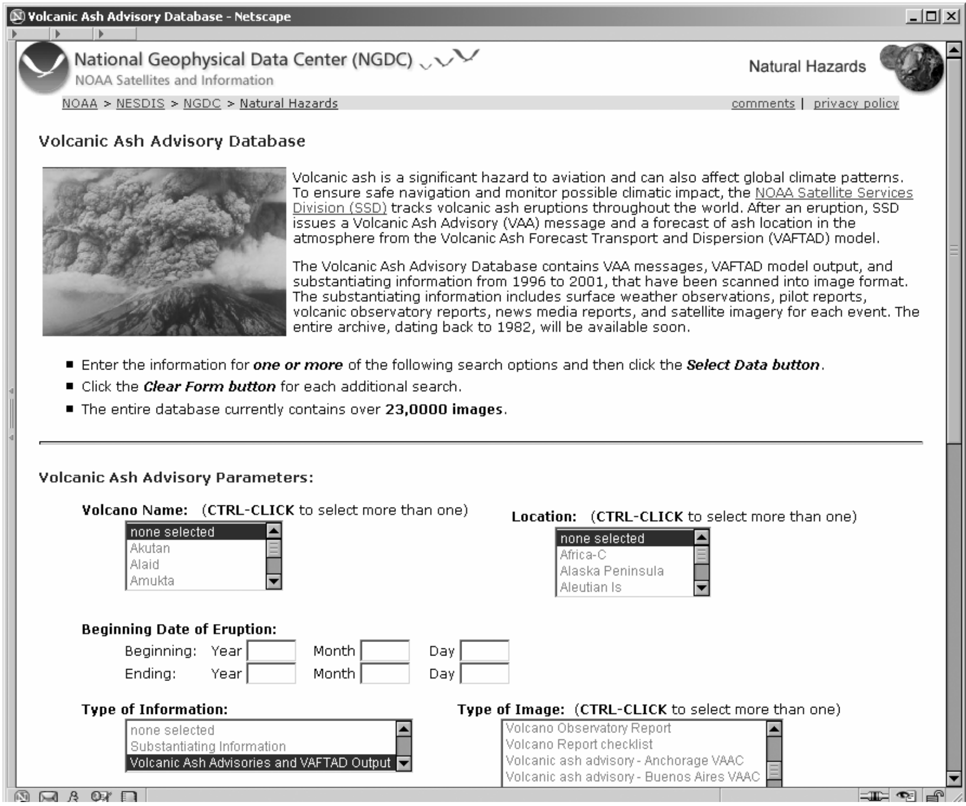
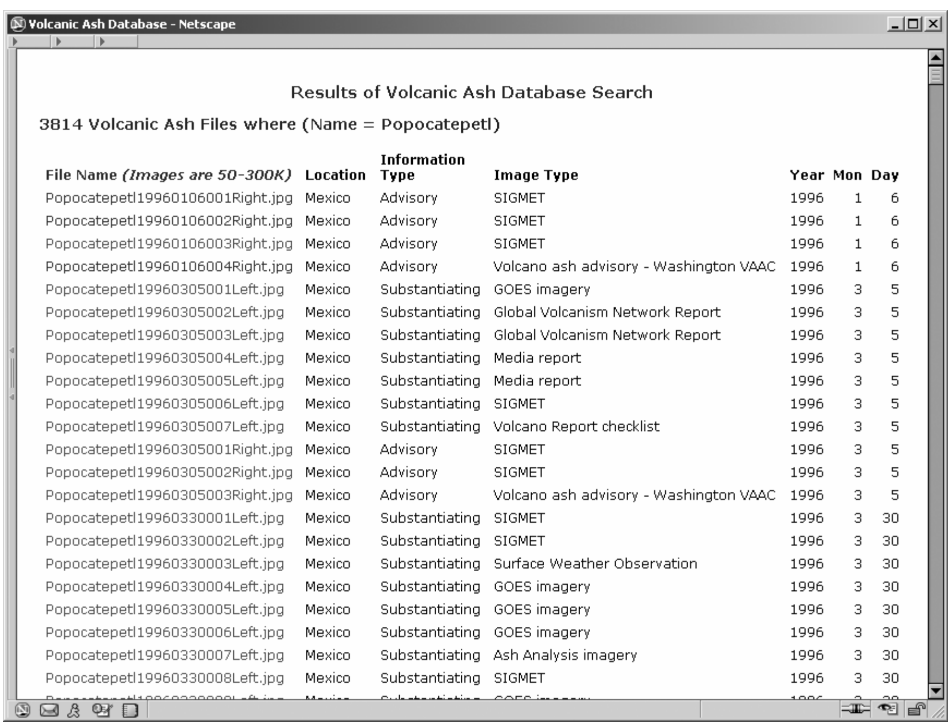
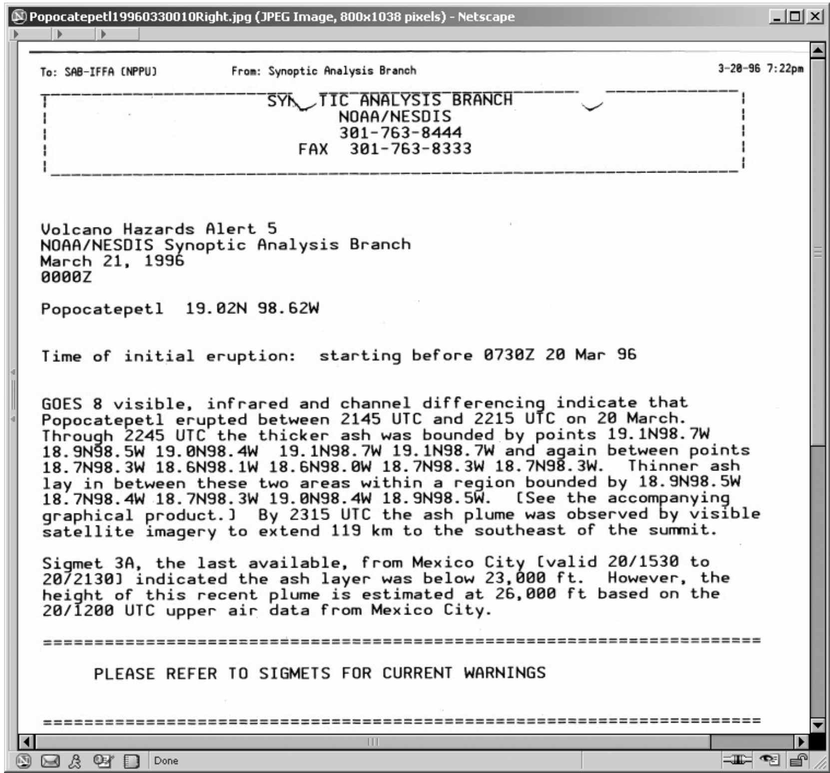


Figure 2. Search interface for the Volcanic Ash Advisory Database.



File Name *(Images are 50-300K)*	Location	Information Type	Image Type	Year	Mon	Day
Popocatepetl19960106001Right.jpg	Mexico	Advisory	SIGMET	1996	1	6
Popocatepetl19960106002Right.jpg	Mexico	Advisory	SIGMET	1996	1	6
Popocatepetl19960106003Right.jpg	Mexico	Advisory	SIGMET	1996	1	6
Popocatepetl19960106004Right.jpg	Mexico	Advisory	Volcano ash advisory - Washington VAAC	1996	1	6
Popocatepetl19960305001Left.jpg	Mexico	Substantiating	GOES imagery	1996	3	5
Popocatepetl19960305002Left.jpg	Mexico	Substantiating	Global Volcanism Network Report	1996	3	5
Popocatepetl19960305003Left.jpg	Mexico	Substantiating	Global Volcanism Network Report	1996	3	5
Popocatepetl19960305004Left.jpg	Mexico	Substantiating	Media report	1996	3	5
Popocatepetl19960305005Left.jpg	Mexico	Substantiating	Media report	1996	3	5
Popocatepetl19960305006Left.jpg	Mexico	Substantiating	SIGMET	1996	3	5
Popocatepetl19960305007Left.jpg	Mexico	Substantiating	Volcano Report checklist	1996	3	5
Popocatepetl19960305001Right.jpg	Mexico	Advisory	SIGMET	1996	3	5
Popocatepetl19960305002Right.jpg	Mexico	Advisory	SIGMET	1996	3	5
Popocatepetl19960305003Right.jpg	Mexico	Advisory	Volcano ash advisory - Washington VAAC	1996	3	5
Popocatepetl19960330001Left.jpg	Mexico	Substantiating	SIGMET	1996	3	30
Popocatepetl19960330002Left.jpg	Mexico	Substantiating	SIGMET	1996	3	30
Popocatepetl19960330003Left.jpg	Mexico	Substantiating	Surface Weather Observation	1996	3	30
Popocatepetl19960330004Left.jpg	Mexico	Substantiating	GOES imagery	1996	3	30
Popocatepetl19960330005Left.jpg	Mexico	Substantiating	GOES imagery	1996	3	30
Popocatepetl19960330006Left.jpg	Mexico	Substantiating	GOES imagery	1996	3	30
Popocatepetl19960330007Left.jpg	Mexico	Substantiating	Ash Analysis imagery	1996	3	30
Popocatepetl19960330008Left.jpg	Mexico	Substantiating	SIGMET	1996	3	30

Figure 3. Results of searching the VAADB for Popocatepetl.



Popocatepetl19960330010Right.jpg (JPEG Image, 800x1038 pixels) - Netscape

To: SAB-IFFA (NPPU)   From: Synoptic Analysis Branch   3-20-96 7:22pm

SYN TIC ANALYSIS BRANCH
NOAA/NESDIS
301-763-8444
FAX 301-763-8333

Volcano Hazards Alert 5
NOAA/NESDIS Synoptic Analysis Branch
March 21, 1996
0000Z

Popocatepetl 19.02N 98.62W

Time of initial eruption: starting before 0730Z 20 Mar 96

GOES 8 visible, infrared and channel differencing indicate that Popocatepetl erupted between 2145 UTC and 2215 UTC on 20 March. Through 2245 UTC the thicker ash was bounded by points 19.1N98.7W 18.9N98.5W 19.0N98.4W 19.1N98.7W 19.1N98.7W and again between points 18.7N98.3W 18.6N98.1W 18.6N98.0W 18.7N98.3W 18.7N98.3W. Thinner ash lay in between these two areas within a region bounded by 18.9N98.5W 18.7N98.4W 18.7N98.3W 19.0N98.4W 18.9N98.5W. [See the accompanying graphical product.] By 2315 UTC the ash plume was observed by visible satellite imagery to extend 119 km to the southeast of the summit.

Sigmet 3A, the last available, from Mexico City [valid 20/1530 to 20/2130] indicated the ash layer was below 23,000 ft. However, the height of this recent plume is estimated at 26,000 ft based on the 20/1200 UTC upper air data from Mexico City.

PLEASE REFER TO SIGMETS FOR CURRENT WARNINGS

Done

Figure 4. Example of Volcanic Ash Message from the VAADB for Popocatepetl.

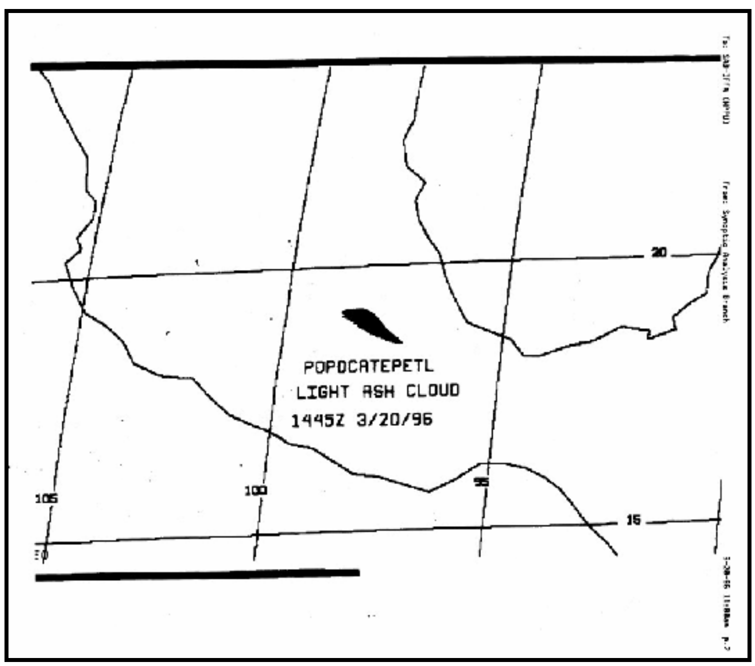


Figure 5. Example of Ash Analysis Graphic from the VAADB for Popocatepetl.

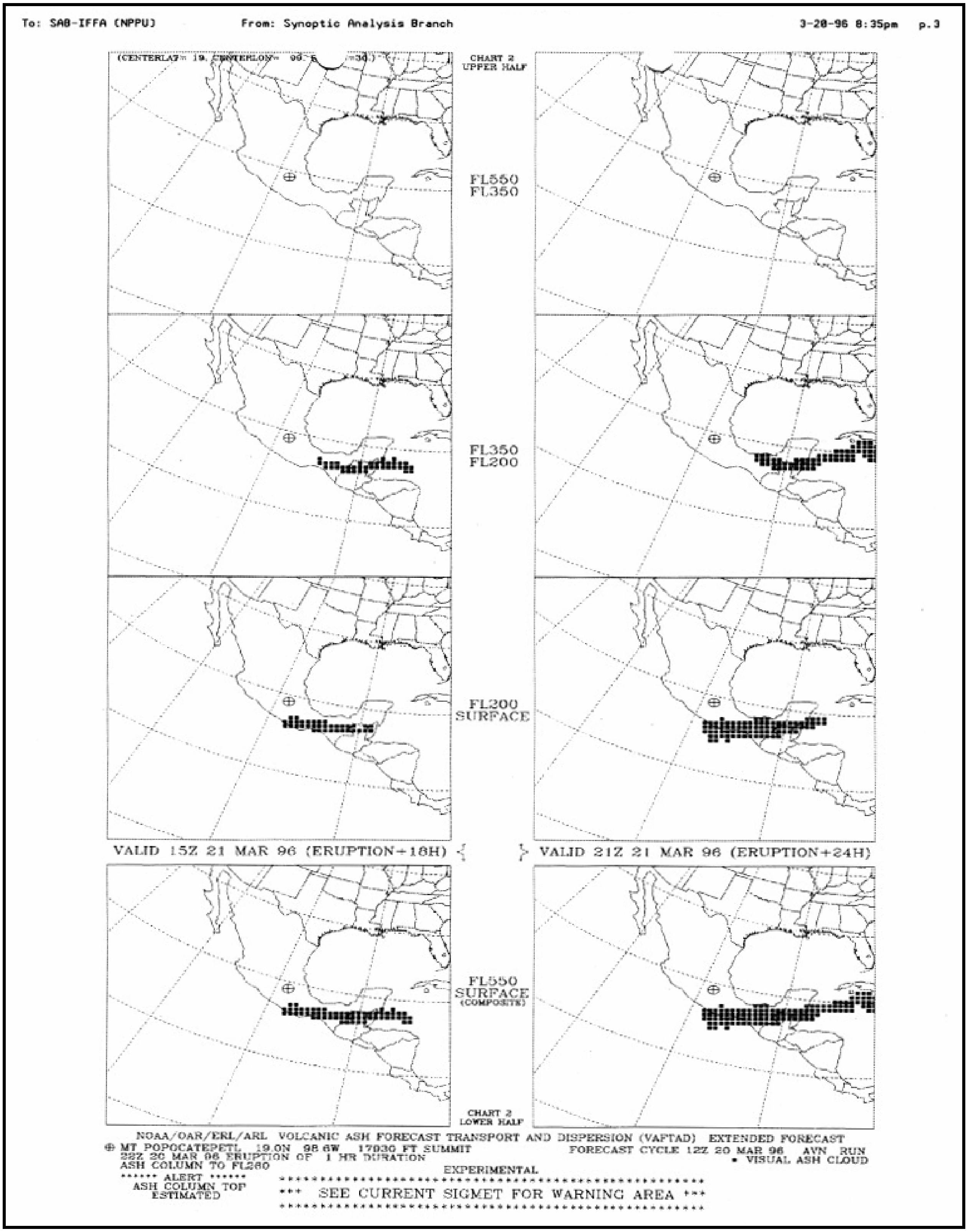


Figure 6. Example of VAFTAD output from the VAADB for Popocatepetl.

WASHINGTON VOLCANIC ASH ADVISORY CENTER (VAAC) OPERATIONS

Gregory M. Gallina and Davida Streett
Washington VAAC-NOAA/NESDIS/Satellite Services Division

Introduction

The Washington Volcanic Ash Advisory Center (VAAC) monitors and tracks airborne volcanic ash and disseminates text and graphical messages to the global aviation community. The Washington VAAC is part of a global network created by the International Civil Aviation Organization to provide nearly worldwide coverage of volcanic ash events. This network of centers includes VAACs, Meteorological Watch Offices (MWOs), and Area Control Centers (ACCs). VAACs provide ash information to MWOs (and vice versa) and the MWOs issue ash warnings for aviators by SIGMETs. VAACs also provide ash information to ACCs, and ACCs issue notices to in-flight aircraft via NOTAMs and ASHTAMs. VAAC information and products are also broadly disseminated to a variety of other users concerned about airborne ash (Fig. 1, not shown).

Globally, there are nine VAACs (Anchorage, Buenos Aires, Darwin, London, Montreal, Tokyo, Toulouse, Washington and Wellington), each having responsibilities for volcanic ash eruptions within their ICAO-determined boundaries (Fig. 2, not shown). Most of the world's airspace is facilitated by one of the VAACs; however, there are some gaps, usually over oceans and areas without active volcanoes. Notice in Figure 2 that the Washington VAAC area of responsibility includes the contiguous U.S., Mexico, Central America, South America north of 10°S, parts of the Pacific (including Hawaii and the Southern Mariana islands) and Atlantic Oceans (including the Caribbean). Under normal circumstances, VAACs will only issue ash advisories and trajectory models when an eruption or ash occurs within their area of responsibility. Each VAAC ensures that ash products (described more in VAAC Products section below) are issued when an eruption or airborne ash occurs within their geographic area of responsibility and the appropriate MWOs are contacted/receive the information so warnings (SIGMETS) can be produced.

The Washington VAAC is a joint collaboration between the Satellite Analysis Branch (SAB) of the National Environmental Satellite, Data, and Information Service (NESDIS) and the NCEP Central Operations (NCO) of the National Weather Service. Although the Washington VAAC was chartered in 1997 by ICAO, NESDIS and the NWS have a long history of monitoring volcanic ash events. The NESDIS component, SAB, has had over 20 years of experience monitoring volcanic ash via satellite imagery. The NWS component, NCO has worked with volcanic ash by utilizing ash trajectory models for the past 10 years. Both organizations are part of the National Oceanic and Atmospheric Administration (NOAA).

Products and Services

When ash is reported or detected within the Washington VAAC boundaries, the person on-duty discontinues other operational activities and immediately begins gathering information about the ash/eruption. The VAAC analyst's first priority is to notify the affected MWO(s) to facilitate their issuance of a Volcanic Ash SIGMET. Next, the analyst prepares a text product known as the Volcanic Ash Advisory (VAA) (Fig. 3). A VAA is intended to provide the aviation community with all of the pertinent information that we have about the airborne volcanic ash. Ideally a VAA will contain information on the eruption, the location, height and amount of ash, the current movement(s) of the ash (noting when different areas of ash move in different directions) and other information. VAA are updated at least every six hours, but sooner if the ash situation changes substantially. In addition to the VAA, the Washington VAAC also issues two graphical products (an ash analysis and an automated forecast) and is preparing to issue a third product (a forecast created by a person). The VAA is distributed through many communication networks, such as: AFTN, AWIPS/N-AWIPS (NWS systems), GTS, WAFs, Family of Services, under the identification header FVXX## KNES (where ## denotes a number in the range of 20 to 27). Also, as a service of the Washington VAAC, a graphical analysis of the detectable ash drawn on a map background (Fig. 4) is issued but is currently available only on our website.

For flight planning purposes, an ash trajectory and dispersion model is also issued. This model, known as the VAFTAD (Volcanic Ash Forecast Transport and Dispersion), graphically depicts predicted ash location at 12, 24, 36 and 48 hours. It is based on the aviation or ETA numerical weather models and manual inputs of ash height, summit height, eruption duration, and an adjustment factor to modify ash amounts. At each time period, the forecasted ash is depicted at low, middle and high levels of the atmosphere, and there is a composite showing all atmospheric levels from surface to 55,000 ft. The VAFTAD is available via the VAAC website and satellite broadcast under bulletin headers PHBE10KWBC and PHBI10KWBC. In the future, a new product (the Volcanic Ash Graphic) will be issued that represents a VAFTAD with its output adjusted and hopefully improved by a forecaster. A variety of current GOES satellite imagery over selected volcanoes can be viewed on our website (Fig. 5, not shown) at www.ssd.noaa.gov/VAAC/. We also expect to soon have available on our website, a Geographic Information System (GIS) based display of ash as seen in MODIS (Moderate-Resolution Imaging Spectroradiometer) satellite imagery using a special optimized multi-spectral algorithm. Although this should provide an excellent snapshot of the ash at a given instance, it will not be nearly as current or frequent as the GOES imagery.

Washington VAAC is staffed 24 by 7; however, its personnel are multi-tasked, performing a number of meteorological tasks unrelated to volcanoes. In the event of a Washington VAAC outage, the United States Air Force Weather Agency serves as the Washington VAAC backup and will create and disseminate the VAA and VAFTAD.

FVXX22 KWBC 112209Z
VOLCANIC ASH ADVISORY
ISSUED: 2003MAY11/2200Z VAAC: WASHINGTON

VOLCANO: ANATAHAN 0804-20
LOCATION: N1621E14540 AREA: MARIANA ISLANDS

SUMMIT ELEVATION: 2585 FT (788 M)
ADVISORY NUMBER: 2003/007

INFORMATION SOURCE: GOES-9 IMAGERY. GFS MODEL WINDS FORECAST. GUAM MWO.

ERUPTION DETAILS: ERUPTION OCCURRED AROUND 10/0730Z AND EMISSIONS CONTINUE TO OCCUR

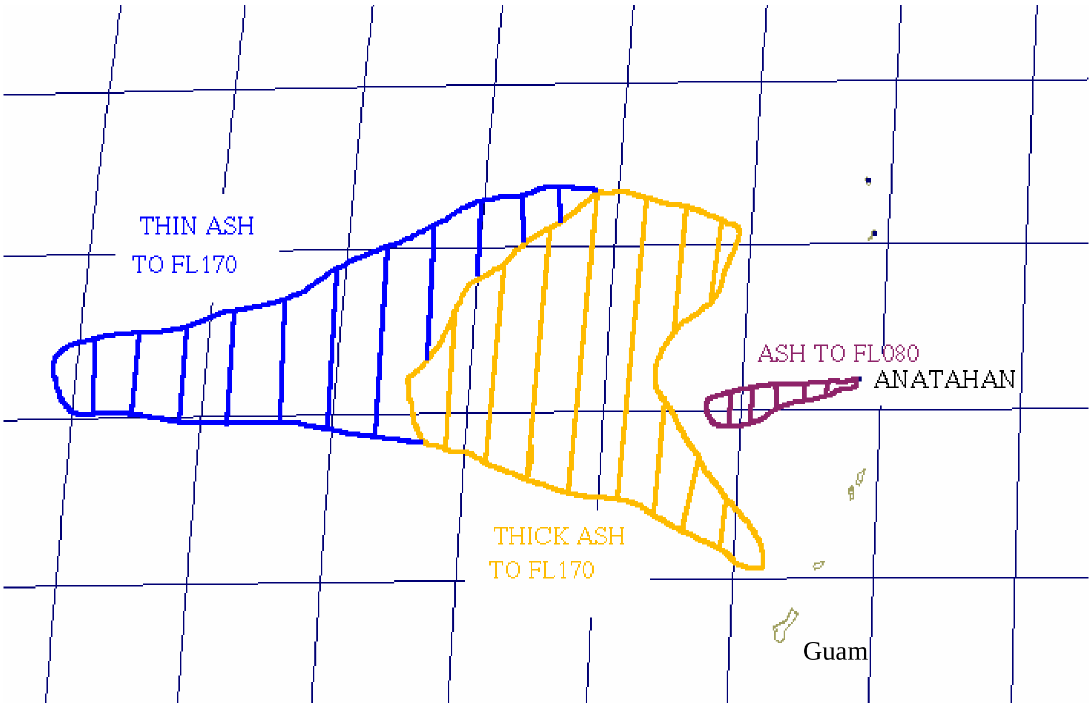
OBS ASH DATE/TIME: 11/2118Z

OBS ASH CLOUD: SFC/FL170 N1621E14256 - N1800E14417 - N1900E14200 - N1706E13403 - N1559E13340 - N1339E14423 - N1428E14502 - N1621E14256 MOVING W 15 KNOTS.
SFC/FL080 17 NM WIDE LINE OF ASH BETWEEN N1621E14540 - N1611E14326.
ASH IS MOVING WEST 20 KNOTS.

FCST ASH CLOUD+06H: NOT AVBL
FCST ASH CLOUD+12H: NOT AVBL
FCST ASH CLOUD+18H: NOT AVBL

REMARKS: A LARGE AREA OF MID-LEVEL ASH IS MOVING WEST WITH THE THICKEST OF THIS ASH BETWEEN 140E AND 143.5E. FAINTER ASH EXTENDS TO ABOUT 134E. IN ADDITION A NARROW LOW LEVEL ASH PLUME CAN STILL BE SEEN EXTENDING FROM THE SUMMIT TOWARD THE WEST.

NEXT ADVISORY: WILL BE ISSUED BY 12/0400Z.



Figures 3 and 4: Example of VAA Text Product and associated Graphic. Example from May 2003 Eruption of Anatahan in Southern Mariana Islands.

Ash Detection Methods

Viewing ash in satellite imagery provides ash location, height and speed information that is useful in creating VAA. The Washington VAAC relies primarily on GOES satellite imagery since it is available every 15 or 30 minutes, throughout most of the VAAC area. Polar orbiting satellites with their high spatial resolution provide supplementary information, but do not have the temporal resolution of GOES imagery.

Satellite detection algorithms using a variety of visible and infrared wavelengths and combinations of wavelengths ("multispectral" imagery) are optimized to enhance ash detection and help discriminate ash from weather clouds. In Fig. 6 (not shown), each panel is an example of GOES satellite imagery used in ash detection: Visible, 10.7 mm Infrared (IR), 3.9 mm "shortwave" IR, Principal Component Imagery (PCI) 3, a multi-spectral technique created by CIRA, and Gary Ellrod's multi-spectral technique.

For volcanoes within the GOES-E footprint, the Washington VAAC primarily uses 2 forms of multispectral imagery that rely on fixed weighting and one form that varies with image content. The CIRA algorithm utilizes channels 2, 4, 2 and with fixed weighting designed to enhance ash versus weather cloud. Gary Ellrod's algorithm uses channels 2 4 and 6 with fixed weighting of the channels. Since late 1999, the Washington VAAC has relied heavily on the use of Principal component analysis of GOES imagery. According to Hillger and Ellrod 2003, the PCI technique "determines which part of the multi-spectral signal is common to all the images (or ... bands) and separates that information from other image information that is sensed only by image differences or multiple image combinations. Whereas the original images…[generally] contain redundant information, the…component images contain independent information separated out of the original images. This allows the image analyst to see the independent components in multi-spectral imagery." The VAAC uses PCI-3 (GOES-12 channels 2, 4, 6) and GOES-10 channels 2, 4, 5) for ash detection and discrimination of ash versus steam. The VAAC uses a split window technique for satellites (GOES 9, GOES 10, NOAA, MODIS) that have a 12 micron channel.

Besides satellite imagery, many other data sources provide crucial information necessary to an accurate VAA. Pilot reports (AIREPS), airline phone calls, surface weather observations (METAR/SPECI), volcanological observatories, SIGMETs, upper air observations (radiosondes), numerical weather models, and media reports are useful. To help find references to volcanic ash in the multitude of telecommunications traffic, the Washington VAAC uses an automatic alert notification program based on a keyword search engine. The program scans for "words" such as ASH, PLUME, VA, WV, FV, VOLCANO, VOLC, and CENIZA as well as some individual volcano names and whenever a message is found with these keywords, an e-mail alert is sent to the VAAC and an audible alarm sounds.

Six Year Statistics

On November 1st, 2003, the Washington VAAC celebrated six full years of service to the aviation community. Coincidently, a mile-stone was surpassed the same day as the 7500th VAA was disseminated. Figure 7 shows the annual distribution of VAA and graphical depiction of ash clouds during the six years of service.

During those six years, VAA were written for 26 volcanoes, 17 that are located inside the VAAC boundaries, as well as, for 9 volcanoes in support of other VAACs or ash that moved across into the Washington VAAC's airspace of responsibility. The majority of VAA have been written for 2 volcanoes: Tungurahua with 2677 VAA, followed by Soufriere Hills with 2589. Popocatepetl (812), Guagua Pichincha (397) and Anatahan (289) round out the top five.

Similarly, the graphical depiction of ash seen on satellite imagery has been produced for 16 volcanoes (13 within the Washington VAAC). Graphics were created mostly for Soufriere Hills (1176), followed by Tungurahua (492), Popocatepetl (275), Anatahan (162), and Colima and San Cristobal tied for fifth with 34 each.

Authors note: Due to the unavailability of color graphics, Figures 1, 2, 5 and 6 are available from the authors. Please contact them at Greg.Gallina@noaa.gov, Davida.Streett@noaa.gov or 301-763-8444 in Camp Springs, Maryland, USA.

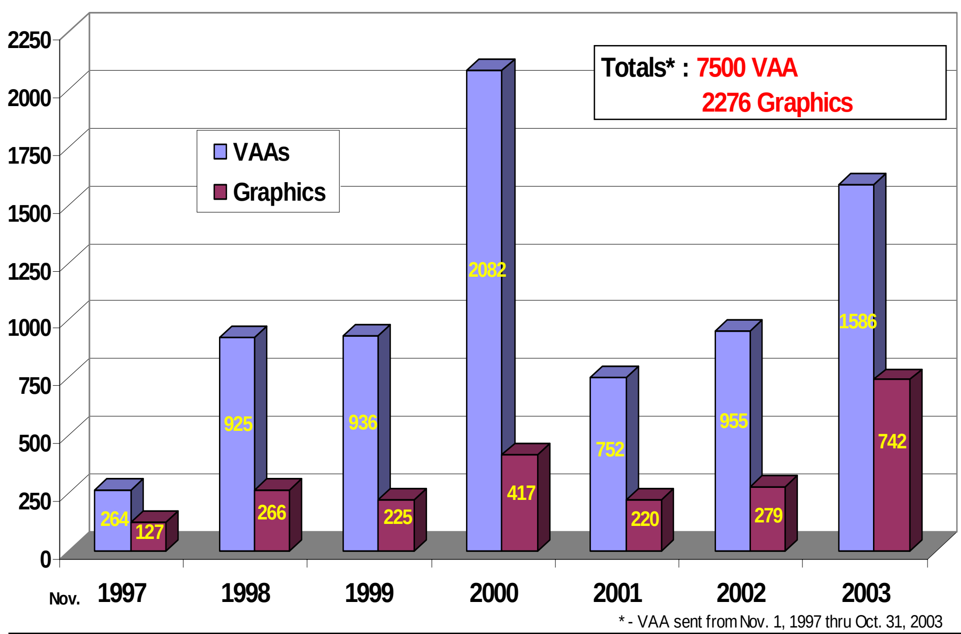


Figure 7: Number of Volcanic Ash Advisories (VAA) and Graphics for the six years since the VAAC was created in November of 1997 through October 2003.

IMPROVEMENT OF ASH CLOUD INFORMATION BY TOKYO VAAC

Takeshi Koizumi, Japan Meteorological Agency, Tokyo, Japan
Yoshihiko Hasegawa, Yasuhiro Kamada, Masamichi Nakamura

Introduction

The Japan Meteorological Agency (JMA) is operating Tokyo Volcanic Ash Advisory Center (Tokyo VAAC) that is responsible for monitoring volcanic ash clouds in Asia/Western Pacific area and issuing Volcanic Ash Advisories (VAAs), one of 9 VAACs are being operated in the world in order to mitigate or prevent disasters of airplanes caused by volcanic ash.

Tokyo VAAC monitors satellite imagery and gathers domestic and foreign reports on volcanic activities. When volcanic ash is likely to affect to any routes in the area of responsibility (Fig. 1), the Tokyo VAAC issues VAAs, which includes the present status and forecast information of volcanic ash clouds in the text and graphical format used by Meteorological Watch Offices, civil aviation authorities and other related organizations**.**

From March 1997 to May 2004, the Tokyo VAAC has issued 411 VAAs regarding volcanic eruptions and volcanic ash clouds within the area of responsibility.

Automatic Issuance of VAA for Volcanoes in Japan

JMA operates not only the Tokyo VAAC but also four Volcano Observations and Information Centers (VOICs) that cover all 108 active volcanoes in Japan.

The four VOICs, namely Sapporo, Sendai, Tokyo and Fukuoka are watching 26 major active volcanoes 24 hours a day, 7 days a week using, for example, seismometers, tilt meters, GPS networks, and television cameras. Quick response teams under the VOICs conduct regular observations for the rest of 82 volcanoes in 'moderate' activities. When eruption reports from VOICs arrive at the Tokyo VAAC, the computer system translates the messages into VAAs and issues them automatically in order to immediately inform the occurrence of eruption (Fig. 2).

The automation is performed taking advantage of the fixed format of eruption reports from the VOICs. The Tokyo VAAC has established several communication routes under cooperation with adjacent VAACs, airlines (e.g., pilot reports), volcano observatories (e.g., KVERT and PHIVOLCS) so that appropriate and accurate information about volcanic eruptions could be immediately and correctly acquired. Based on such information, though, VAAs are issued manually because the software used in the automatic transaction cannot cope with various 'free' format massages.

After the issuance of each VAA triggered by an eruption report, VAAs, which contain ash cloud dispersion, are issued manually when ash clouds are detected on satellite imagery.

Improvement of Forecast Precision of Volcanic Ash Cloud Dispersion

Based on the improvement of numerical weather prediction model for the area in and around Japan, the Tokyo VAAC developed a detailed Lagrangian model that takes the effect of vertical wind into account. The grid and time interval has been improved to 20 km from 100 km and 1 hour from 6 hours, respectively. The model has been available since November 2003.

When ash clouds are released from volcanoes in Japan and Kuril Is. area, the improved model above (New Model) is used to calculate ash cloud dispersion for the issuance of VAA. Because of the limited application area of the New Model, the previous model (grid interval: 100 km; time interval: 6 hours) takes over the calculation using the final forecasted area by the New Model as an initial when the forecasted area of ash clouds reaches the boundary of the model.

Open to Public using Website

The web-site of the Tokyo VAAC has been open to public since December 2003. The contents, though, have not included issued VAAs. The Tokyo VAAC is now conducting a revision to the web-site so that VAAs will be available by the end of next March. The URL of Tokyo VAAC web-site is:

http://www.jma.go.jp/JMA_HP/jma/jma-eng/jma-center/vaac/index.html

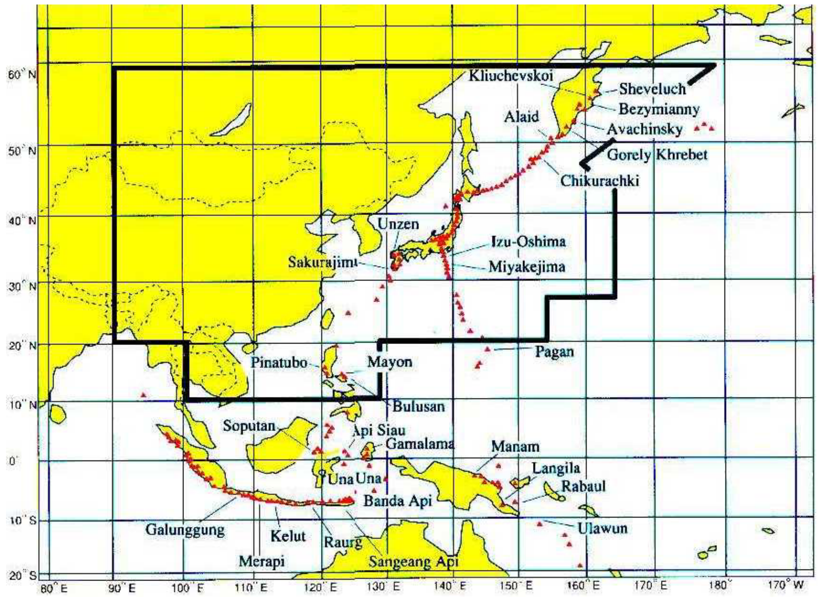


Fig.1 Area of responsibility of Tokyo VAAC (inside of the bold line)

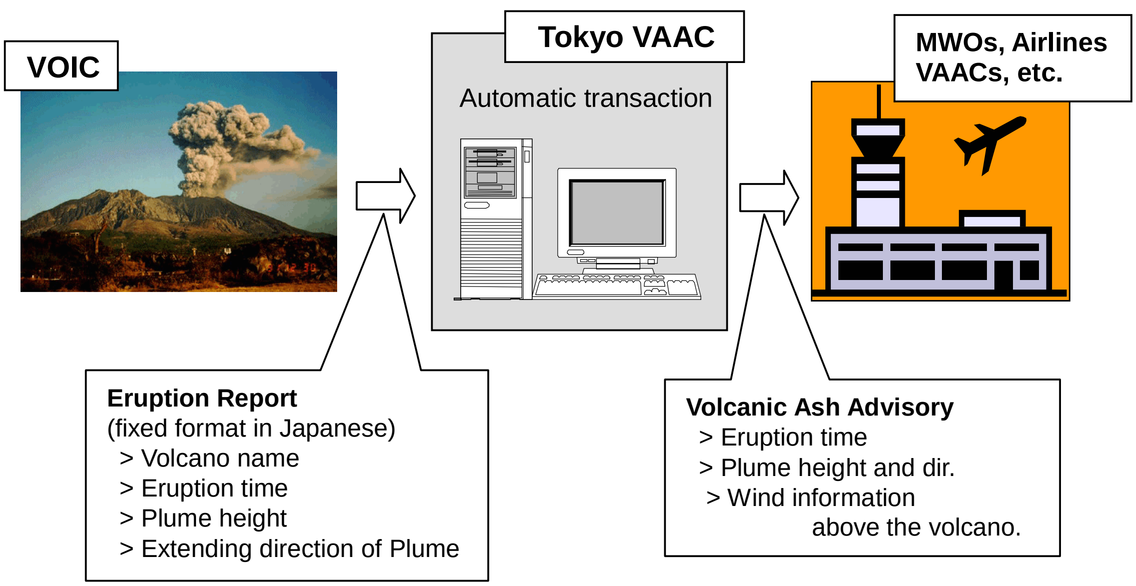


Fig. 2 Automatic issuance of VAA triggered by eruption report from Volcano Observations and Information Center (VOIC)

THE MONTREAL VAAC TOOLBOX: WHEN EVERY SECOND COUNTS

Mark McCrady, Serge Trudel, Jean-Philippe Gauthier and Rene Servranckx
Canadian Meteorological Centre, Meteorological Service of Canada, Dorval, Quebec, Canada

Following the designation of the Montreal VAAC, the task of volcanic ash detection and forecasting was given to the 24/7 operational meteorologists of the Canadian Meteorological Centre (CMC). This was done so that, in the case of an actual volcanic eruption on Canadian territory, or in the case of inherited volcanic ash from neighbouring VAACs, a fast first response would be possible in order to support the Meteorological Watch Offices (MWOs) that issue SIGMETS, air traffic controls centres, flight dispatch centres, etc. To consolidate all the necessary monitoring and forecasting tasks into one place, a TCL based software known as the "Toolbox" was created which, since its inception, has undergone several revisions. It allows the on duty shift supervisor to continuously monitor various bulletins or pilot reports that may contain reference to volcanic ash and to track ash clouds with satellite data. The supervisor can also launch the CMC Trajectory Model and/or the CMC Canadian Emergency Response Model (CANERM) transport and dispersion Model. With the Toolbox, the results can be quickly posted on the public Montreal VAAC web-page or transmitted on national and international communications circuits as well as the WAFS. The toolbox also allows for the composition, transmission or re-transmission of volcanic ash advisory bulletins (FV). The latitude/longitude points of the ash cloud are extracted directly from the CANERM outputs with a few clicks of the mouse and automatically inserted in the FV, thus saving precious time.

ERUPTION OF ANATAHAN VOLCANO: OPERATIONS AND OBSERVATIONS

Michael G. Middlebrooke
NOAA/National Weather Service Forecast Office, Barrigada, Guam

The first historic eruption of a volcano on the island of Anatahan, located in the Northern Mariana Islands in the western North Pacific Ocean, occurred on 10 May 2003 (Fig. 1, Fig. 2). Cooperation and coordination between the NOAA/National Weather Service Forecast Office on Guam, Washington VAAC, Saipan Emergency Management Office and the airlines were important for monitoring, processing and releasing information on the eruption. Imagery from polar-orbiting satellites proved to be an invaluable complement to imagery from the geostationary satellites for monitoring Anatahan's ash plume (Figs 3, 4, 5, 6, and 7).

Fig. 1 – Anatahan on May 11, 2003, the morning after the eruption began. This view is looking toward the southwest. The ash cloud reaches as high as 40,000 feet.

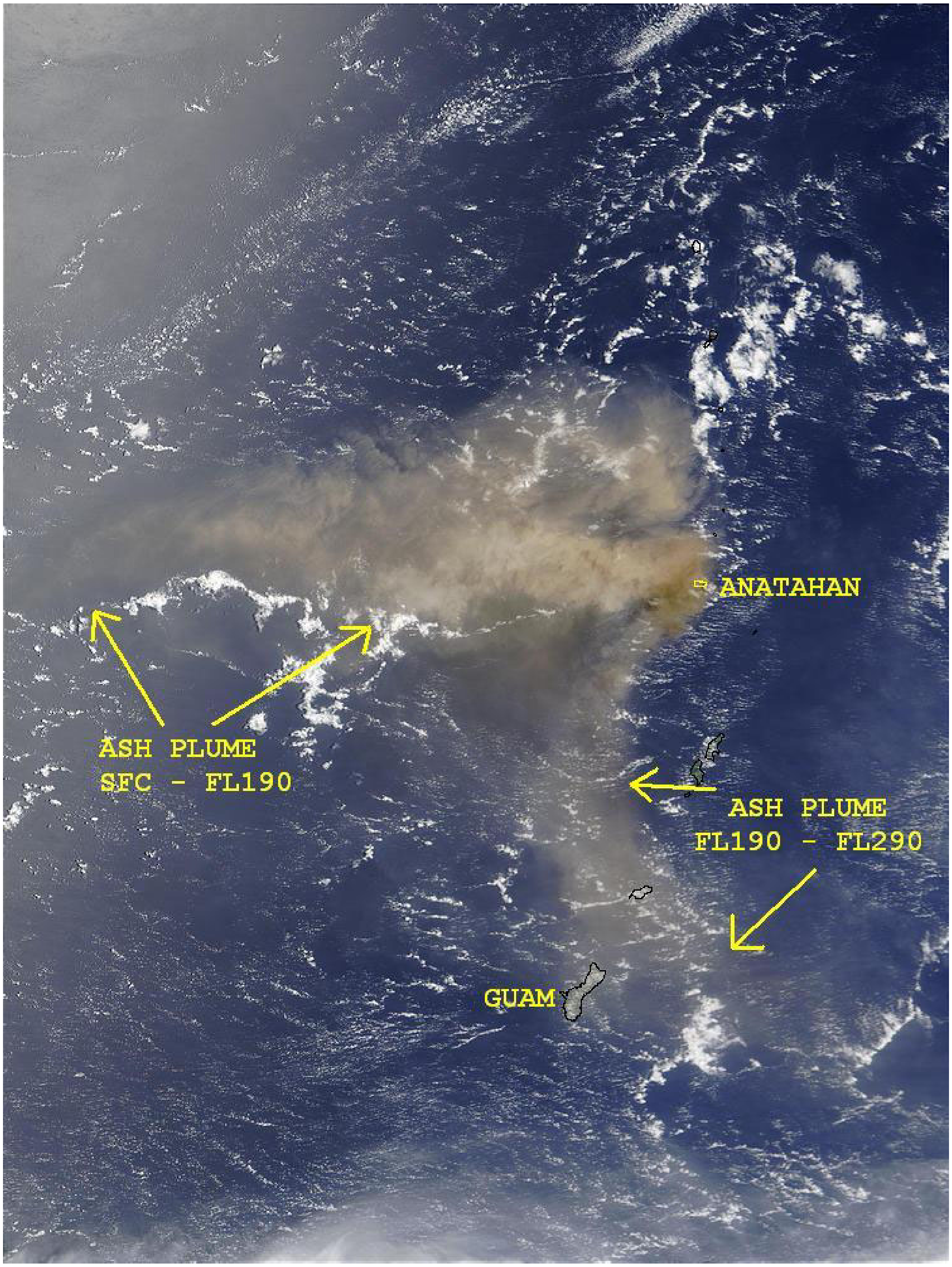


Fig. 2 – View from NASA's Terra satellite of Anatahan and its ash plume on May 11, 2003. The upper-level plume brought volcanic haze aloft to the skies of Guam and Rota.

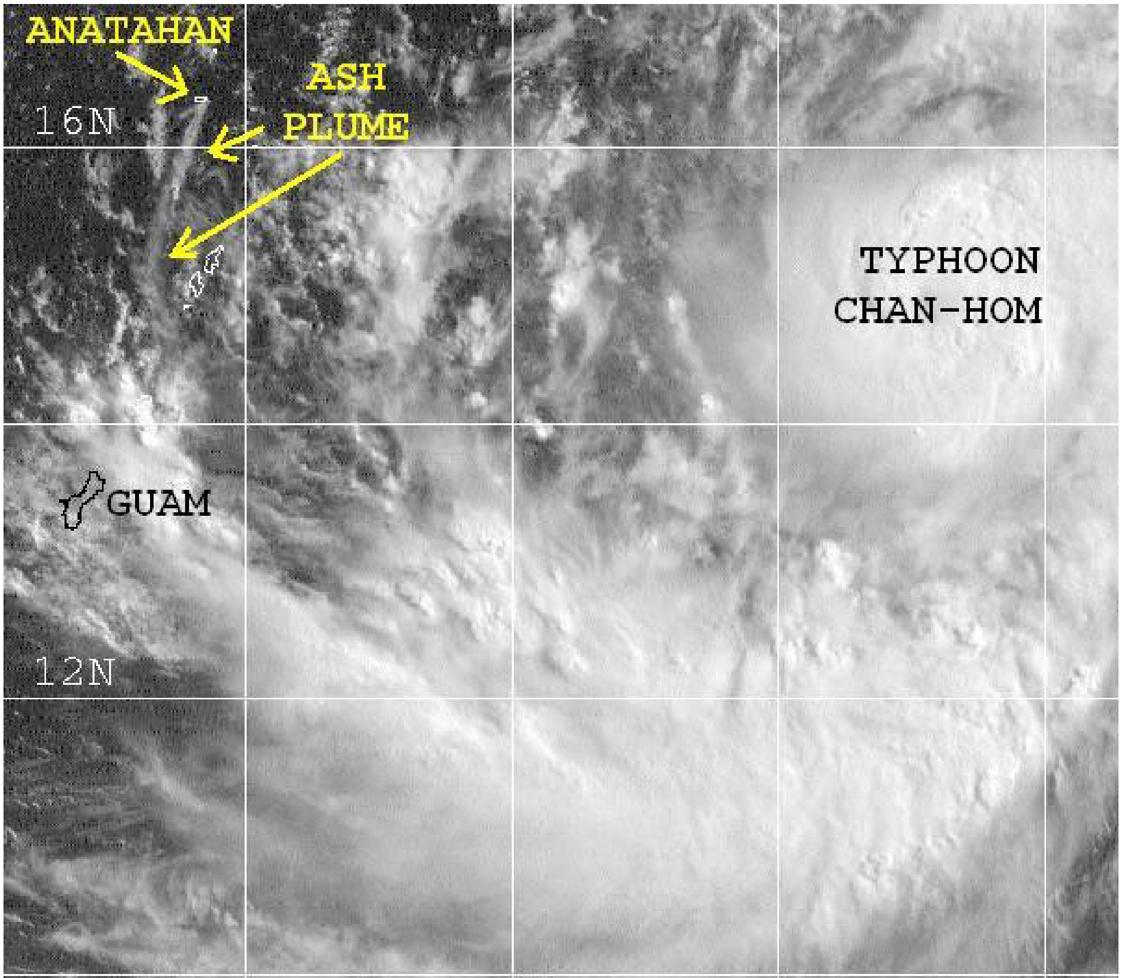


Fig. 3 – GOES-9 visible image for May 22 at 2213 UTC (May 23 at 8:13 a.m. Guam time). The circulation around Typhoon Chan-hom has brought the plume south-southwest over Guam and Rota. On Guam, a light dusting of ash fell, and there was a strong smell of sulphur. Because of the ash, Continental Airlines canceled six flights into and out of Saipan.

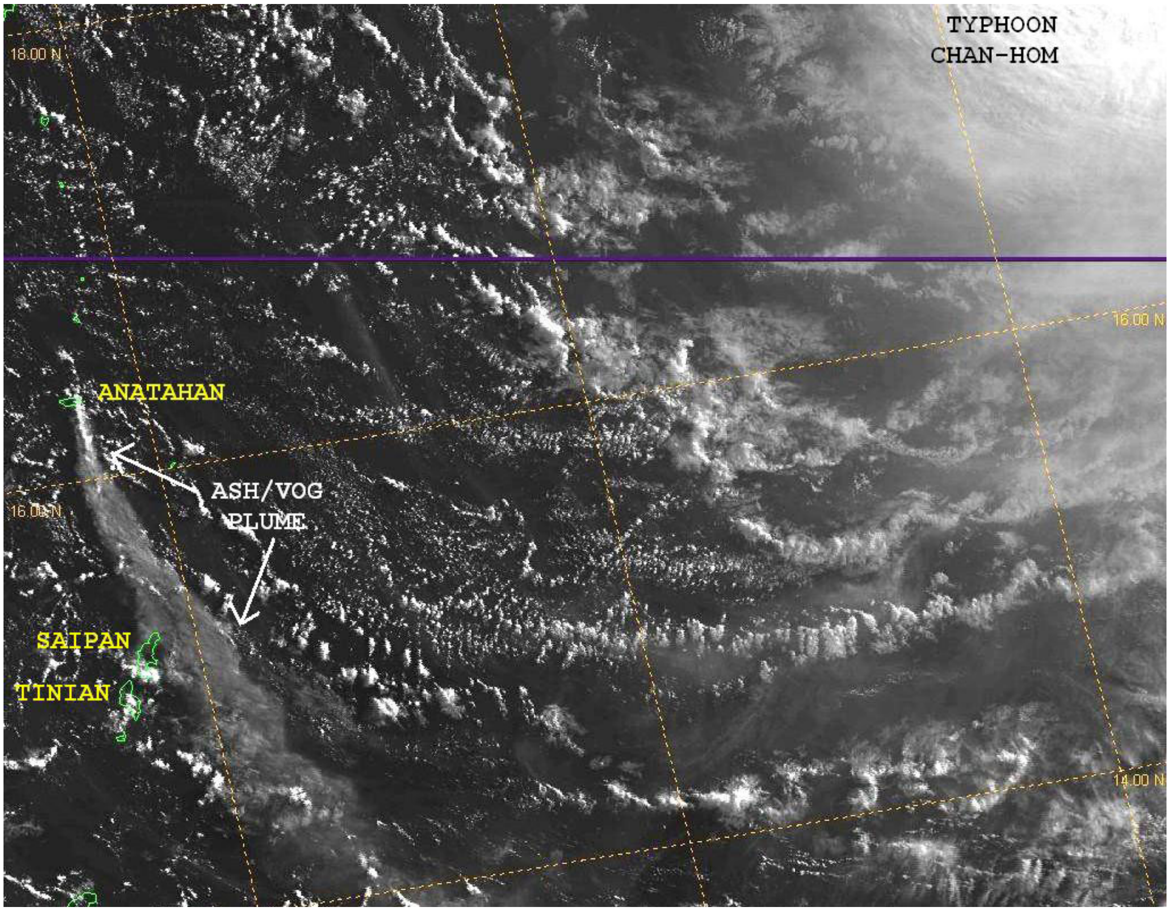


Fig. 4 – DMSP polar orbiter visible imagery showing the plume at 2034 UTC on May 23, 2003 (6:34 a.m. on May 24 Guam time). Ash fell on Tinian and Saipan, again prompting the cancellation of flights to and from Tinian and Saipan.

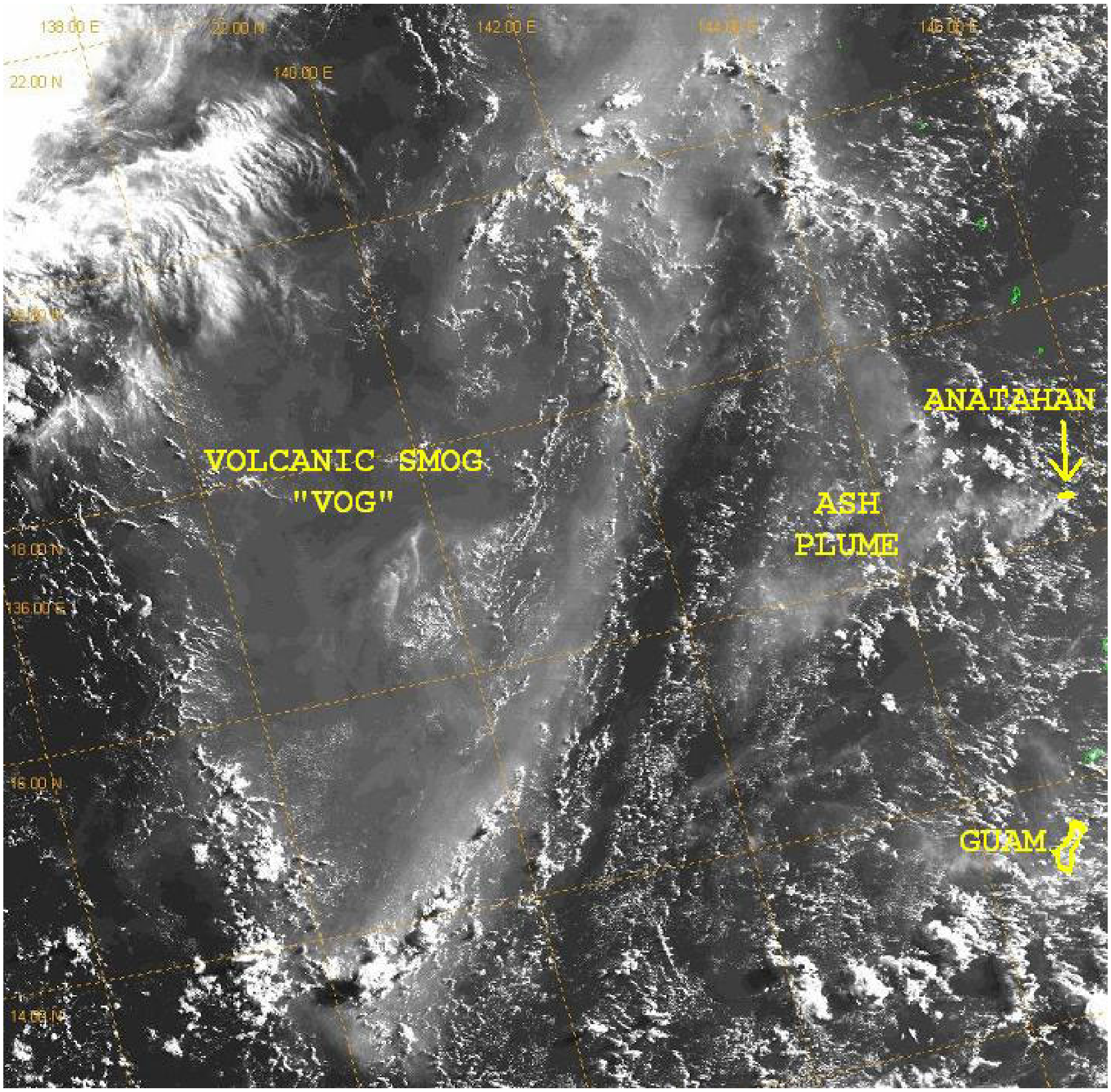


Fig. 5 – DMSP polar orbiter visible imagery from 2142 UTC on June 9, 2003 (7:42 a.m. on June 10 Guam time). In addition to the low-level ash/aerosol plume streaming west and northwest from Anatahan, volcanic smog or "vog" covers a large area further west. This vog is an aerosol that results from the chemical reaction between the volcano's sulphurous gas emissions, oxygen, and atmospheric moisture. Note the shadows cast by towering cumulus clouds onto the vog layer below.

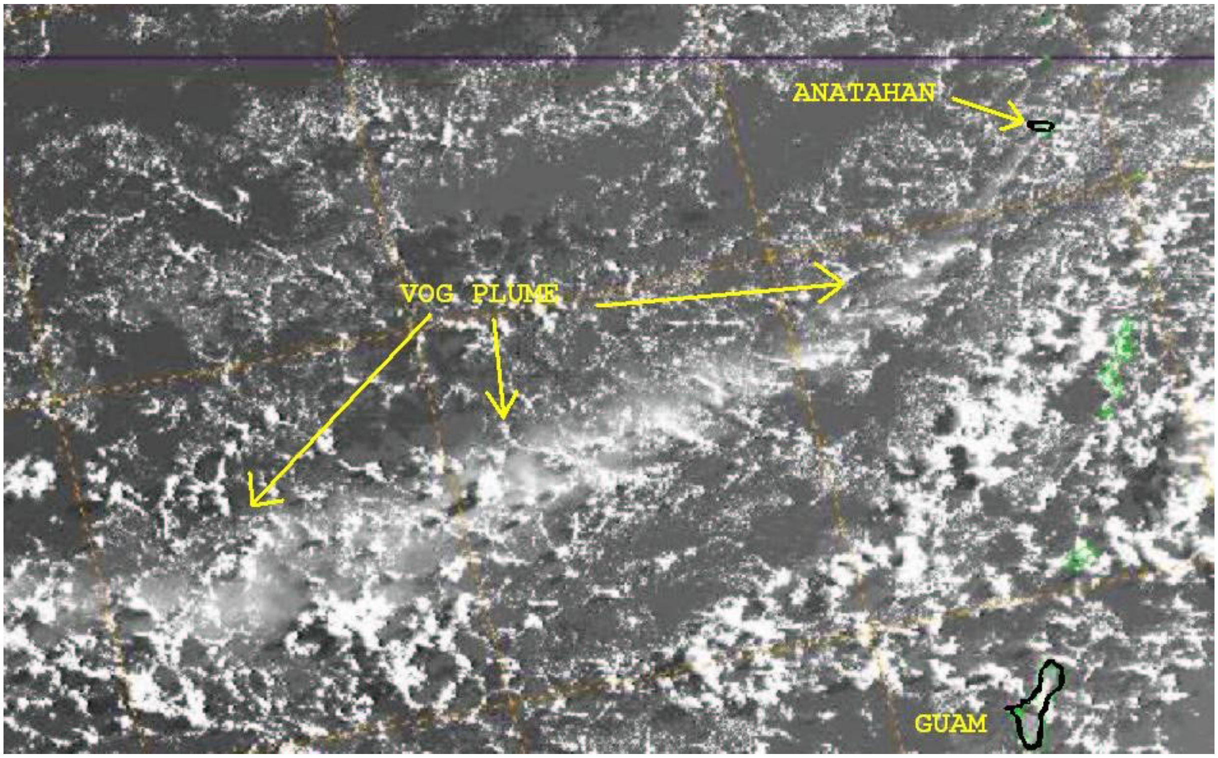


Fig. 6 – DMSP polar orbiter visible imagery from 2226 UTC July 9, 2003 (8:26 a.m. July 10 Guam time). The plume streams over 300 miles west from Anatahan. By this time, the plume is restricted to between the surface and about 8,000 feet, and it consists mostly of vog. The contrast in this image has been greatly enhanced to bring out the plume. Indeed, throughout July the plume was not visible in GOES-9 visible or IR imagery, and could only be seen under low sun-angle conditions by the DMSP satellite.

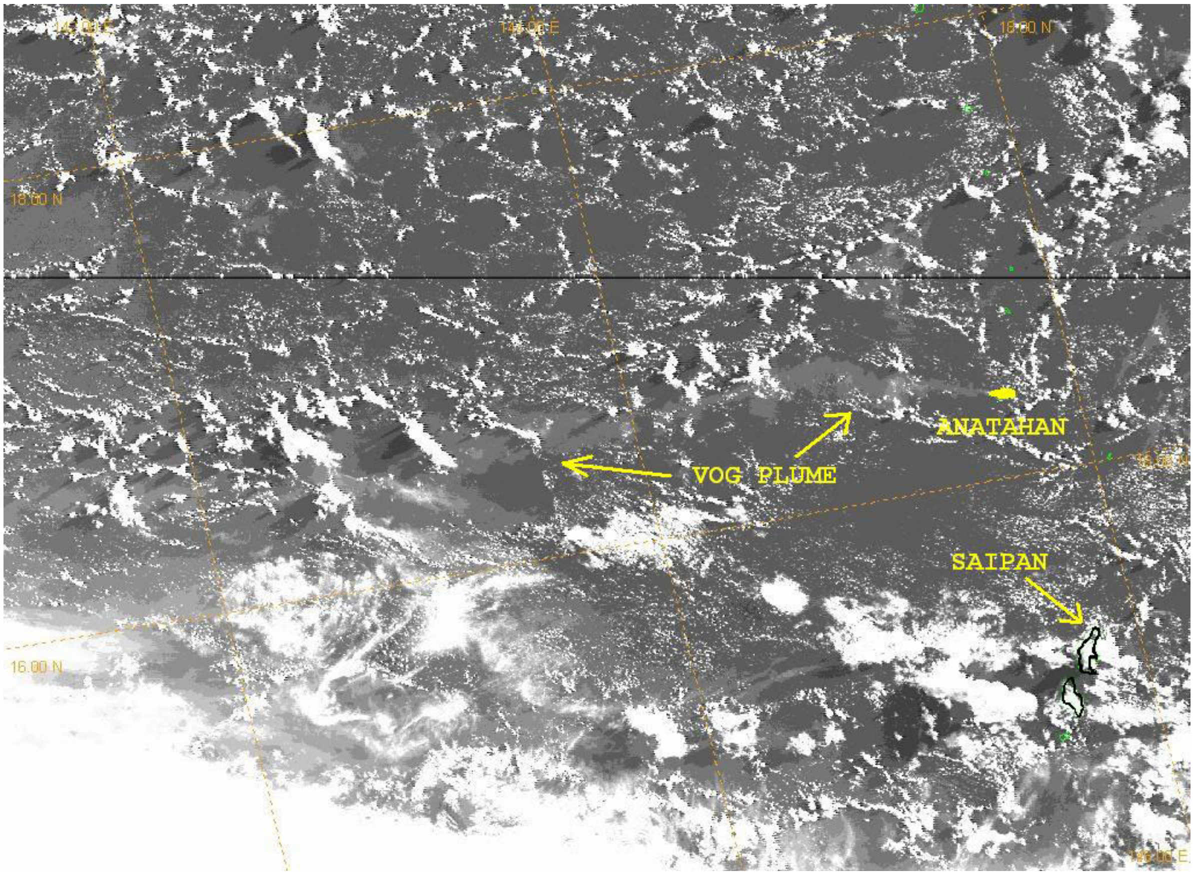


Fig. 7 – In this DMSP polar orbiter visible image from 2100 UTC on July 18, 2003 (7 a.m. Guam time on July 19), the vog plume is barely seen, even after greatly enhancing the image's contrast. At this point, the plume was judged to consist solely of vog. As a result, volcanic ash SIGMETs on the plume were discontinued the following day.

THE VOLCANIC ASH COLLABORATION TOOL (VACT)

Jeffrey M. Osiensky, NWS Alaska Aviation Weather Unit, Anchorage, AK, USA
Greg Pratt, NOAA Forecast Systems Laboratory, Boulder, CO, USA
David J. Schneider, USGS Alaska Volcano Observatory, Anchorage, AK, USA
Lynn Sherretz, NOAA Forecast Systems Laboratory, Boulder, CO, USA

In order to facilitate real-time collaboration during North Pacific eruptions, a pilot project was instituted in 2003 to develop the Volcanic Ash Collaboration Tool (VACT). The VACT consists of workstations located at the Anchorage VAAC, the Anchorage Center Weather Service Unit, and the USGS Alaska Volcano Observatory, with shared access to satellite and meteorological data. The VACT allows for shared situational awareness by providing common views of the data sources, and by allowing all groups to view, enhance and annotate graphical data. This poster session will give participants the opportunity to gain hands-on experience with the VACT in order to explore its capabilities.

VOLCANIC ASH MONITORING AND FORECASTING AT THE LONDON VAAC

Sarah Watkin[1], Sigrún Karlsdóttir[2], Nigel Gait[1], Derrick Ryall[1] & Helen Watkin[1]
[1]Met Office, Exeter, U.K.
[2]Icelandic Meteorological Office, Reykjavik, Iceland

Introduction to the London VAAC

The London VAAC (Volcanic Ash Advisory Centre) is responsible for monitoring and forecasting the movement of volcanic ash over the United Kingdom, Iceland and the north-eastern part of the North Atlantic Ocean (Figure 1). Although this is a relatively small area, it covers some of the busiest airways in the world. A volcanic eruption on Iceland can quickly affect a large area of airspace, as strong winds spread the ash downwind from the volcano. Air traffic control organizations need to react quickly to the forecasts issued by the VAAC so that aircraft can be diverted onto alternative safe tracks.

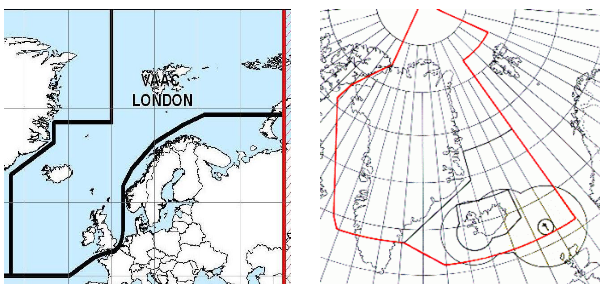


Figure 1: *The London VAAC area (on left) and the IOCA (on right in red).*

During a volcanic eruption on Iceland, the London VAAC liaises closely with forecasters at the Icelandic Meteorological Office (IMO), where monitoring of the Icelandic volcanic zone takes place. The London VAAC has access to the latest observational data as it emerges. This may be data from: seismic surveys, eye witness accounts (often from aircraft) of current plume behaviour or volcanic activity, or analysis of satellite pictures. During an eruption forecasters issue regularly updated Volcanic Ash Advisories Statements based on observational and forecast data about the current and predicted location of volcanic ash.

Volcano monitoring at the Icelandic Met Office

A volcanic eruption occurs in Iceland every four to five years on average. These eruptions can have a large impact on jet aircarft flying through the Icelandic Ocean Control Area (IOCA), which is one of the largest in the world (Figure 1). Approximately 250 jet planes cross the area daily and up to 500 utilize the area during favourable weather conditions (Sveinbjörnsson, 2001).

A monitoring system (Stefánsson et al., 1993) covers the active volcanic zone in Iceland, and data from this system are analysed continuously by the IMO. Currently (in July 2004), two Icelandic volcanoes show signs of an impending eruption. Those are Mt. Katla (63°59’N, 19°05’W), and Grímsvötn (64°41’N, 17°27’W). The last eruption of Mt. Katla was in 1918, hence a large eruption can be expected. Grímsvötn, on the other hand, erupted in 1998. In readiness for these eruptions, IMO receives two sets of images every day from the NAME model (see description below) run by the London VAAC. These images show the dispersal of volcanic plumes from hypothetical eruptions at the two locations, mentioned above (Figure 4). The height of the volcanic plume is an important input parameter into the model, and this information is based on research on previous eruptions at the same locations. This procedure makes it possible to issue a SIGMET indicating the forecast area of ash, only a few minutes after the onset of an eruption. Similar methods will take place when other volcanic areas show sign of impending eruptions.

When an eruption occurs in Iceland the following working procedure takes place. At the start of the eruption IMO informs the Icelandic Civil Aviation

Authorities and London VAAC about the eruption location and its estimated plume height. With this information the London VAAC calculates the spread of the plume with NAME, and the results are sent to IMO together with additional advisory information. During the eruption IMO and London VAAC forecasters monitor the volcanic plume via satellite images and with an Icelandic-based weather radar, which has shown to give valuable information (Lacasse et al., 2004) (Figure 2).

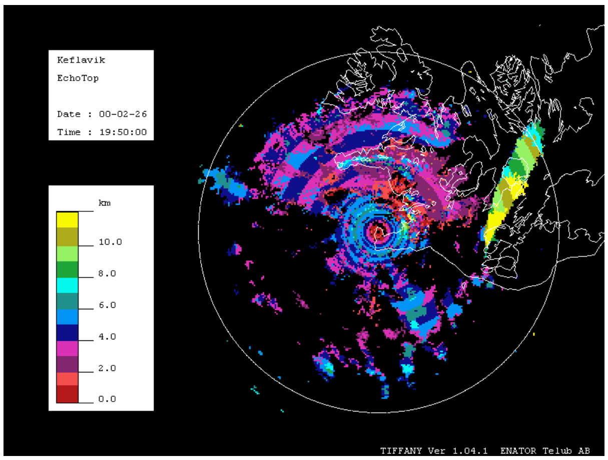


Figure 2: *C-band weather radar observations of the eruption plume from Mt. Hekla on 26 February 2000, approx. 1½ hours after the start of the eruption, showing the estimated height of the eruption plume.*

Eruption detection system

The Met Office has developed an automatic volcanic eruption detection system using Meteosat infrared images and forecast meteorological data. The system uses a shape-matching technique to search for suspected volcanic eruption clouds in the London VAAC area each time a new satellite image becomes available (every quarter of an hour with MSG).

Clouds are identified as possible ash clouds by checking for good correlation between the shape of the actual cloud and that which might be expected for an eruption cloud in the prevailing meteorological conditions. This shape is either circular, or a plume shape spreading downwind. The left image in Figure 3 shows the expected cloud shape that the system would have produced for Hekla at 1900Z on 26 February 2000 and used to search the image around Hekla for close shape-matches. The right image shows the Meteosat infrared image at that time. The cloud would have been detected in the outlined position 40 minutes after the eruption began.

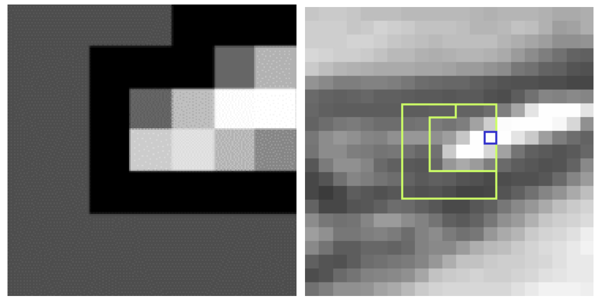


Figure 3: *Eruption of Hekla, Iceland on 26/02/00: the expected cloud shape produced by the detection system (left), would have detected the eruption in the 1900Z Meteosat IR image (right).*

The detection algorithm checks that the cloud that has been shape-matched exhibits other characteristics consistent with them being volcanic in origin:
Location - cloud top should be close to a volcano, or downwind of a volcano.
Contrast - cloud top brightness temperature should differ from the immediate surroundings.
Height - the cloud top height should be at the same height as the wind used for establishing the shape and location conditions.

In order to rule out as many false alarms as possible, the cloud must also pass the following checks to give sufficient confidence that it is not a meteorological cloud:
Temporal check - the cloud was not present upwind of the volcano in a previous image.
Grey level check - there are no other clouds in the vicinity at the same height.
Sudden appearance check - the cloud has suddenly appeared in the image.
Convective cloud check - no convective cloud has been forecast at that height.

The eruption detection system detected 12 of the 18 eruptions in the Meteosat field of view that were used to develop and test the system. The detection system was also tested on a month's data in order to investigate how many false alarms would be produced. A false alarm is when the eruption detection system detects a candidate cloud that passes all of the tests, but no eruption had actually occurred. These results show that the system could monitor the London VAAC's area of responsibility with the production of only a few false alarms each day. During 2004 the system will be upgraded to use MSG images. The performance of the system will be re-evaluated and a decision made regarding possible operational implementation.

Volcanic ash forecasting using NAME

NAME is the Met Office's medium-to-long range atmospheric dispersion model. It has evolved into an all-purpose dispersion model capable of predicting the transport, transformation and deposition of a wide class of airborne materials, e.g. nuclear material, volcanic emissions, biomass smoke, chemical spills, Foot and Mouth disease. It is a Lagrangian particle dispersion model which predicts 3D concentrations and deposition of airborne particles and covers horizontal scales from ~1km to many 1000s km. It uses detailed 3D meteorology from the Met Office's Unified Model (horizontal resolution of 60 km globally and 12 km over northwest Europe and the UK).

During an eruption, forecasters run NAME to predict the dispersion of volcanic ash particles up to six days ahead. Where possible the plume height and release duration are derived from observations (e.g. satellite, radar or pilot reports). A release quantity of 1g ash is used (1g per six hour period if the eruption continues for more than six hours). A look up table based on summit and ash cloud height is used to determine the concentration corresponding to a 'visual ash cloud'. If good observational data is available then the release rate can be adjusted to provide a better match between observed and modelled visual ash clouds. An assumed particle size distribution is used, with a continuous distribution between 0.1-50um.

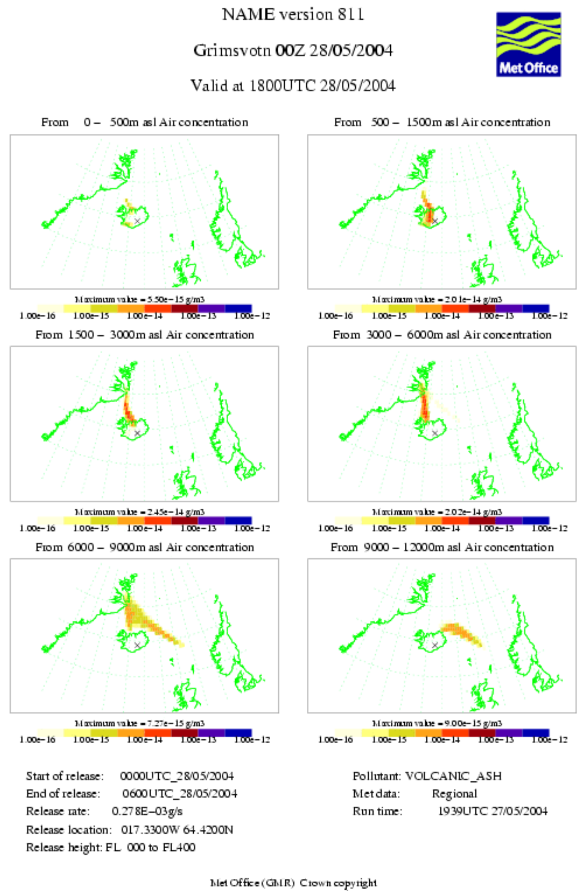


Figure 4: *NAME forecasted dispersion for a hypothetical eruption of Mt. Grímsvötn.*

The output from NAME is a graphic showing the extent of the visible ash cloud at three levels: surface-FL200, FL200-FL350, FL350-FL550 for the next 24 hours at 6 hour intervals. More detailed plots are available to forecasters, representing concentration maps over 6 layers. The NAME forecast forms the basis of the volcanic ash advisory issued by forecasters. They are validated by comparison in real-time with satellite observations (see Figure 5 and the next section). In addition to using NAME during volcanic events, it is run twice daily, as mentioned above, to provide guidance to the IMO about the dispersion of ash from two volcanoes, Mt. Katla and Grímsvötn (Figure 4).

There are several key modelling issues that remain. A clearer definition of a visual ash cloud is needed, along with a better understanding about what is hazardous to aircraft. Improved source terms are needed, particularly information about vertical extents and multiple or intermittent sources. Also, improvements in the NWP model that drives NAME in terms of the representation of orographic features are needed.

Volcanic ash tracking using satellite data

Once forecasters are notified about an eruption they need to track the transport of the ejected volcanic ash particles. Satellite observations offer the only possibility of tracking ash over large distances. However, discriminating between volcanic ash clouds and water or ice clouds can be difficult. The Met Office generates "volcanic ash images" routinely from Advanced Very High Resolution (AVHRR) data for regions covering the London VAAC area, Iceland and Mt. Etna (Watkin, 2003). These images are used by forecasters to discriminate between ash and water/ice clouds and enable them to track the ash and thus validate the NAME forecasts. The volcanic ash images show values of $BT_{10.8} - BT_{12.0}$. In general: $BT_{10.8} - BT_{12.0} < 0$ for volcanic ash, $BT_{10.8} - BT_{12.0} > 0$ for water/ice clouds.

These images have been used to study eruptions of Mt. Etna (there have been no Icelandic eruptions since their implementation in 2001). Figure 5 shows AVHRR $BT_{10.8} - BT_{12.0}$ images alongside NAME forecasts for two days during the eruption of Mt. Etna in 2002. This example demonstrates the usefulness of studying the two data sets in conjunction; e.g. the NAME forecasts confirm that the weak ash-signal (i.e. values are in a negative sense compared to surrounding clear-sky values) north-west of Sicily in the AVHRR image on 31 October 2002 is volcanic ash.

Meteosat-8 (Meteosat Second Generation) is a new geostationary satellite located at 0° longitude with a 15 minute imagery repeat cycle. The Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board Meteosat-8 has 12 channels at: 0.6, 0.8, 1.6, 3.9, 6.2, 7.3, 8.7, 9.7, 10.8, 12.0, 13.4 μm and high resolution visible. Data from several of these channels could provide useful information about volcanic emissions (e.g. volcanic ash and sulphur dioxide).

Currently, SEVIRI data are operationally received and processed to generate nowcasting products and imagery, including "volcanic ash images" ($BT_{10.8} - BT_{12.0}$) every 15 minutes. The application of SEVIRI data offers a unique opportunity to advance satellite-based detection and retrieval of volcanic emissions. Work is underway to further exploit MSG data for volcanic emission monitoring.

Summary

The London VAAC provides a service to the aviation industry which advises about the presence of volcanic ash in a region encompassing Iceland, U.K. and the north-east Atlantic. To provide this service forecasters make use of a range of information: from the Icelandic Meteorological Office, from Icelandic radar, from NAME dispersion model forecasts and from satellite imagery. These information sources are supported by research into improving and extending the quality of the information. Research is currently underway in improving the NAME model for volcanic ash forecasting, in developing an eruption detection system and in the exploitation of Meteosat-8 (MSG) satellite data for volcanic ash and sulphur dioxide tracking. Close collaboration between the Icelandic Meteorological Office and the U.K. Met Office ensure that observational data about an eruption is transferred efficiently, that appropriate developmental work is undertaken and that Volcanic Ash Advisory Statements are timely and contain all available information.

References

Lacasse, C., Karlsdóttir, S., Larsen, G., Soosalu, H., Rose, W.I., and Ernst, G.G.J., 2004. Weather radar observations of the Hekla 2000 eruption cloud, Iceland. Bulletin of Volcanology, vol. 66, no. 5, pp. 457-473.

Stefánsson R, Bödvarsson R, Slunga R, Einarsson P, Jakobsdóttir S, Bungum H, Gregersen S, Havskov J, Hjelme J, Korhonen H, Earthquake prediction research in the South Iceland Seismic Zone and the SIL project. Bull Seismol Soc Am 83: 696-716, 1993.

Sveinbjörnsson M., Volcanic eruptions in Iceland: potential hazards and aviation safety. Unpublished MSc thesis, University of Iceland, 71 pp, 2001.

Watkin, S.C., 2003: The application of AVHRR data for the detection of volcanic ash in a Volcanic Ash Advisory Centre. Meteorological Applications, 10, 301-311.

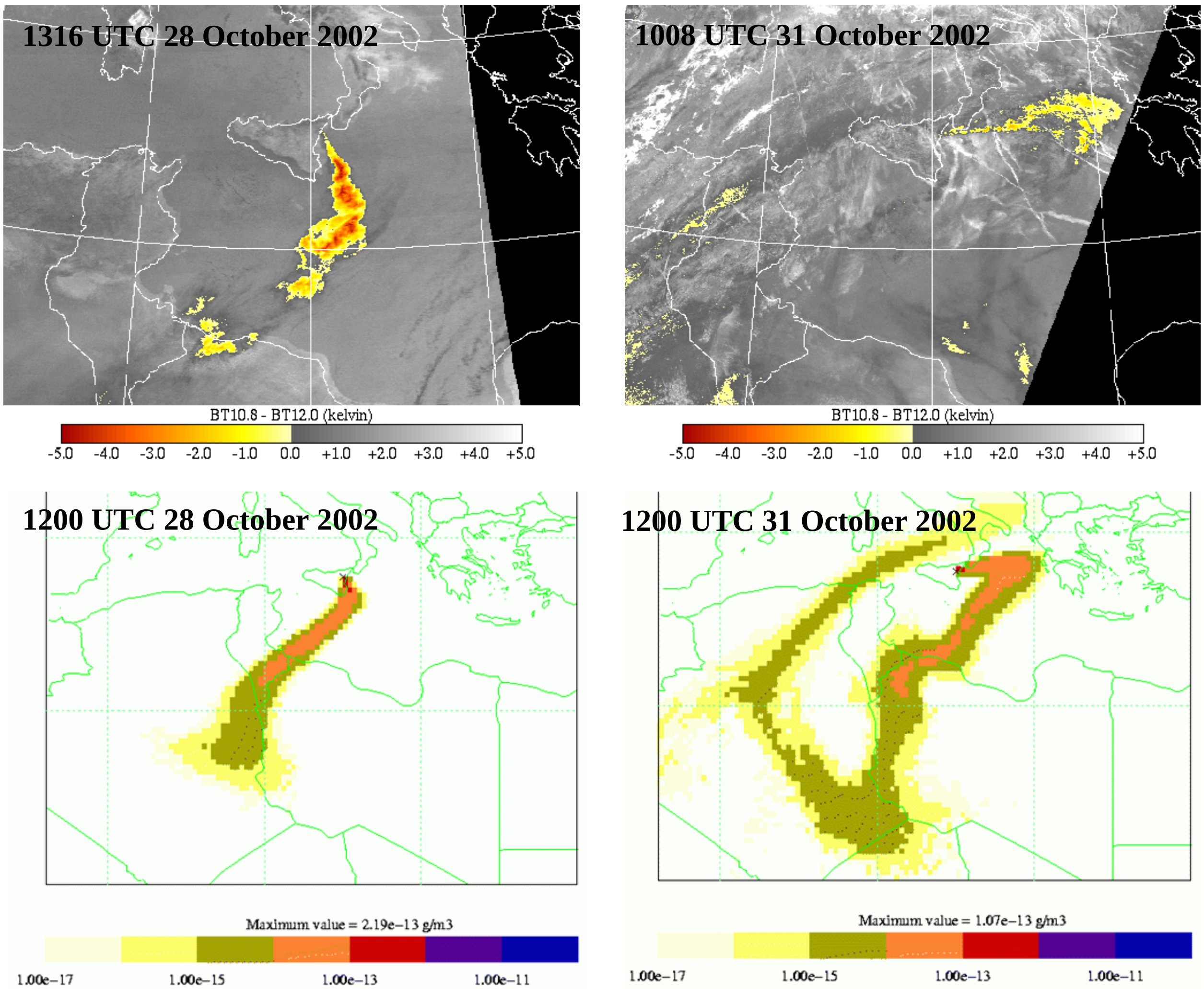


Figure 5: *Eruption of Mt. Etna in October 2002. Top: AVHRR $BT_{10.8} - BT_{12.0}$ images showing areas with negative values in red to yellow (indicating ash). Bottom: Forecasts from NAME showing show total column concentration (a continuous release rate of 0.278 mg/s from surface to FL200 was used).*

Web Access to the Digital Archive of VAA Messages and VAFTAD Model Output

Paula Dunbar, National Geophysical Data Center, Boulder, Colorado, USA
Grace Swanson, NOAA Satellite Services Division, Camp Springs, Maryland, USA

To ensure safe navigation and monitor possible climatic impact, NOAA tracks volcanic ash eruptions throughout the world and monitors all available satellite images for ash clouds. After an eruption, NOAA issues a VAA message and a forecast of ash location in the atmosphere from the VAFTAD model. The National Geophysical Data Center (NGDC) has digitized and archived 20 years of VAA messages, VAFTAD model output, and substantiating information for both foreign and domestic volcanoes issued by NOAA's Volcanic Ash Advisory Centers (VAACs) and collected by the NESDIS Office of Satellite Data Processing Division (OSDPD). The substantiating information includes surface weather observations, pilot reports, volcanic observatory reports, news media reports, and satellite imagery for each event. During the next year these data will be input into a geospatially-enabled relational database management system (RDBMS) and made accessible over the Web. The database will also include links to GOES imagery from the CLASS GOES active archive. This database will provide researchers with access to all of the information concerning a past volcanic event, facilitating model evaluation. A prototype of the new website will be presented and comments and suggestions for improvement will be solicited.

[This was given as an electronic poster.]

TECHNOLOGY TRANSFER: MOVING R&D TO OPERATIONS

Steven R. Albersheim, Federal Aviation Administration
Washington, DC, USA

Introduction

The Federal Aviation Administration (FAA) under the new Air Traffic Organization (ATO) has adopted performance-based management of air traffic control system delivery of new technologies. FAA modernization projects are to "focus more on accountability and tracking costs related to service goals: and not change the technologies themselves."[1] To accomplish this, senior management, before committing resources to move a product into operations, requires a good sound business case to demonstrate how new products and services will improve efficiency and safety of the National Airspace System (NAS). Thus the best idea needs a path to implementation on an operational platform that can support goals in the Administrator's Flight Plan 2004-2008.

The Aviation Weather Technology Transfer (AWTT) process, established in 1999, supports the concept of developing a business case to move weather R&D products into operations. The AWTT process falls under the auspices of Air Traffic Operations Planning and is led by a governing board. Since, its inception it has evolved significantly and will continue to change to meet the operational needs of the new ATO Organization.

The board is comprised of members that cut across FAA services and includes representation from NWS. The AWTT board encourages the development of new aviation weather products to improve the depiction and forecasting of weather events that affect not only the safety of the NAS but also the efficiency. This paper describes the functions of the board and the AWTT process.

Functions of the AWTT Board

In 1999 FAA's Air Traffic Requirements Services agreed that there was a need to have program to provide oversight on the transfer of new aviation weather products into operations. Products were being developed in the R&D community did not have a well-defined path to implementation on an operational platform. Having senior FAA and NWS managers on the AWTT Board brings together decision makers who can obligate the required resources to implement the product development onto operational platforms.

In addition, the senior leaders on the Board provide direction to developers of new products on the needs for service that do not require major material procurement or in other words non-material solutions. For example, it has been recognized and widely accepted that weather is a major contributor to delays and accidents in the National Airspace System (NAS). Many of the solutions to mitigate weather impacts on operations are geared towards non-material solutions. But for the most part many of the proposed changes in providing timely information on hazardous weather are software development issues using existing technology or platforms to display or provide a new or different product so decision makers have more timely and factual information on the hazardous weather.

R&D to Operations—the AWTT Process

Organizationally, the AWTT process is a four part series with four key decisions points, each requiring different input and supporting documentation. In some circumstances the information requested for the Board is a refinement or expansion of existing documentation to further embrace the development of the product. Figure 1 shows the conceptual process of the AWTT process. Under the auspices of the Board there is AWTT Steering Group (ASG) who serves as staff to the board. The ASG advises the Board members on the progress of the various programs that require the Board's oversight. One key element that needs to be understood is that the AWTT oversees programs being supported by FAA's R&D or Facility and Equipment (F&E) funds. The Board does not have authority to obligate funds. However, members to the Board who have operational platforms under their responsibility can thus plan accordingly to budget resources based on an agreed implementation plan.

D1 Stage

The AWTT Board only becomes engaged in decision making for those actions that require a D3 or D4 approval. For D1 and D2 actions the ASG has oversight and responsibility to ensure that the work being performed under R&D is in support of FAA

[1] "Setting up the ATO", Development and Training News, FAA, Dec 5, 2003, www.ato.faa.gov.

mission and requirements to develop operational aviation weather products. Decisions approved at the D1 and D2 stage are approved jointly by first line managers in the respective Air Traffic Operations Planning, National Weather Service, and Flight Standards offices who serve on the ASG. Note that a D1 decision requires developers to have a sponsor to support the work they are performing. As part of that process a developer should be responding to a user needs assessment or analysis that provides direction on what is being requested in services but does not drive the solution. To further support a D1 decision an initial Concept of Use (ConUse) document should be prepared to describe conceptually how the product would be used in operations or meet a stated goal or requirements. By necessity, this initial ConUse will be general and flexible enough to accommodate changes in direction of the research as opportunities arise.

D2 Stage

A D2 decision by the ASG allows the developer to move from a concept to a product that needs to be tested in a lab or simulated environment. The product may remain in the D2 stage for several years until the developer believes that the product is ready for advancement. The ASG does not have direct input during this process but should be kept informed of the work that is under progress and be consulted on a periodic basis to help support the continuation of this work during situations that may require budgetary support.

D3 Stage

When entering a D3 decision, the Board is requested to convene and make a determination that the proposed product is ready for experimental testing. This is a critical stage in that the FAA is sanctioning the potential use of the product. Crucial to obtaining Board approval is the preparation of a detailed ConUse plan. Table 1 provides an outline of what is to be included in a ConUse plan. Even though the product is still in an experimental stage the developer, in consultation with the users, should have a clear consensus and understanding of how the product is to be used in operations for the purpose of the testing. This understanding then leads to the need to develop a detailed test plan that will demonstrate how the product can be accessed, used, and verified. Included in the test plan is the need to develop a metric or standard to measure against the success of the product. Quite often the minimum for success is that the product does no worse than existing capabilities; however, under today's austere budgets developers need to set higher standards of success if the Board is to agree that a product is beneficial to users of the NAS. Another requirement is an initial scientific/technical review. A favorable conclusion on the scientific merits of the project helps show that the product shows promise, though it may need further refinement. The goal in this evaluation process is to facilitate the weeding out of any proposed products that may not be based on sound scientific principles or that appear to have no potential for future maturation.

Also, this D3 stage is critical because it begins the process for requesting an Operational and Maintenance (O&M) budget with the anticipation that the product will be operational on a FAA platform for a defined out year. It also further defines whether there is need to enter the FAA Acquisition Management System (AMS) process that requires the development of a mission needs analysis and other supporting documents. Most important and critical at this stage is obtaining concurrence from FAA's Flight Standards Service before being released to a controlled test group where it can be displayed on a sanctioned FAA test bed such as the NWS Aviation Weather Center Aviation Digital Data Server (ADDS). As part of this approval process the developers are required to prepare and present a test plan that describes the objectives of the project, how the testing will be conducted and how the test supports the ConUse. In addition, an initial Implementation Plan (IP) is written to detail tasks each responsible organization must accomplish to ensure smooth transition through the experimental applications stage into operational implementation. The IP includes, among other issues, actions on system architecture, product integration, training, and labor-management relations.

D4 Stage

Once a product has completed its experimental testing it can be considered ready for a D4 decision. In this stage, a final ConUse is written to describe how the product will be used in an operational environment. Included in this ConUse is direction to change other supporting documents on the use of the product such as the Airmen Information Manual (AIM), and further refinement of risks and benefits. In addition, the product has undergone more intensive scientific/technical review and has been judged as technically valid and scientifically sound. The sole basis for the technical review panel conclusion is the scientific and technical validity of the product. The technical review panel does not consider operational utility and human factors qualities, which are evaluated separately with the end users.

Also, if all goes as planned there should be an O&M budget in place to transition the product into an operational environment. To ensure that the product can be advanced to operational a D4 decision requires an implementation plan. The plan identifies the responsibilities of various services to ensure that the product can be operational on the agreed too implementation date. Critical to the implementation plan is the identification of users and platforms that product is to be made available to. Funding is more forth coming from the FAA to further advance this project as in this stage a more refined con use emerges and risks have been identified with the possibility of success.

Public involvement

The proceeding sections described the boxes that had to be checked to move through each stage to the end state. Critical to meeting the requirements for Stages 3 and 4 is public involvement. The FAA has learned that public user input is key to the success to the deployment of any new product. Without customer acceptance of the new product it will never succeed. Not to be forgotten are the FAA's bargaining units. Their input is solicited and critical to any successful deployment of a new product. Implementation of any new product on an operational platform requires procedures and training.

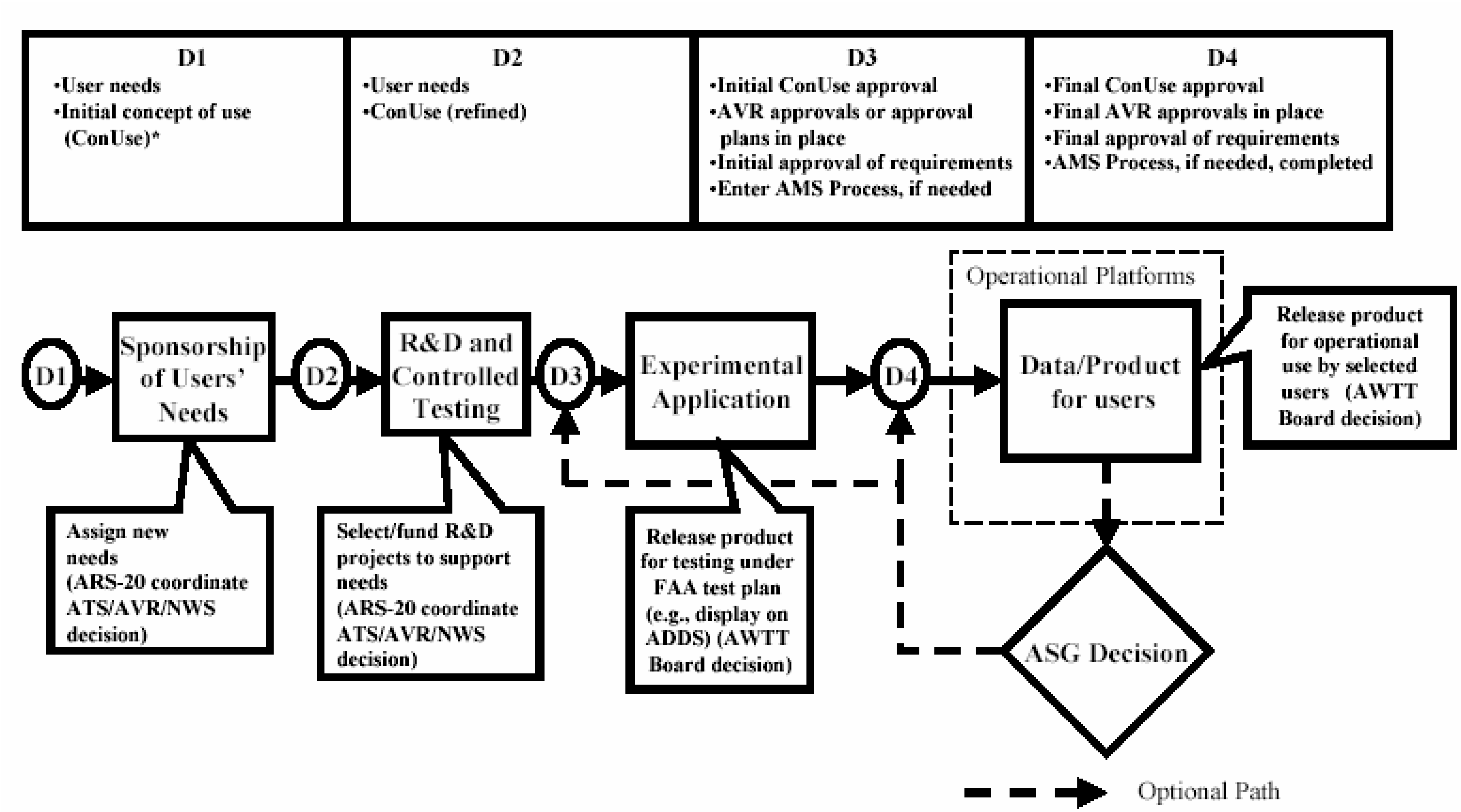
Obtaining customer input and addressing bargaining units concerns can be a formidable challenge at times. As a means to gather public input the FAA conducts quarterly public meetings to solicit input from the public by reviewing the status of various programs, discussing a roadmap to implementation and allowing users to interact with the developers. During the public discussion the FAA describes the attributes of the product and describes how it will be used in the NAS. It should not be assumed that a product will be given *carte blanche* approval for use by all users of the NAS. Experience has shown that many of the new products and innovations are not ready for stand-alone operation to replace existing hazardous messages. On the other hand these new products are used to supplement existing capabilities or can be used as guidance for input to the official hazardous message. The eventual end stage is to develop products that have greater capability to provide timely and more accurate information than existing messages, but the FAA deems it useful to phase in products when it believes there is value added to the services. Bargaining units issues are addressed separately but at the end all significant issues have to be addressed and resolved for both the public and the bargaining units.

Conclusion

The FAA has established a process that helps to accelerate the transfer of technology into operations. At the present time the FAA is further refining its management and oversight of this approach. New products bring new challenges that must be resolved before they can be approved in an experimental and operational mode. The FAA needs to ensure that the information being provided is not misleading and that those users who may be participating in an experimental phase or plan on using the product to support operational decisions fully understand the attributes of the product and information being provided.

Table 1 Guidelines for Con Use Plans to support Experimental or Operational Decisions for the AWTT Board

1. Introduction
   1.1. Purpose
   1.2. Drivers
2. Description of the Need
3. Description of the Product
   3.1. Technical Description
   3.2. How New Product/Capability Address Shortfalls
   3.3. Product Output
   3.4. Regulatory Impact
   3.5. Relationship to Other Domestic or International Products
4. Product Usage
   4.1. Impact of New Product/Capability on Operations
   4.2. Accessibility
   4.3. Limitations
   4.4. Training
5. Evolution of the Product
   5.1. Replacement and Changes
6. Performance, Benefits and Costs
   6.1. Performance Metrics
      6.1.1. Description of how to measure "goodness" of the product
      6.1.2. Criteria for success
      6.1.3. Technical performance standards
   6.2. Description of the Benefits
      6.2.1. Benefits of Using the Product
      6.2.2. Impact of Not Implementing the Product
   6.3. Description of the Costs
      6.3.1. Budget Impacts
      6.3.2. Other Costs
      6.3.3. Who pays?



- These product improvements are not currently under the AWTT process

Figure 1. Aviation Weather Technology Transfer (AWTT) process, showing major milestones and key tasks associated with each milestone.

EFFECTS OF VOLCANIC ACTIVITY ON AIRPORTS

Marianne Guffanti, U.S. Geological Survey, Reston VA, USA
Gari C. Mayberry, U.S. Geological Survey, Washington DC 20560, USA
Richard Wunderman, Smithsonian Institution, Washington DC 20560, USA
Thomas J. Casadevall, U.S. Geological Survey, Denver CO 80225, USA

Introduction

In addition to posing a hazard to in-flight aircraft from airborne volcanic ash, volcanic activity also can disrupt operations at airports, with both local and global consequences for modern life and commerce. Worldwide, approximately 500 airports lie within 100 km of volcanoes that have erupted since 1900 AD. The primary volcanic hazard to airports is ashfall, which causes loss of visibility, structural damage, contamination of ground systems and parked aircraft, and slippery runways. Temporary airport closures have resulted from accumulation of just a few millimeters of ash. On rare occasions, airports also have been damaged by pyroclastic flows (e.g., on the island of Montserrat, British West Indies, in 1997) and lava flows (notably, at Goma, Dem. Rep. of Congo, in 2002). Ash in airspace around airports has damaged in-flight aircraft (e.g., near Guatemala City, Guatemala, in 1999), and airport closures may involve loss of alternate landing sites required for operation of long-distance twin-engine flights (particularly for flights over the North Atlantic).

Ash-contaminated airports can operate with due caution. Practical operational guidelines, based on experience at numerous airports, have been published by ICAO (International Civil Aviation Organization, 2001) and the U.S. Geological Survey (Casadevall, 1993). At-risk airports should have such information on hand as a basic preparedness measure and consider developing operational plans for ashfall events.

Extent of the Volcanic Hazard to Airports

Airport and volcanic data collected by the U.S. Geological Survey's Volcano Hazards Program and the Smithsonian Institution's Global Volcanism Program illustrates the extent of the volcanic hazard to airports. Information about reported instances of airports affected by volcanic activity was gleaned from various sources, including news outlets, volcanological reports (particularly the Smithsonian Bulletin of the Global Volcanism Network), and previous publications on the topic (e.g., Casadevall, 1993). For each instance, information about the airport (such as latitude, longitude, country) and a brief description of the operational disruption have been compiled along with data on the volcanic source (such as latitude, longitude, eruption date, volcanic explosivity index).

Analysis of the resulting database reveals that from 1944 through 2003, operations at airports in at least 75 cities, towns, and military bases in 20 countries (Table 1) were disrupted on 108 occasions by eruptions at 34 volcanoes. This is not a complete inventory of airport disruptions because incidents are not always reported; nevertheless, it is a good sample from diverse parts of the world. About 50% of the impacted airports are located within 100 km of the source volcano, but operations at airports as far away as 500 to 1700 km from the eruptive sources have been disrupted. Some airports have been affected repeatedly – *viz*., at Anchorage in the USA, Bramble (now destroyed) on Montserrat, Catania in Italy, Guatemala City in Guatemala, Kagoshima City in Japan, Mexico City in Mexico, Quito in Ecuador, and San Juan in Puerto Rico.

The 34 source volcanoes are in 14 countries (Table 2). The volcanoes that most often disrupt airports are Mount Etna in Italy, Sakura-jima in Japan, Popocatepetl in Mexico, and Soufriere Hills on the Island of Montserrat in the British West Indies. Soufriere Hills Volcano, although the source of relatively small ash clouds since 1995, has affected the most airports (11), which is not surprising given its proximity to many other islands with airports. Indonesia and the United States have the most volcanoes (5 each) reported to have caused airport disruptions.

An important factor in determining whether an eruption will affect a specific airport is the wind field at the time of eruption. For example, the prevailing winds in the Pacific over the Mariana Islands blow predominantly but not exclusively toward the west, and during most of the May-July 2003 eruption of Anatahan Volcano ash was dispersed away from population centers lying south of the volcano. But on 23 May 2003, winds from Typhoon Chan-Hom pushed the ash plume southward, dusting Saipan and causing flight cancellations there and at Guam, 320 km south of the volcano.

Reducing Operational Disruptions

With some forewarning of imminent volcanic hazards and an operational plan for ash events in hand, a vulnerable airport can take measures to mitigate the disruptive effects of ashfall. Such measures include conducting cleanup quickly and efficiently, moving or covering parked aircraft, optimizing runway usage, and reducing closure time. Recommended clean-up procedures and other mitigation actions are summarized online at: **http://volcanoes.usgs.gov/ash/trans/index.html**

Methods of forewarning of volcanic activity that have been used by airports include: (1) real-time detection of explosive volcanic activity; (2) forecasts of ash-plume paths; and (3) detection of approaching ash plumes using ground-based Doppler RADAR.

Real-time detection of explosive volcanic activity at Sakura-jima Volcano, Japan, allows use of the nearby airport in Kagoshima City despite the volcano's frequent eruptions (>7,300 eruptive events since 1955). Eruptive phenomena are monitored around the clock and in all weather conditions with continuously transmitting seismic and infrasonic instruments designed to distinguish explosive, ash-producing eruptions from volcanic earthquakes and tremor without ash production. When the monitoring system detects an explosive eruption, a warning is automatically sent to flight dispatchers at Kagoshima International Airport. Dispatchers then check wind data and visibility and rapidly issue a recommendation to pilots (e.g., divert to another airport, maintain holding position, select alternate arrival route, or select normal arrival route). The monitoring/warning system used at Sakura-jima has proven very effective at reducing risks to aviation in an unfavorable volcanic environment (Onodera and Kamo, 1994).

Forecasts of ash-plume paths, based on ash-trajectory models for eruptions from proximal volcanoes, provided valuable forewarning to airport operators and the airline industry during the 1989-1990 eruption of Redoubt Volcano in Alaska (Murray and others, 1994). The Alaska Volcano Observatory (AVO) and the Anchorage Weather Service Forecast Office adapted a NOAA model that predicted plume trajectories for 3-hr intervals based on forecast wind fields. Before an eruption, the model was used to estimate where and when ash would be blown. Twice daily, after the predicted wind fields were updated, AVO would plot the trajectories predicted for the next 72 hours. These trajectories were on hand when an eruptive event occurred and were distributed by fax to all interested parties who could then act accordingly to mitigate the effects of volcanic ash. For example, Anchorage airports could optimize the times that runways were kept open. In general for airport needs, ash-dispersion and trajectory models should have the capability to: indicate where ash would go in the first one to two hours after an eruption; estimate arrival time of ash at a particular location in addition to estimating ashfall thickness; and deal with small- to moderate-sized recurring eruptions with little ashfall as well as major ash-producing events.

Detection of approaching ash plumes using ground-based Doppler RADAR was applied in Mexico City, located about 60 km from Popocatepetl's summit and within the volcano's ash-hazard zone. In 1997, Mexico's National Center for the Prevention of Disasters (CENAPRED) and the U.S. Geological Survey used an experimental ground-based Doppler RADAR to track the direction and speed of ash plumes, especially when visual confirmation was difficult at night and in bad weather (Hoblitt and Quaas Weppen, 1999). When the combination of seismic and RADAR data confirmed an eruption had occurred, alerts were given to air-traffic controllers at Mexico City International Airport to prevent encounters of aircraft with ash around the airport. The experimental system used in Mexico eventually suffered a hardware failure, and development of a robust system is needed for further volcanic applications.

Conclusions

Given the demonstrated vulnerability of airports to disruption from volcanic activity, vulnerable airports should have basic preparedness information on hand, evaluate appropriate systems that can provide forewarning of imminent volcanic-ash hazards, and develop operational plans for ashfall events. Such a plan describes: methods and available equipment for clean-up, procedures for incorporating up-to-date information from a volcanological agency about eruptive activity from the proximal volcano(es) into operational decisions, protocols for making the decision to close an airport to ensure aircraft and passenger safety, and procedures for managing air traffic in ash-contaminated airspace in the vicinity of the airspace.

References Cited

Casadevall, T. J., 1993, Volcanic Ash and Airports – Discussion and Recommendations from the Workshop on Impacts of Volcanic Ash on Airport Facilities: U.S. Geological Survey Open-File Report 93-518, 52 pp.

Hoblitt, R.P., and Quaas Weppen, R., 1999, Doppler radar as a volcano monitoring tool [abstract.]: International Symposium on Popocatepetl volcano, 22-24 March, 1999, Mexico City, p. 19.

International Civil Aviation Organization, 2001, Manual on Volcanic Ash, Radioactive Material, and Toxic Chemical Clouds: Doc 9691-AN/954.

Murray, T.L., Bauer, C. I., and Paskievitch, J., F., 1994, Using a personal computer to obtain predicted plume trajectories during the 1989-1990 eruption of Redoubt Volcano Alaska: U.S. Geological Survey Bulletin 2047, p. 253-256.

Onodera, S., and Kamo, K., 1994, Aviation safety measures for ash clouds in Japan and the system of Japan Air Lines for monitoring eruptions at Sakurajima Volcano: U.S. Geological Survey Bulletin 2047, p. 213-219.

Table 1. List of cities, towns, and military bases in which airport operations were disrupted by volcanic activity, 1944 through 2003, organized by country.

Antigua
- Saint John’s

Argentina
- Buenos Aires, Comodoro Rivadavia, Cordoba, Jujuy, Mar del Plata, Neuquen, Puerto Deseado, San Julian, Salta

Colombia
- Pasto

Dem. Rep. of Congo
- Goma

Dominica
- Roseau

Ecuador
- Ambato, Cuenca, Guayaquil, Quito, Riobamba

France
- Unnamed airport(s) on Guadeloupe

Guatemala
- Guatemala City

Indonesia
- Bandung, Gorontola, Manado, Medan, Surabaya, Unnamed airport west of Gamalama volcano

Italy
- Catania, Reggio di Calabria, Naples, Sigonella Naval Air Station

Japan
- Kagoshima, Mijake-jima

Mexico
- Colima, Mexico City, Puebla, Unnamed airports in SE Mexico

Netherland Antilles
- Sint Maarten

New Zealand
- Auckland, Tauranga

Paraguay
- Asuncion

Philippines
- Basa Air Base, Clark Field, Cubi Point, Legaspi, Manila, Puerto Princesa, Sangley Pt. Air Base

Papua New Guinea
- Kimbe, Kavieng, Port Moresby, Rabaul

St. Kitts
- Unnamed airport

United Kingdom
- Unnamed airport on Anguilla, Bramble (Montserrat), Stanley (Falkland Islands)

USA and Territories
- Anchorage, Elemendorf Air Force Base, Grant County, Guam, Kenai, Merrill Field, Missoula, Portland area, Pullman, Roosevelt Roads Naval Air Station (Puerto Rico), Saipan (Mariana Islands), San Juan (Puerto Rico), St. Croix (US Virgin Islands), St. Thomas (US Virgin Islands), Spokane, Unnamed airports on south Texas coast, Yakima

Table 2. Volcanoes whose eruptions are known to have caused operational disruptions at airports, 1944 through 2003, organized by country.

Chile
    Hudson, Llaima, Lascar
Colombi
    Galeras
Democratic Republic of the Congo
    Nyiragongo
Ecuador
    Guagua Pinchincha, Reventador, Tungurahua
Guatemala
    Fuego, Pacaya
Indonesia
    Agung, Galunggung, Gamalama, Lokon, Soputan
Italy
    Etna, Vesuvius
Japan
    Miyake-jima, Sakura-jima
Mexico
    El Chichon, Colima, Popocatepetl
New Zealand
    Ruapehu, White Island
Papua New Guinea
    Lamington, Pago, Rabaul
Philippines
    Pinatubo
United Kingdom
    Soufriere Hills (Montserrat)
USA and Territories
    Augustine, Redoubt, Spurr, St. Helens, Anatahan (Mariana Islands)

AN AIR TRAFFIC CONTROL PERSPECTIVE ON VOLCANIC ASH: HOW TO DEAL WITH IT

Richard Hernandez, FAA San Juan Automated International Flight Service Station
Puerto Rico, USA

The majority of the air traffic controllers in the National Airspace System have limited or no experience in controlling traffic when there is volcanic ash. Although controllers who work specifically at San Juan have little knowledge of the affects of volcanic ash, they have to deal with this hazard on a routine basis.

This paper will discuss the weather issues associated with ash from the Soufreire Hills volcano located on the island of Montserrat and provide a historical overview of how it affects aviation airways in the San Juan airspace.

The two most important factors in determining volcanic ash are forecasting and observations. Within the Federal Aviation Administration, three specific organizations collect volcanic ash information, the towers, the centers, and the flight service stations. Pilot reports are the name given to the collected weather observations by airborne aircraft. The function of the flight service station is to receive pilot reports and disseminate the information to its users. The goal of the flight service station is to keep everyone informed expeditiously. The aviation industry and the flight service station are the other eyes and ears of the National Weather Service. After pilot reports are processed, they are issued to the National Weather Service and other concerned agencies. Whereas the purpose of forecasting is to predict, the purpose of observations is to verify. Whenever mid-level clouds block satellite imagery, the use of pilot report enhances forecasting. There are occasions when pilot reports do not conform to the forecasted models. Weather information received from the flight service station is trustworthy for all types of pilot reports.

Puerto Rico the smallest of the Greater Antilles is located 350 nautical miles northwest of the island of Montserrat. This geographical position places it in the direct path of volcanic ash. In addition, St. Croix, the southern most of the U. S. Virgin Islands and the Puerto Rico municipal islands of Vieques and Culebra located on the east and southeast coast of Puerto Rico are also in the direct path of volcanic ash.

WEATHER ISSUES ASSOCIATED WITH VOLCANIC ASH

The determining factors for the movement of volcanic ash are the atmospheric conditions that surround it.

Historically, volcanic ash creates an aviation hazard at both the lower and upper altitudes. Surface high pressure over the Atlantic will generate a southeast wind component that can lift volcanic ash to about 10,000 feet and move it in a northwesterly trajectory. The normal trade wind flow will usually keep volcanic ash within the airspace of the Lesser Antilles. However, any changes to the position of the high pressure will change the prevailing direction of the wind. When the pressure gradient generates moderate to strong southeasterly winds, it can act as the medium for pushing volcanic ash into the San Juan airspace. Anytime the low-level winds are from the southeast, volcanic ash can carry into Puerto Rico.

As volcanic ash lifts into the upper atmosphere, other factors influence its movement. Sub tropical jet stream currents, upper level westerly winds and upper level troughs with an axis over Puerto Rico and a southwest flow aloft; can induce volcanic ash into the Atlantic and away from aviation airways. The result is that weather systems in the Caribbean and their movement greatly influence aviation in the San Juan and the Lesser Antilles airspace.

From Puerto Rico, the principal airways into the Caribbean are to the southeast and into the path of volcanic ash. Consequently, all facets of the air traffic system are equally impacted.
The affects of volcanic ash on aviation in the San Juan airspace –

FROM THE VIEWPOINT OF THE AIR TRAFFIC CONTROL CENTER

1. Availability of altitudes – because of the different types of aircraft characteristics, not all aircraft can fly above the tops of volcanic ash.

2. Availability of airspace – volcanic ash affects navigational routes causing aircraft to fly around airspace with hazardous weather.

3. Lack of pilot reports – pilots are not sharing information in a timely manner so that other aircraft entering the affected airspace can plan accordingly.

4. Wastes of fuel – The routing of aircraft away from hazardous weather, will always incur the cost of extra fuel consumption. This, in turn, can lead to prioritizing aircraft out of sequence for arrival due to their fuel being below minimums.

5. Increase controller workload – aircraft that are in volcanic ash increase the workload at the adjacent control sectors. Controllers have to transition aircraft safely away from adverse weather.

6. Arrivals and departures delays – arrivals and departures become late in order to compensate for aircraft saturation in the different control sectors.

FROM THE VIEWPOINT OF THE FLIGHT SERVICE STATION

1. Pilot weather briefings increase – whenever there is an aviation weather hazard, all aviation interest including the ports authority request the latest and most current information.

2. Keeping the air traffic center updated – updates on weather advisories and pilot reports need to be timely and current.

3. Weather advisories – the receipt of significant weather advisories from the adjacent meteorological providers are either late or non-existent.

FROM THE VIEWPOINT OF THE AIR TRAFFIC CONTROL TOWER

1. Lack of knowledge - The lack of training and familiarization by general aviation limits their capacity to manage effectively the affects of volcanic ash on engine intake. The Federal Aviation Administration strongly recommends aircraft not to depart when there is the presence of volcanic ash

2. Engine intake - The possibility of engine intake from volcanic ash can greatly reduce aircraft mobility at the airport.

3. Pilot reports – The system users need to be more responsible and comply with request for pilot reports.

4. Aircraft scheduling - Airlines have the authority to determine aircraft scheduling. However, the lack of timely pilot reports and weather advisories makes it difficult to determine if the aviation hazard is either haze or volcanic ash.

5. Availability of gates – Scheduling also affects the availability of gates and create saturation by reducing the number of spaces open to parking.

6. Increase workload – When aviation hazards are lifted traffic on the ground increases. General aviation will tend to call the tower for volcanic ash information when they should be calling the flight service station for a proper weather briefing.

7. Reporting training disagreement – There have been instances where observers and the National Weather Service have reported volcanic ash or haze or a combination of both. Tower personnel have requested training to help them visibly identify and distinguish what is haze and what is volcanic ash.

FROM THE VIEWPOINT OF THE PORTS AUTHORITY

1. Breaking action of aircraft – Volcanic ash on the runway limits the breaking action of aircraft. In addition, the presence of precipitation mixed with volcanic ash creates a soapy substance and affects the runway drainage system. The outcome is that the runway has to be re-grooved.

2. Temperature variation – Because of the airport proximity to water there is a temperature variation between the surrounding land area, the runway, and the water. Wind direction can create a vortex that causes an uneven displacement of volcanic ash. Uneven accumulation of volcanic ash caused by a microburst can also affect the breaking action of aircraft.

3. Aircraft and airport equipment - Because volcanic ash is an abrasive, corrosion acts upon the movement of aircraft and airport equipment.

4. Reduced visibility - volcanic ash affects the airport lighting system reducing visibility.

5. The need for a letter of agreement - No joint letter of agreement exists between the National Weather Service, the flight service station, and the tower to keep the ports authority informed in a timely manner of aviation hazards.

6. Health hazard - in addition to an aviation hazard, volcanic ash is also a health hazard. Several employees at both the tower and the ports authority have complained that the presence of volcanic ash has caused bronchial asthma, sinusitis and respiratory ailments.

THE NEW ZEALAND VOLCANIC ASH ADVISORY SYSTEM

Peter Lechner
Civil Aviation Authority of New Zealand, Lower Hutt, New Zealand

1. INTRODUCTION

The Civil Aviation Authority of New Zealand (CAA) now recognise the New Zealand civil aviation industry's ability to manage it's operations in proximity to volcanic ash with the aid of accepted civil aviation procedures and new information flow systems described in this paper. The Volcanic Ash Advisory System (NZVAAS) is primarily provided through the interactions of aircraft operators, Airways Corporation of New Zealand (ACNZ) and Meteorological Service of New Zealand (MetService). There is also important ground based volcanic information input from the Institute of Geological and Nuclear Sciences (IGNS).

The CAA no longer takes any part in the provision of operational volcanic ash information; however, it does continue to promote awareness of the NZVAAS and an understanding of the volcanic ash threat to civil aviation in New Zealand.

This paper is intended to illustrate the relationships between the NZVAAS participating agencies and show their various obligations in providing enhanced volcanic ash information to the civil aviation industry. In doing so it sets out supplementary procedures to the accepted ICAO practices, in particular the International Airways Volcanic Watch (IAVW) and Volcanic Ash Advisory Centre (VAAC) obligations and responsibilities.

2. DEVELOPMENT BACKGROUND

The volcanic activity of Mt Ruapehu had a significant impact on civil aviation in New Zealand during 1995 and 1996. Many flights were cancelled and many more diverted or re-routed. These episodes were the first time volcanic ash has impacted on modern aviation in New Zealand. New Zealand has a number of active volcanoes on or near the mainland and a number of volcanoes within its IAVW area of obligation.

The CAA operated a special Volcanic Ash Watch Office throughout the 1995/6 periods of volcanic activity at Mt Ruapehu. The Office's prime task was to manage volcanic ash affected airspace, restricted and danger areas, through the issue of formal Notices to Aviation (NOTAM).

A CAA and airline industry fact-finding team went to North America in July/August 1996 where it sought advice on ways of operating aircraft near volcanic ash with minimum disruption. It was widely accepted that there was an increasing risk to aviation worldwide from the ejection of volcanic ash into the atmosphere. As a result of the fact-finding team's report, the way that ash affected airspace was managed and the type and volume of information available on that airspace was reviewed. The main issues to safely allow civil aviation to continue in proximity to volcanic ash were; ownership of the advisory system, improving alerts, improved tracking and drift prediction, airline discretion, contingent airspace management, operational communications and on-going education.

Work has continued in New Zealand to address these issues including: awareness promotion articles and posters printed and distributed by the CAA; incorporation by airlines of procedures to routinely report volcanic and ash activity using the standard Volcanic Ash Report (VAR) forms and procedures; improved ground based monitoring of volcanoes and implementation of alert paging systems linked to seismic monitoring equipment by IGNS; MetService has reviewed and strengthened its production of volcanic ash warnings (SIGMET) and its use of ash trajectory and dispersion models and ACNZ has set up a system to manage alternative routes affected by volcanic ash and implemented a CAA defined set of standard, ready to use, Volcanic Hazard Zone NOTAM.

Success in reducing the disruptive effects of ash on aviation is determined by information on the eruptions and the communication of relevant information to all interested parties. The NZVAAS primarily contemplates the three most risky volcanoes; Ruapehu, Ngauruhoe and White Island and takes into account other volcanoes in New Zealand.

3. THE MAIN VOLCANOES

New Zealand has a number of volcanoes, each with its own eruptive characteristics. Scientific study indicates that the majority must be considered as dormant, rather than extinct, and that they will produce eruptions at some indeterminate time in the future. New Zealand volcanoes can be classed as those that are frequently active or reawakening and those that are not. The cone volcanoes Ruapehu, White Island and Ngauruhoe are classified as frequently active and pose a real threat to aviation in New Zealand. Prior to any eruption, physical precursors are expected to be identifiable; these may develop over time frames of days (and possibly only hours) for the basaltic sites, over months for andesitic sites, and over years for the rhyolitic sites. Such precursors provide the basis for the formulation and issue of warning information.

A volcanic eruption will produce a number of hazards, including ash that will have an effect on hundreds of kilometres of airspace. A volcanic event may build up over weeks to years and be relatively difficult to predict in its probable course and timing. However, ash ejected into the atmosphere can be tracked and its course predicted using conventional and developing meteorological methods. There is therefore a need for flexibility when undertaking volcanic planning. How these issues are managed can depend upon the known characteristics of each volcano, the amount of ash ejected and the prevailing conditions at the time of, or during, the event.

4. VOLCANO ALERT LEVEL

Ongoing volcano surveillance enables the background, or normal status, of a volcano or volcanic field to be determined. Variations of monitored parameters may indicate a change of status and the onset of an eruptive episode. An assigned 'Scientific Alert Level' defines the status of a volcano at any given time. Table 1 sets out the Scientific Alert Level criteria.

The New Zealand Volcano Scientific Alert Levels are based on a six-level system, with each level defining a change of status at the volcano or field. The lowest level *(dormancy) is* signified by '0' and the highest (large hazardous eruption) by '5'. The scale or size of an event will vary from volcano to volcano, ie; a Level '3' event at Ruapehu will be larger than a Level '3' at Ngauruhoe. Where information from the IGNS volcano surveillance programme indicates a change in a volcano's status (either up or down), IGNS will adjust the Scientific Alert Level by issuing a 'Science Alert Bulletin'

In the case of a volcano in the 're-awakening' category, a move from Level '0' to Level '1' does not necessarily signal imminent volcanic activity. Historically, seismic and deformation episodes have occurred at Taupo, Auckland, Rotorua, Okataina, and Raoul Island, which would have resulted in an adjustment to a level '1' alert with no accompanying eruption threat. Similar episodes leading to Level '1' alerts for volcanoes in the 're-awakening' category may be expected every 5 - 10 years.

Importantly, for the civil aviation community a change in the Scientific Alert Level triggers the immediate generation, or change of, a NOTAM on a Volcanic Hazard Zone (VHZ).

5. SYSTEM PARTICIPATION ROLES

Set out in Schematic 1 is a diagram showing the lines of communication and responsibility of participants in the NZVAAS.

5.2 Civil Aviation Authority of New Zealand

The CAA is responsible for ensuring a satisfactory means exists whereby civil aviation aircraft operations can be safely carried out near volcanic ash. The CAA is not responsible for providing any service to airlines to directly assist them with such operations. The CAA's role is to:

(a) Review the effectiveness of the volcanic ash information system from time to time.

(b) Ensure ACNZ, MetService and IGNS have any delegations or permissions required under the Civil Aviation Act 1990 to carry out their roles.

(c) Publish, in the appropriate medium, a clear statement of how the volcanic ash information system works in New Zealand.

(d) Continue to publish any appropriate educational or technical information on aircraft operation in or near volcanic ash, the volcanic situation in New Zealand or any other relevant material.

(e) Establish any new Volcanic Hazard Zone (VHZ) that may be needed to cover volcanoes other than those currently contemplated.

5.3 Meteorological Service of New Zealand

MetService's responsibility is to provide civil aviation with enhanced and timely volcanic ash SIGMETs and any other volcanic activity or ash information packages required pursuant to New Zealand's ICAO obligations, and to maintain volcanic NOTAMs. MetService's role is to:

(a) Maintain a watch over actual and possible volcanic events through the use of satellite and land based meteorological information systems and the use of atmospheric trajectory and dispersion models.

(b) Notify IGNS of any possible eruption detected in New Zealand not already notified by IGNS.

(c) Use suitable atmospheric trajectory and dispersion models to identify the probable path of ejected ash.

(d) Use all appropriate internal and external procedures to generate timely SIGMETs to notify civil aviation of the present and likely future position of volcanic ash in New Zealand's area of responsibility.

(e) Maintain a Volcanic SIGMET watch and update the SIGMET bulletin as frequently as possible and within the ICAO guide-lines.

(f) Provide any extra information such as satellite imagery, ash trajectory information or other graphics that may be requested by civil aircraft operators.

(g) Provide information to IGNS such as wind profile data or independent observation information that may be appropriate.

(h) When notified by IGNS of a change in the official activity level (Scientific Alert Levels) immediately request ACNZ to issue the appropriate NOTAM.

(i) Maintain the currency of any related NOTAM in liaison with ACNZ.

(j) Maintain a watch on technological developments and apply any advances in this area to operations.

5.4 Airways Corporation of New Zealand

The responsibility of ACNZ is to provide to civil aviation the NOTAM service, access to volcanic SIGMET and appropriate VAR information pursuant to New Zealand's ICAO obligations. It also collects, from aircraft, VAR information and disseminates this information to MetService, IGNS and accessible aircraft operators. The ACNZ role is to:

(a) Ensure that meteorological reports (METARs, SPECIs) passed to MetService and civil aviation contains appropriate information on the presence (or not as the case may be during a volcanic episode) of volcanic ash or other volcanic phenomena.

(b) Ensure that all AIREPs containing information on volcanic ash and Volcanic Activity Reports (VARs) received from aircraft are passed with utmost urgency to MetService and any other addressees on the VAR distribution list.

(c) Ensure that updated Volcanic SIGMETs provided by MetService are expeditiously passed to aircraft in flight, especially those operating in the vicinity of any ash.

(d) Upon the receipt of a notification from MetService that the Scientific Alert Level of a given volcano has been changed, immediately issue the appropriate NOTAM. (Table 2 defines the vertical and horizontal limits of the VHZ for given scientific alert levels)

(e) Notify MetService 24 hours before the expiry of any given NOTAM and request an update or confirmation of cancellation.

(f) Set up a system to notify operators which routes and procedures will be affected by each level of volcanic activity.

(g) Ensure that VFR or IFR aircraft that require an ATC clearance to operate within the areas of concern will not be granted a clearance without a specific route request from the pilot.

5.5 Institute of Geological and Nuclear Sciences

The prime responsibility of IGNS is to keep MetService informed as to any volcanic activity taking place in New Zealand. The role of IGNS is:

(a) Maintain monitoring of volcanoes in New Zealand territory, particularly Ruapehu, Ngauruhoe and White Island, on a 24-hour basis. This should encompass the ability to confirm or deny any reported or suspected ash eruption.

(b) Notify MetService of any change in assessed official activity level (ie; Scientific Alert Levels) immediately that decision has been made.

(c) Notify MetService should the risk assessment of any volcano change positively or negatively (ie; Scientific Alert Bulletin).

(d) Advise MetService of any new eruption information as it becomes available. This includes information on; eruption time and expected activity period, eruption type (steam, gas, and ash) and any other relevant advice.

5.6 Aircraft Operators

The responsibility of aircraft operators is to ensure their aircraft do not operate in volcanic ash and to provide Volcanic Activity Reports (VARs) when appropriate. Their role is to:

(a) Ensure procedures are incorporated in operations manuals for the reporting of volcanic events and ash, including the generation and distribution of these reports (VARs) following the prescribed international guidelines (ICAO).

(b) Ensure that aircrew are fully aware of their civil aviation regulatory obligations insofar as Volcanic Hazard Zones (NOTAM) are concerned.

(c) Ensure that aircrew have adequate background knowledge of the atmospheric and airframe effects of volcanic events especially in the context of the New Zealand volcanic situation.

(d) Ensure procedures are incorporated in operations manuals for the safe operation of aircraft near areas of volcanic ash.

(e) Ensure ACNZ is aware of their particular ash episode re-route preferences.

6. EXPERIENCE

Since the implementation of the NZVAAS in 1999, mainland New Zealand has not experienced any significant eruption events, although the NZVAAS system has been operating on a number of occasions. To ensure the system will operate well when the inevitable more significant volcanic event does occur, MetService conducts annual exercises, internally producing simulated agency outputs, interaction and responses. These exercises have been very helpful in both maintaining the currency of staff involved and in streamlining and improving processes.

Experience with the issue of volcanic ash information in New Zealand has highlighted the difficulty on occasion of providing detailed information about volcanic ash in both textual and graphical formats. This can be a significant issue when eruptions from a particular volcano are continuous or quasi-continuous over a period of time, and when wind direction varies with height causing ash to move in different directions with height. Depicting this information graphically has proven to be difficult, and describing the information in textual messages has often resulted in lengthy and very complex messages.

Over the time the NZVAAS has been operating, there has been increased interest in Government regarding overall geophysical risk mitigation. This has proved fortunate for the NZVAAS as it has resulted in better monitoring of New Zealand's mainland volcanoes, and to a lesser extent, the offshore volcanoes.

Foreign airline operators taking up operations to or within New Zealand have had difficulty in understanding the context of the NZVAAS in relation to State IAVW responsibilities. There have also been charging issues arising out of the separate contracting for the NZVAAS as opposed to the standard service contract for ICAO Annex 3 prescribed meteorological services to individual airlines. In every case these issues have been resolved through careful explanation of the two systems. Nevertheless, it would be advantageous to move toward a structure that identifies the NZVAAS as a State based operational part of the overall IAVW.

In the absence of volcanic activity there is a natural tendency for airline operators to place less emphasis on volcanic ash risk mitigation procedures and systems. This seems to be inversely related to the size of the airline operation – the bigger operations have risk management personnel ensuring that their companies do maintain systems and carry out recurrency training. This is not always so with smaller operations. To increase the profile of volcanic activity risk, the CAA, MetService and ACNZ continue to highlight the NZVAAS and its advantages to the New Zealand aviation community.

7. CONCLUSION

The NZVAAS has proven to be a very effective system for New Zealand and this can be attributed largely to the formal arrangements between the participating organisations. It has also highlighted the importance of having co-operative and collaborative relationships between the regulator, the meteorological service provider, the air traffic service provider, the aircraft operators and the local volcanological organisation.

Schematic 1, New Zealand Volcanic Ash Advisory System

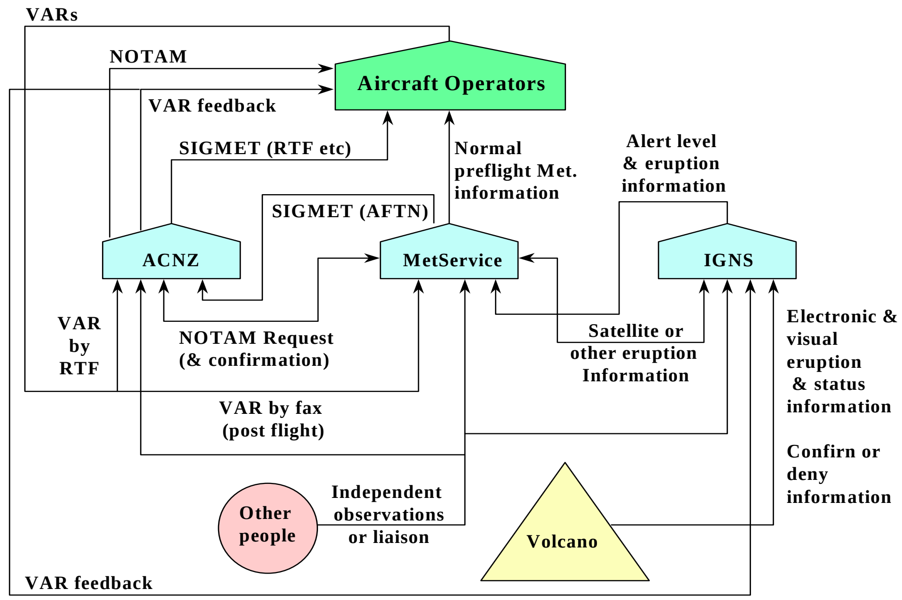


Table 1, New Zealand Volcanic Scientific Alert Level System

FREQUENTLY ACTIVE VOLCANOES White Island, Tongariro -Ngauruhoe, Ruapehu		SCIENTIFIC ALERT LEVEL	REAWAKENING VOLCANOES Kermadecs, Northland, Auckland, Mayor Island, Rotorua, Okataina, Taupo, Egmont	
Volcano Status	***Indicative Phenomena***		***Indicative Phenomena***	***Volcano Status***
Usual dormant or quiescent state.	Typical background surface activity; seismicity, deformation and heat flow at low levels.	**0**	Typical background surface activity; seismicity, deformation and heat flow at low levels.	Usual dormant or quiescent state.
Signs of volcano unrest.	Departure from typical background surface activity.	**1**	Apparent seismic, geodetic, thermal or other unrest indicators	Initial signs of possible volcano unrest. No eruption threat.
Minor eruptive activity.	Onset of eruptive activity, accompanied by changes to monitored indicators.	**2**	Increase in number or intensity of unrest indicators (seismicity, deformation, heat flow etc.).	Confirmation of volcano unrest. Eruption threat.
Significant local eruption in progress.	Increased vigour of ongoing activity and monitored indicators.	**3**	Minor eruptions. High increasing trends of unrest indicators, significant effects on volcano and possibly beyond.	Minor eruptions commenced. Real possibility of hazardous eruptions.
Hazardous local eruption in progress.	Significant change to ongoing activity and monitoring indicators. Effects beyond volcano.	**4**	Eruption of new magma. Sustained high levels of unrest indicators, significant effects beyond volcano.	Hazardous local eruption in progress. Large scale eruption now possible.
Large hazardous eruption in progress.	Destruction with major damage beyond volcano. Significant risk over wider areas.	**5**	Destruction with major damage beyond active volcano. Significant risk over wider areas.	Large hazardous volcanic eruption in progress.

Table 2, Automatic Volcanic Hazard Zone Limits for NOTAM

Volcano Alert Level	*Radius from Vent (nm)*	*Volcanic Hazard Zone Upper Limit*			
		Ruapehu (VHZ 314)	*Ngauruhoe (VHZ313)*	*White Island (VHZ 211)*	*Any other NZ volcano*
1	3	12,200ft AMSL	10,500ft AMSL	4,500ft AMSL	3000 ft above vent
2	8	FL 150	FL 150	FL 150	FL 150
3	16	FL 330	FL 330	FL 330	FL 330
4	27	FL 480	FL 480	FL 480	FL 480
5	>50	unlimited	unlimited	unlimited	Unlimited

PREVENTION OF VOLCANIC ASH ENCOUNTERS IN THE PROXIMITY AREA BETWEEN ACTIVE VOLCANOES AND HEAVY AIR TRAFFIC ROUTES

Saburo Onodera, Flight Crew Training Department,
Japan Airlines, Tokyo, Japan

1. Introduction

At the First International Symposium on Volcanic Ash and Aviation Safety in 1991, countermeasures against volcanic ash encounters were discussed and proposed by various scientific, aviation and government leaders. One of the most significant results that came out of this symposium was the establishment of the ICAO VAAC (International Civil Aviation Organization Volcanic Ash Advisory Center). However, recent reports indicate that the volcanic ash encounter from the Miyakejima volcano eruptions in 2000 could not have been prevented under the current ICAO system. This paper discusses issues on prevention of volcanic ash encounter in the proximity area between active volcanoes and heavy air traffic routes, by reviewing, as a case study, the Miyakejima volcano eruption case in Japan on Aug.18th, 2000, along with the incident from the Izu-Oshima volcano eruption in 1986.

2. Volcanic ash encountering incidents at the Miyakejima Volcano eruption on Aug. 18th, 2000

Miyakejima volcano is located approximately 110 nautical miles southwest of Narita airport in Japan. The explosive eruptions at Miyakejima volcano on Aug.18th, 2000 caused volcanic ash encounter by large transport aircraft in the vicinity of the volcano. **Fig1** shows the location of Miyakejima volcano and the estimated points of volcanic ash encounters by two aircraft. In this region, there are many airways which have heavy air traffic volume in the proximity of the active volcano. The question that arises from this Miyakejima incident in 2000 is why couldn't the volcanic ash encounters be prevented under the current ICAO regime, which was supported by various types of new technologies. In order to prevent further encounter incidents in this region it will be necessary to review the facts at the time of the volcanic ash encounter. The actions by the pilot and ATC (Air Traffic Control) controller are to be reviewed as well as information available at the time of encounter.

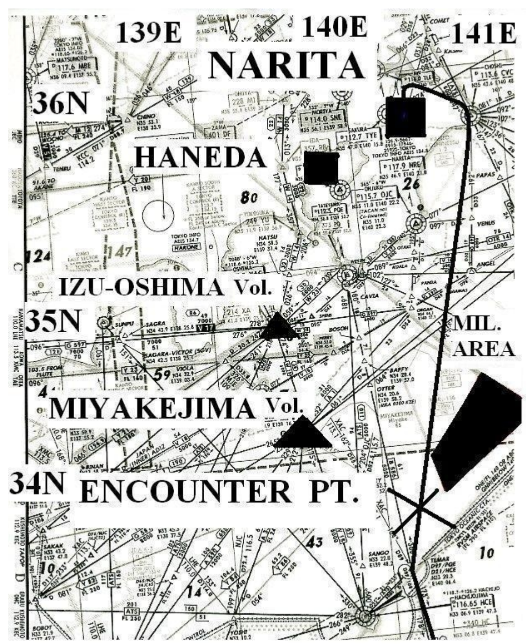


Fig.1. Area chart around volcanoes and encounter point on the avoidance route

2.1. Actions Taken By the Pilot

On Aug.18th, 2000, shortly after the explosive eruption had begun, volcanic ash encounters were reported by two Narita inbound flights, one was a B747 from Saipan, and the other was a B737 from Guam. Serious damage was found on both aircraft during a maintenance check at Narita. Both aircraft encountered volcanic ash while flying at FL340 and FL360 respectively on an air route to Narita near the Miyakejima volcano. The air space south of Narita is complicated by the structure of heavily flown air routes that are located in close proximity to an active volcano. In this air space, options for pilots and ATC controllers to alter a planned route during flight are very limited due to the threat of a possible mid air collision. In this area, arriving/departing routes to/from Narita and Haneda are closely located and/or crossing each other. In this region, it is especially important for pilots to fly strictly by following ATC instructions. Pilots, therefore, rely very heavily on the ATC controllers's decision making. The two aircraft which suffered a volcanic ash encounter were following ATC instructions at the time of the encounter, believing that ATC were radar vectoring them safely away from any volcanic ash encounter. But eventually the two aircraft inadvertently encountered volcanic ash. The pilot's ensuing actions were in accordance with the recommended procedures in the event of a volcanic ash encounter, which prevented an inflight engine shut down and led them to a safe landing at Narita. Even though an inflight engine flame out was prevented by the pilots' appropriate actions, the engines were seriously damaged, as well as other airplane components by the volcanic ash encounter. Questions still remain as to why both aircraft volcanic ash encounters could not be prevented while the pilots were flying in accordance to ATC instructions.

2.2. Actions by ATC Controller

After Miyakejima volcano erupted, on Aug.18th, 2000, ATC controllers directed all Narita inbound flights from south to the furthest easterly route, believing that it was the safest course of action. However, the routes gradually became invaded with volcanic ash, and ATC could no longer provide effective radar vectoring (**Table1**). The information available at that time, which affected decision making in ATC, were SIGMET (Significant Meteorological information) and PIREP (Pilot Report). The volcanic ash transport and dispersion forecast were also provided to ATC. The ATC controllers were supposed to coordinate traffic flow and provide safe avoidance vectoring to concerned aircraft based on relevant information such as the volcanic ash forecast and/or SIGMETs, PIREPs and etc,.

Aircraft Type	Airport of Origin	Estimated ATO(z)	Narita Arrival(z)	Flight Condition
B747	SPN	0824	0859	Normal
B747	SYD	0831	0906	Normal
B747	GUM	0849	0924	Normal
B747	CNS	0905	0940	Normal
DC10	GUM	0916	0951	Normal
B747	**SPN**	**0930**	**1003**	**Encounter**
B737	**GUM**	**0932**	**1005**	**Encounter**

Note: Estimated ATO incident point are based on available data and calculation by the author

Table 1. Flight conditions of the encountered aircraft and the preceding aircraft on the same route

2.3. Information on the location and movement of volcanic ash, by the volcanic ash transport and dispersion forecast SIGMET, and PIREP

A various type of information had been issued at explosive eruptions at Miyakejima volcano on Aug.18th, 2000. The information was disseminated to relevant organizations according to the pre-determined destination table. Critical information, which would have affected the decision making on volcanic ash avoidance route by ATC, was thought to be included within the distributed information such as SIGMETs, VAAs (Volcanic Ash Advisory), and PIREPs.

2.3.1. Volcanic ash transport and dispersion forecast

Since the eruptions began at Miyakejima volcano in June, 2000, the volcanic ash transport and dispersion forecast was published and distributed to relevant organizations. On Aug.18th, 2000, at the time of the explosive eruptions of Miyakejima volcano, the volcanic ash transport and dispersion forecast was issued. However, the forecasted direction of the volcanic ash movement was southward from the crater, while the observed wind direction was southeastward. This slight disagreement of movement direction, between the forecast and the observed one, may have affected, to some extent, the decision making process by ATC on which route to select as the volcanic ash avoidance route for approaching aircraft to the area. It was also revealed that the volcanic ash transport and dispersion forecast included, more or less, a forecast error, which could have adversely affected the decision by ATC on selecting the correct volcanic ash avoidance route. This case shows us that in an area where the air route is densely located, we cannot depend too much on the forecast in the contaminated area.

2.3.2. SIGMET, VAA

An extract of SIGMETs and VAAs is shown in **Table2**. The record of SIGMET and VAA indicates that the explosive eruption at 0802z on Aug.18th, 2000, was notified by VAA issued at 0815z, which mentioned that the plume height was above FL190. Then SIGMET No1 was issued at 0825z, stating that volcanic ash top FL190 and intensifying. VAA No2 at 0835z reported that the ash top above FL400 extending southeast. SIGMET No2 at 0840z stated, quoting PIREP at 0829z, that the volcanic ash top above FL400 drifting to E-SE and intensifying. VAA No3 at 0925z delineated area of volcanic ash as of 0832z and added the forecast area of volcanic ash contamination through the next day. Based on the record of SIGMETs and VAAs, the

Type of Information	Time of Issue (z)	Outline of Content
VAA No1	0815	Erupted at 0802z, ash climbing to above FL190……
SIGMET No1	0825	Obs at 0802z VA top FL190 Movement unknown, intensifying…
VAA No2	0835	VA above FL400, extended SE, by PIREP at 0829z….....
SIGMET No2	**0840**	**VA above FL400, moving E-SE, intensifying ,by B747 at 0829z….**
SIGMET No3	0855	VA above FL400 moving E-SE, intensifying at 0829z by B747…
VAA No3	0925	VA obs by Satellite at 0832z 34.1N 139.4E,…. Outlook at 12z…….
B747	**0930**	**Encounter VA at FL340 at approx 50 nm SE of volcano.**
B737	**0932**	**Encounter VA at FL360 at approx 50 nm SE of volcano.**

Table 2. Extract from SIGMET and VAA on the Miyakejima explosive eruption initiated at 0802UTC on Aug.18th, 2000

issuance of the initial warning, VAA, was 13 minutes after the initiation of the explosive eruption. The timing of issuance of SIGMETs and VAAs were rather swift and quick under the circumstances. Although the SIGMET mentioned the height of the volcanic ash and the movement direction of volcanic ash from an early stage, the moving speed and the contaminated area of volcanic ash were not included until a later SIGMET. The lack of the critical information was another factor unfavourable to volcanic ash avoidance.

3. Comparison to the Izu-Oshima case in 1986

Aircraft Type	B747	DC8	DC10	B747
Time of Encounter (Z)	approx. 0900	approx. 0900	approx. 0920	Unknown
Portion	NRT－HKG	TPE－NRT	NRT－BKK	BOM－NRT
Location	60nm S of NRT	40nm E of Vol.	60nm E of Vol.	Unknown
Flight Phase	Climb	Descent	Climb	Descent
Altitude (feet)	20,000-30,000	30,000-26,000	20,000-23,000	17,000-10,000
Condition (Visibility)	Night(good)	Night(good)	Nighr(good)	Unknown
Observed Phenomena	**Spark. Smell of burning wood**	**Unusual odour**	**Static discharge on windshield**	Light to Mod turbulence
Aircraft Damage	None	**Small particle like fog**	**Erosion (1). VA in pitot tube**	**Fine scratches on windshield**

(1) Erosion was found on windsheild , horizontal and verical stabilizer.

Table 3. VA Encounter at Izu-Oshima volcano eruption on Nov.21st 1986

3.1. Izu-Oshima volcano eruption on Nov. 21st, 1986.

Izu-Oshima volcano is located approximately 80nm southwest of Narita airport and 38nm north northwest of Miyakejima volcano. On Nov. 21st, 1986, Izu-Oshima volcano erupted explosively and a volcanic ash cloud top soon reached a height of more than 10km above the crater. After this eruption, a volcanic ash encounter took place as shown in **Table3**. In this eruption, the volcanic ash encounter was approximately 40 to 60 nm east of the volcano, while at the Miyakejima volcano eruption in 2000, the encounter took place approximately 50 nm southeast of volcano. The relative distance between the crater and the encountering point in Miyakejima case is similar to that in the Izu-Oshima case.

3.2. Countermeasures against volcanic ash encounter

Table4 shows the countermeasures against volcanic ash encounters in 1986 and in 2000. It is clear that in 2000, we had much more data available than what we had in 1986. It can be said that, in 2000 we had better quantity and quality of data at hand than in 1986. In spite of much better conditions, the fact is that the volcanic ash incidents could not be prevented.

Year/Volcano / Countermeasures	1986 Izu-Oshima	2000 Miyakejima
Eruption Detection	Available	Available
SIGMET	Available	Available
NOTAM	Available	Available
Satellite Imagery	Available	Available
Split Window	N/A	Available
VAAC. VAA	N/A	Available
Dispersion Forecast	N/A	Available

Table 4. Improvement of countermeasures

3.3. Lead Time before encounter

Table5 shows the time sequence after the start of the explosive eruption until the actual volcanic ash encounter. The lead time of the explosive eruptions before the encounter is approximately 1 hour 40 minutes in the Izu-Oshima case and 1 hour 28 minutes in the Miyakejima case. This fact shows that we had plenty of lead time before the actual encounter. We may have had more desirable results if we could have better utilized the lead time by continually updating and assessing the situation.

Time	Nov.21 1986 Izu-Oshima	Aug.18 2000 Miyakejima	Dec.15 1989 Redoubt
Eruption time	0720z	0802z	1915z
Encounter time	0900z	0930z	2045z
Lead time before encounter	**1hour 40 min**	**1 hour 28 min**	**1 hour 30 min**

Table 5. Lead time before volcanic ash encounter

4. Lessons learned from the incidents and the proposals for the area

These volcanic ash encounter cases are similar in the region of proximity of active volcano and heavy air traffic route. The Izu-Oshima volcano case in 1986 and Miyakejima volcano case in 2000 seems to indicate the following facts.

a. Volcanic ash encounters took place even after 14 years of progress in the international volcanic ash prevention program and the volcanic ash detection and movement prediction technique.

b. Even though pilot reports were submitted from an early stage after the eruption and SIGMETs were also issued consecutively, the volcanic ash avoidance route provided to Narita inbound flights from the southern airspace were not changed until after the encounter had taken place. This infers the difficulties of dealing with the information derived from SIGMET and PIREP, and the difficulty of applying them into the ATC decision making process for volcanic ash avoidance

c. In the area where the air route structure is complex with a heavy load of air traffic in the proximity area to an active volcano, positive ATC decision making is crucially important for preventing volcanic ash encounters.

d. In those areas like c. above, basic education on the knowledge of volcanic ash encounter incident and practical education on the knowledge of volcanic ash avoidance is critical. Annual drills for ATC are essential in the area where heavy air traffic route are located in the proximity to active volcanoes.

Acknowledgement

I would like to thank those persons who provided me data pertinent to volcanic ash encounter incident in this region. At the same time I would like to thank those people who contribute to the prevention of volcanic ash encounter. I would like to specially thank the ex-director of SVO (Sakurajima Volcano Observatory, Kyoto University) and professor emeritus of Kyoto University, Dr.Kosuke Kamo, and the director of SVO, Dr.Kazuhiro Ishihara and SVO staff, and Dr. Hiroshi Tanaka, Tsukuba University, and Mr.Michael Kelly, Japan Airlines, for their continuous advise and help to the author since 1980s.

Reference

Brantley, S. R., (Editor), 1990, The eruption of Redoubt Volcano, Alaska, December 14, 1989 - August 31, 1990, *U.S. Geological Survey Circular* 1061, p 7-24.

A PROGRAM FOR RESEARCH AND SYSTEMS INTEGRATION TO HELP MITIGATE THE VOLCANIC ASH HAZARD TO AVIATION

Tenny A. Lindholm, The National Center for Atmospheric Research (NCAR)
Boulder, Colorado, USA

Introduction

The National Center for Atmospheric Research (NCAR) Research Applications Program (RAP) is currently addressing five aviation weather hazard areas through emerging weather products: convection and convective hazards; in-flight icing; turbulence (terrain-induced, convective-induced, jet stream, and shear); remote and oceanic weather hazard diagnosis and forecasts; ceiling and visibility. The National Weather Service (NWS) and Federal Aviation Administration (FAA) are transitioning these products to operations for use by pilots, dispatchers, flight service specialists, and air traffic controllers and managers. Underlying research, verification, dissemination methods, and user interface/display development have been sponsored primarily by the FAA Aviation Weather Research Program (AWRP), with joint sponsorship from the NASA Aviation Safety Program (AvSP).

The Oceanic Weather Product Development Team (OWPDT), one of eleven PDTs sponsored by the AWRP, is developing and introducing remote and oceanic weather products. The OWPDT, as one of its taskings in response to formal FAA requirements, is developing advanced techniques that will detect, forecast, and disseminate information on volcanic ash plume hazards to aviation operators and users. Airborne volcanic ash constitutes a recognized threat to aviation that can severely damage jet aircraft engines through erosion, corrosion and congestion. A number of well-documented near-fatal accidents have occurred, and even relatively minor encounters have resulted in extensive aircraft damage. Volcanic ash contamination may render large volumes of airspace unavailable, necessitating costly rerouting contingencies, and problematic ash-related aircraft encounters have been reported days after an eruption and thousands of miles from the source.

Current Volcanic Ash Products Available to Users

Current volcanic ash products available to aviation users include (as extracted from the FAA User Needs Analysis [UNA] document, dated 5 September 2001):

Volcanic Ash Significant Meteorological Information (SIGMET): The product generally describes the horizontal and vertical extent and the expected trajectory of the volcanic ash cloud.

Aviation Routine Weather Report/Special Aviation Weather Report (METAR/SPECI): An aviation weather observation for a specific airport.

Notice to Airmen (NOTAM)/Volcanic Ash NOTAM (ASHTAM): A NOTAM is a statement concerning the establishment, condition or change (e.g., hazard) in any component of the NAS. The ASHTAM serves as a status report for volcanoes that are active, but not necessarily erupting.

Pilot Report (PIREP): A report of meteorological phenomena encountered or observed by the flight crew while the aircraft is in flight.

Aerodrome Forecast (TAF): A forecast prepared for specific airports of important aviation parameters such as ceiling and visibility, winds and weather/obstructions to vision.

Volcanic Ash Forecast Transport and Dispersion Model (VAFTAD): A graphic depiction of the Volcanic Ash Advisory and a projection of the expected transport of the ash cloud over a specified period of time in space and flight level.

Volcanic Ash Advisory Statement (VAA): A report distributed in text form to air traffic service units and meteorological watch offices concerning the presence of a volcanic ash cloud.

User Needs as Documented in the FAA's User Needs Analysis

Capability shortfalls and goals are stated quantitatively in the UNA for each attribute. Qualitative descriptions of stated needs can be summarized as follows:

- In general, integration of the various agencies responsible for generating information on volcanic eruptions and ash clouds, to include a collaborative approach that (a) informs all stakeholders on the most current information and (b) permits all stakeholders to participate in updating information. There is no common database of text and graphic products that all users can access, which adversely affects the collaborative decision-making process. Stakeholders include airlines (dispatch, flight operations, meteorology), air traffic management and control, NWS, USGS.
- Improved detection of volcanic eruptions globally, to include forecasts of volcanic activity and characterization of the initial ash cloud.
- Better characterization of the ash cloud as the event progresses:
    - Detection accuracy, location, horizontal extent
    - Vertical extent of hazard
    - Ash density and chemistry
    - Differentiate volcanic ash hazard from meteorological cloud
- More frequent product updates.
- Improved timeliness of updates (from observation or product generation to user access).
- Better forecasts:
    - Location, horizontal extent
    - Vertical extent of hazard
    - Ash density and chemistry
    - Longer valid time
    - Dissemination for flight planning
- Better training for airline operation centers (AOCs), flight crews, and air traffic control specialists.
- Ready access to all information for all users (AOCs, flight crews, and air traffic control specialists) including graphical updates to the airborne flight crew.
- Regarding graphical products, they need to be higher resolution and referenced to planned flight profile.

Specific scientific and engineering plans and tasks have been defined by the OWPDT in response to these formal user needs. We emphasize that considerable research on defining volcanic ash hazards and detection of dangerous eruptions is already underway. The OWPDT plans to assume an integration role as these new capabilities emerge, as well as defining new research areas as satellite detection capability improves. Although the OWPDT's initial focus is on the Washington and Anchorage Volcanic Ash Advisory Centers (VAAC), coordination with the Darwin, Tokyo, and Montreal VAACs is also planned. The Team also includes NASA, the U.S. Geological Survey, the U.S. National Weather Service, and other centers of expertise in satellite sensing technologies and the characterization of volcanic ash hazards.

Plans and Progress

In its role as integrator, the OWPDT hopes to bring together the research and development that targets the volcanic ash hazard to optimize the quality of information provided to users, recognizing that no one piece of data will complete the process. Therefore, our focus will be on the use of "expert system" or fuzzy engine integration of diverse data sources and diagnostics to address the detection and dispersion problems. The OWPDT is also teaming with the NWS and NOAA's Forecast Systems Laboratory to develop a collaborative display concept and tool that will host emerging automated products and allow the stakeholders to view them and collaboratively alter them as required. These, of course, are long-range goals; however, they represent the best path to operations that will begin to address the formally documented user needs. We plan to introduce new capabilities to operations as they complete user evaluations and verification. Finally, through applied research, we intend to identify new satellite sensing capabilities that in the long term might be included in future geostationary satellites that can better detect and track volcanic ash plumes.

Some of the specific tasks the OWPDT has identified thus far include:

- Integration and display of VA SIGMET graphics and advisories on the OW web site (http://www.rap.ucar.edu/projects/owpdt/), representing an early capability. This display is currently running in test mode, creating global graphics from textual SIGMETs with a 97% success rate. Figure 1 shows the current OW domains and an example display.
- Ultimately, near-complete automation, with minimal mandatory human intervention.
- Capability to issue short-term pre-eruption advisories during episodes of potential volcanic unrest. Inclusion of geophysical data and input from the geosciences community.
- Improved detection of remote, unmonitored volcanic eruptions, possibly using a combination of teleseismic and satellite data.
- Incorporation of recently developed satellite interpretation technologies (e.g., multispectral analysis and channel splitting) to enhance ash cloud tracking. The OWPDT collaborates with several satellite centers of excellence with the goals of using current sensing technologies better, and identifying promising future technologies as well. For example (there are others),
    - The Moderate Resolution Imaging Spectroradiometer (MODIS) data has demonstrated considerable potential for mapping several characteristic constituents of the ash cloud, including the ash particles, on the basis of distinct radiative properties in the thermal infrared.
    - The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrumentation is ideal for detecting the thermal anomalies associated with volcanic eruptions. It has even been suggested that ASTER data may be used to identify regions of volcanic unrest, potentially allowing the forecast of an increased eruption risk. Although ASTER data has limitations that are inherently associated with the "on demand" nature of the instrument, the high spatial resolution of the data set may be extremely useful when available.
    - The Multi-angle Imaging Spectroradiometer (MISR), which heavily emphasizes aerosol measurements, may provide additional capability to detect and monitor ash clouds of sufficient age that they are no longer thermally anomalous.
    - The Advanced Microwave Scanning Radiometer for EOS (AMSR-E) may prove useful for detection of young ash plumes when millimeter-sized particles may still be entrained. Data from this sensor may alleviate problems mentioned above in the detection of young ash plumes.
- Improvements to plume and ash cloud dispersion modeling, including high-resolution wind-field modeling and realistic particle size distributions. A fuzzy integration of several dispersion modeling systems, taking advantage of the strengths of each, could improve dispersion forecasts.
- Development of a global, high-resolution, satellite-derived wind field that can be integrated with the dispersion model system.
- Incorporation of "intelligent systems" capability, allowing the integration of a wide variety of input sources.
- Output will be graphical and generated in response to a user request, accessible even to airborne flight crews.
- Ash cloud characterizations will consist of detailed density contours, as opposed to the simple "visible cloud outlines" that are currently distributed.
- Task-oriented training for both meteorological and aviation user communities.

Conclusion

The OWPDT has an ambitious plan to help improve the current volcanic ash information provided to aviation end-users, and is continuing work to establish collaborations with agencies and institutions that have needed expertise. Of particular interest is the realization that current sensing technologies might not have the capabilities to satisfy needs completely, and NASA's remote sensing work supporting the design of future satellite sensing suites will definitely be a crucial element of the OWPDT's efforts. Meanwhile, as incremental capabilities emerge and are verified, they will be introduced to the operational community to help mitigate both the safety and efficiency impacts the volcanic ash hazard has on aviation.

This research is in response to requirements and funding by the Federal Aviation Administration (FAA). The views expressed are those of the author and do not necessarily represent the official policy or position of the FAA.

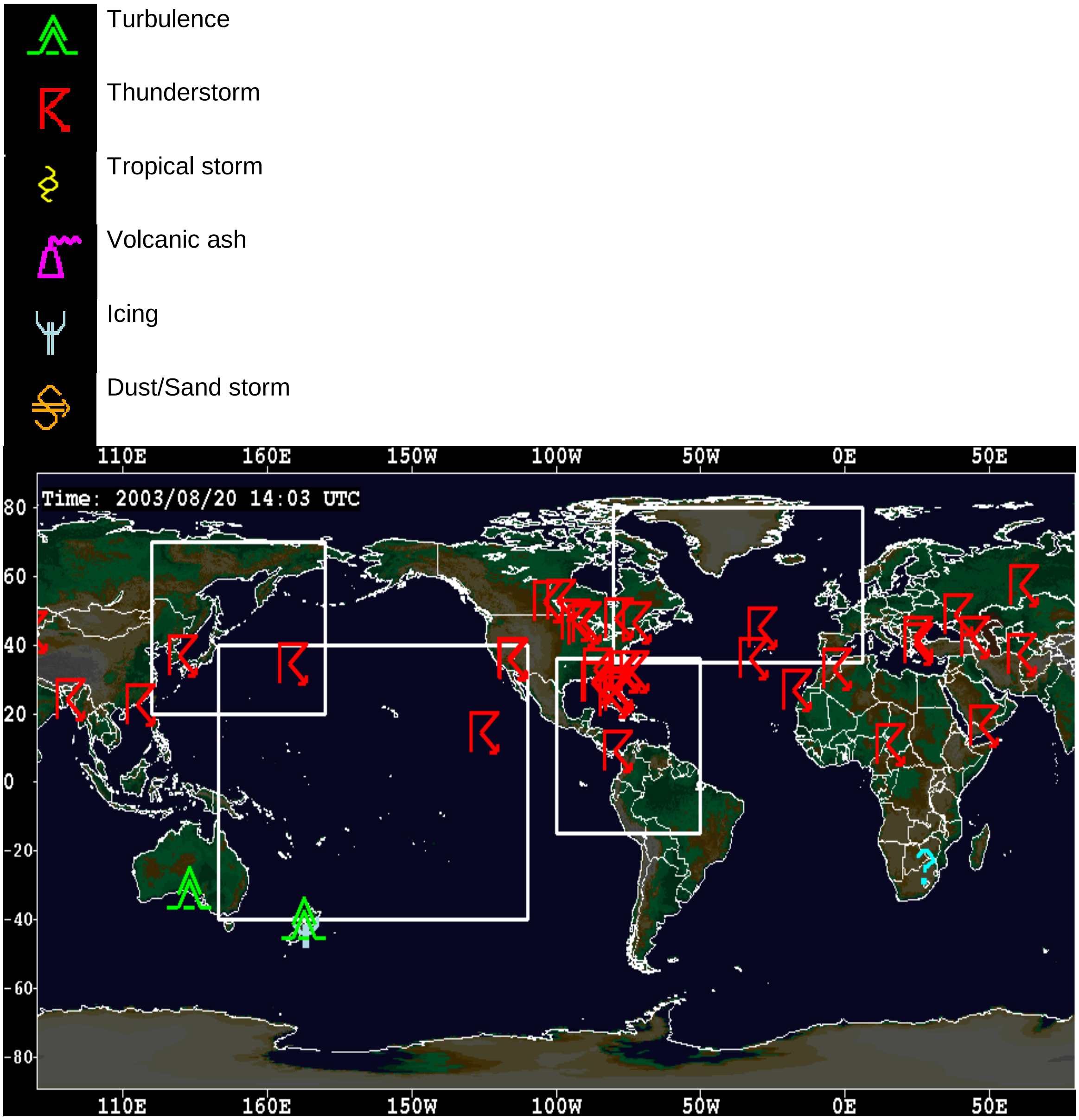


Figure 1

EXPLOSIVE VOLCANIC ERUPTIONS ACROSS THE HEAVILY TRAVELED NORTH PACIFIC AIR ROUTES: FREQUENCY, DURATION, AND IMPACT ON AVIATION

Thomas P. Miller, U.S. Geological Survey, Alaska Volcano Observatory, Anchorage, AK, USA
[tmiller@usgs.gov]

The 100 historically active volcanoes (about 1/6 of the world's active volcanoes) that rim the North Pacific along the Alaska Peninsula, Aleutian Islands, Kamchatka Peninsula, and the Kurile Islands are part of the highly explosive "Pacific Rim of Fire". Analysis of the past 200-year record indicates that these volcanoes collectively average 3-5 eruptions/year. Most of these eruptions are relatively short-lived events lasting only a few days producing limited ash emission to low altitudes; however, a significant minority of eruptions last for months or even a few years. The 1989-90 eruption of Redoubt volcano near Anchorage, for example, lasted 4 months and had at least 20 explosive events that resulted in ejection of volcanic ash to >30,000 feet. Prevailing winds commonly carry volcanic ash across the North Pacific (NOPAC) and Russian Far East air route tracks that carry as many as 240 cargo and passenger flights per day. About 5 days/year, volcanic ash from these eruptions is at cruise altitudes of > 30,000 feet ASL and perhaps on another 10-15 days, airborne volcanic ash is at sufficient altitude to be of potential concern to aircraft routing, payloads, and scheduling. The severity of the hazard is indicated by the past 20 year record that shows encounters between airborne volcanic ash and commercial aircraft in the North Pacific have caused an estimated $100 million dollars damage to aircraft, frequently disrupted air traffic, and occasionally required the closing of airports. This impact on aviation has led to the establishment of a color code to rapidly alert the aviation community to hazardous conditions, increased seismic and satellite monitoring, and detailed geologic studies to determine eruptive histories of active volcanoes throughout the region.

FIRST 8 HOURS OF VOLCANIC ERUPTIONS: A NORTHWEST AIRLINES EXAMPLE & RECOMMENDATION OF REVISED FLOW OF ASH INFORMATION FOR AVIATION

Tom Fahey, Manager, Meteorology, Northwest Airlines,
Minneapolis/St. Paul, Minnesota, USA

Currently, according to ICAO Annex 3, there are five steps in the process of notifying pilots and dispatchers of volcanic ash or volcanic eruptions. This process cuts across a spectrum of organizations and professionals. It requires close coordination to ensure that all airlines in the affected airspace receive the needed information for the safety of flight. Time is of the utmost importance in getting the message out. Even though ICAO describes the functional responsibilities for Meteorological Watch Offices, Volcanic Ash Advisory Centers, Volcano Observatories, and Area Control Centers, there is a need to re-examine the inter-relationships between these organizations and how information is gathered and exchanged. This paper will describe not only the existing protocol but provide a conceptual framework of how to streamline or improve the standardization of exchanging information and data based on prior Northwest Airlines experience and deficiencies in the system.

INTERAGENCY
WORKING GROUP FOR VOLCANIC ASH (WG/VA)

MS. GRACE SWANSON, Chairperson*
NOAA/NESDIS
Department of Commerce

MR. STEVEN ALBERSHEIM
Federal Aviation Administration
Department of Transportation

MS. MARIANNE GUFFANTI
U. S. Geological Survey
Department of the Interior

MR. JOHN HAYNES
National Aeronautics and Space Administration

MR. CHARLES HOLIDAY
Air Force Weather Agency
Department of Defense

MR. RICHARD WUNDERMAN
Smithsonian Institution

MS. BARBARA STUNDER
NOAA/ARL
Department of Commerce

MR. CHRISTOPHER STRAGER
NOAA/NWS
Department of Commerce

MR. LEONARD SALINAS (Technical Advisor)
United Air Lines

MR. ED MILLER (Technical Advisor)
Air Line Pilots Association

Mr. Donald "Doc" Carver, Executive Secretary
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

* Working Group Chair rotates among NOAA, FAA, and USGS

THE 2ND INTERNATIONAL CONFERENCE ON VOLCANIC ASH AND AVIATION SAFETY
PLANNING COMMITTEE

MS. MARY CAIRNS, Chairperson
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

MR. DONALD "DOC" CARVER
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

MR. STEVEN ALBERSHEIM
Federal Aviation Administration

MS. GRACE SWANSON
NOAA/NESDIS

MS. MARIANNE GUFFANTI
U. S. Geological Survey

MR. ED MILLER
Air Line Pilots Association

MR. THOMAS FRAIM
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

MS. ERIN McNAMARA
Office of the Federal Coordinator for
Meteorological Services and Supporting Research

MR. KENNETH BARNETT
Office of the Federal Coordinator for
Meteorological Services and Supporting Research