COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES

Annual Report on NOAA Cooperative Agreement NA67RJ0153

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CIRES as a joint institute between the University of Colorado and NOAA by definition establishes links between many different units in both organizations. It is the largest of seven institutes within the University of Colorado system and maintains eight departmental plus three programmatic affiliations on campus. The various departments can be thought of as providing the academic foundation for the *disciplinary* research we conduct within CIRES. The university programs tend to be academic activities that focus along *interdisciplinary* themes. As the largest of the eleven NOAA Cooperative or Joint Institutes, CIRES maintains a close affiliation with nine NOAA laboratories, most within the Boulder community. CIRES is internally structured into both divisions and centers. The four divisions tend to group themselves along *disciplinary* lines, while *interdisciplinary* research can be thought of in terms of the CIRES centers of which there are now five.

CIRES currently has over five hundred employees distributed amongst Fellows, graduate students, undergraduate students, research scientists, associate scientists, and administrative staff. This distribution when broken down by affiliation reveals that approximately half of the organization is associated or affiliated with NOAA laboratories, while the remaining half is associated with university laboratories.

In the attempt to foster interdisciplinary research plus promote further collaboration between the university and the NOAA laboratories, CIRES has recently created two new Centers that cross traditional boundaries. Our *Colorado Center for Chaos and Complexity (C4)* seeks a better understanding of non-linear systems and has stretched CIRES beyond the physical sciences into understanding their impacts upon the social domain. It focuses upon newly emerging ideas in nonlinear sciences, both for low dimensional deterministic systems and for high dimensional complex systems subject to noise and uncertainty. As part of its outreach activities, *C4* has made considerable progress in forming a business network to establish a dialogue with the business community that will be mutually beneficial. The *Climate Diagnostic Center (CDC)* is an outgrowth of the strong CIRES/NOAA collaboration that now has sponsorship both within the University and through NOAA. This Center is in its infancy and a new CU-based Associate Director has just been named.

CIRES has recently established and is developing a *K-12 Outreach Program* that has already been recognized as an exemplary model by a scientific research institute. Its projects are of high quality and combine rigorous science with innovative learning practices. Ongoing projects include teacher training, scientist training, classroom presentations, and public exhibits. Proposed projects included a major initiative for girls and women in science which will incorporate extensive collaboration between local and regional organizations, and a curriculum development project based on NOAA/NASA field missions.

Rather than individually list all research activities, we have chosen to highlight some of our major research initiatives. NOAA's recent review of CIRES provides a more detailed summary of scientific accomplishments over the past few years. A list of recent CIRES publications and presentations plus a concept paper highlighting the *Water in the Interior West* initiative are also attached.

Seasonal to Interannual Forecasting

During the severe Pacific storm season of 1998, the Environmental Technology Laboratory (ETL) brought together research scientists, forecasters, emergency response agencies and resource managers to improve short-term coastal forecasts. Scientists investigated land-falling jets, a key feature of coastal storms, as a means of better predicting the storm's impact on the coast. Aircraft flights into the storm observed its structure and collected data that were used to predict the storm's landfall. Based on this predicted storm track, mobile instruments were deployed to observe the storm as it encountered the coastal region. These data were also relayed to NWS forecasters, resource managers and emergency agencies for incorporation into their forecasts and planning. The preliminary results show:

- Real-time data gathered by the research aircraft helped forecasters issue timely flash flood warnings a remarkable 8 hours before flooding occurred.

- Incorporation of offshore data into numerical models improved the 24-hour forecast of a storm.
- The data collected was useful in assessing a storm's position, strength and moisture content up to one day before it hit the coast.

- Wind profilers can provide real-time information to improve coastal rainfall forecasts.

The Climate Diagnostic Center (CDC) successfully predicted the El Niño of 1997-98 nine months in advance, although like most other prediction systems, it severely underestimated the rapid development and magnitude of the event. The empirical-dynamical model used is based on an assumption of stable multi-linear dynamics of tropical SST evolution. Its success in this and many other cases challenges the view that

El Niño arises from an instability of coupled tropical atmosphere-ocean system. CDC scientists have investigated this using dynamical coupled models of intermediate complexity in collaboration with the universities of Texas and Washington (JISAO). The air-sea coupling in these models can be rendered stable or unstable by adjusting a single parameter. Interestingly, the models give the most realistic results in the stable regime, lending further support to our "Stable Multi-Linear" paradigm. A similar model has also been developed for the tropical Atlantic coupled system and is now routinely being used for making SST predictions in the region.

CDC scientists took a rather original and scientific approach to the question of whether El Niño affects individual storms. They ran two-week forecast ensembles with and without the El Niño SST anomalies and examined the extent to which the evolution of individual weather events was affected. They were able to demonstrate a large El Niño impact on the February 1998 California rains, but unexpectedly were also able to demonstrate a large impact on the devastating January 1998 "ice-storm" in the northeast U.S. and Canada, an area with an historically weak El Niño connection. This study has generated considerable interest because it hints at unusual El Niño impacts and because it highlights the importance of having accurate tropical SST information even in the medium range, especially for predicting extreme weather events. Given that ENSO (El Niño Southern Oscillation) is possibly the only predictable signal in the climate system on seasonal to interannual time scales, it is important to be able to predict it and its global ramifications.

Using the NCEP climate GCM to perform more than 500 years of integrations, we showed the importance of knowing the month that SST anomalies reach their maximum and demonstrated significant asymmetries in the extratropical responses to El Niño and La Niña forcing. They showed that even in regions with a historically weak composite ENSO signal (the simple average of many different events), the signal for a particular event can be strong and strongly affect the risks of floods and droughts. We also showed that many aspects of the U.S. climate are just as sensitive to SST anomalies in other regions as they are to anomalies in the eastern tropical Pacific. Although the SST variability in these other regions is generally weaker, the anomalies may attain appreciable magnitudes in individual cases and appreciably affect the U.S. The details of the SST anomaly patterns during individual ENSO events can then indeed be important.

The Climate Diagnostics Center was especially active in public outreach in response to the recent El Niño event. We developed a Web site on the subject that is consistently receiving more than a million hits per month. We also gave numerous interviews to the local, national, and international TV and print media to raise public awareness of the developing event and help make El Niño a household name. Locally, many were also involved in public education, particularly at the middle school level, in leading school discussions on climate topics and participating in science fairs.

Health of the Atmosphere

Southern Oxidant Study (SOS)

The Nashville/Middle Tennessee study was aimed at understanding the processes that shape the distribution of ozone on regional scales in the eastern United States. This ozone is one of the most persistent air-quality problems in the United States. The results of the 1995 field study were published in the Sept. 20, 1998 issue of the Journal of Geophysical Research and included ten manuscripts authored or co-authored by CIRES scientists. One of these manuscripts describes the relative contribution of large point sources to regional ozone production. This paper will have a major impact on the approaches taken to reduce regional ozone pollution. Manuscripts for a second special issue are being finished for submission by October 1, 1998.

North Atlantic regional Study (NARE)

The NARE component of the *International Global Atmospheric Chemistry (IGAC)* project conducted a major field study in September 1997. The aim of this study was to determine the influence of photochemically produced ozone of continental origin on the ozone distribution over the North Atlantic. The study also investigated the transport and chemical processing of ozone and ozone precursors over the region. A large number of CIRES scientists were involved in the campaign. A workshop was held at CIRES in August 1998 to discuss mission results along with cooperative studies carried out at the same time by NASA and EUROTRAC. In addition, CIRES scientists co-authored five manuscripts for a special issue that appeared in the June 20, 1998 of the Journal of Geophysical research that describe the results for earlier NARE studies.

Identification and Quantification of Compounds Emitted from Harvested Biomass

The mechanisms responsible for the emission of volatile organic compounds from harvested biomass have been investigated by CIRES scientists from the Chemistry and Biochemistry Department of the University of Colorado and from the NOAA Aeronomy Laboratory. The release of volatile organic compounds (VOC's) by drying grass and clover leaves and stems was studied in the laboratory using proton-transfer chemical-ionization mass spectrometry, which enables the simultaneous, on-line monitoring of VOC concentrations. A burst of VOC emissions due to cutting the leaves and stems was followed by a second, more intense and longer lasting emission when the vegetation was starting to dry out. In addition to (Z)-3-hexenal, (Z)-3-hexenol and (Z)-3-hexenyl acetate, which were emitted by the plant tissue in response to the wounding, enhanced emissions of formaldehyde, methanol, acetaldehyde, acetone and butanone were observed. These findings may have identified an important additional source photochemical ozone precursors and thus have important implications for regional air quality over agricultural and urban areas.

Stratospheric Chemistry Modeling

Modeling studies indicate that increases in NO_x catalyzed O_3 loss are subject to photochemical buffering in the lower stratosphere through reduced HO_x catalyzed O_3 loss and reduced halogen-catalyzed O_3 loss. Consequently, an NO_y increase that reaches the

middle stratosphere could lead to modest depletion of column O_3, while an NO_Y increase confined to the lower stratosphere should have a neutral or slightly positive effect on column O_3. Other studies have focused on N_2O, an anthropogenic trace species with 200-300 times the greenhouse forcing potential of CO_2 (on a per molecule basis). While recent measurements have hypothesized a missing stratospheric sink of major significance, comparisons of aircraft and model tracer correlations in the lower stratosphere provide evidence in support of conventional N_2O sinks and argue against a new undiscovered sink that contributes >20% to the total.

Earth Observing Systems

Chemistry

Development of Nitric Acid Measurement Techniques

Nitric acid is the end product of the oxidation of the oxides of nitrogen in the atmosphere. As such the formation of nitric acid and its removal from the atmosphere plays a key role in determining the role of the oxides of nitrogen in the formation of tropospheric ozone. CIRES Research Scientists participated in reporting the results of an informal intercomparison of nitric acid measurement techniques that appeared in February 1998 in the Journal of Geophysical Research. Two of the manuscripts describe important new methods for the measurement of HNO_3.

Technique for Estimating Denitrification Rates

The Center for Limnology developed a new kind of detector for estimating denitrification rates under field conditions. Denitrification is a critical component of the nitrogen cycle that also produces N_2O, a greenhouse gas.

High Precision CO_2 Detector

A new instrument was developed for measuring atmospheric carbon dioxide mixing ratios for deployment from kites, balloons and light aircraft. The modified total organic carbon (TOC) analyzer uses a bundle of semi-permeable hollow fiber membranes to continuously equilibrate CO_2 in air with a recirculating stream of deionized water. Aqueous CO_2 hydrolyses and dissociates to form H_3O^+ and HCO_3^- ions and thereby increasing conductivity. Potential interferents that may also increase the conductivity (such as acids and bases) are removed at the inlet with scrubbers. The detector has been field-tested and exhibits a 1/e response time of ~30 seconds and precision (RSD) of 0.1%. Field results for measurements at altitudes in the range of 1700 to 3600 m exhibited an average deviation of 0.16% from values obtained by flask sampling and laboratory measurement at CMDL.

Upper Atmospheric Aerosol Particles

A theoretical study of the influence of dynamo forces on electrically charged aerosol particles in the upper atmosphere has been completed. It appears that the theory may explain the occurrence of particles in narrow sharply bounded layers, whose steep

gradients are probably responsible for anomalously strong radar echoes from the polar mesopause region during summer.

Atmospheric Dynamics and Physics

Boundary Layer Measurements by Kite

The "kite group" at CIRES continues to be involved in comparison measurements with ETL. Recent measurements included joint high-resolution measurements of water vapor profiles, temperature, etc. in the first km of the atmosphere using our kite/TRAM platform at the ARM CART site in Oklahoma. Measurements made this past summer obtained in-situ samples of insect population densities that produce strong interfering echoes on the MMCR (cloud radar) system up to 5 km. Finally, we have initiated discussions with ETL scientists to compare C_T^2 and C_N^2 profiles obtained from kites with those obtained using conventional radar techniques.

Long-term Studies of the Tropopause

Radiosonde measurements of temperatures and geopotential heights made at island stations in the western tropical Pacific Ocean are being examined to look for long-term trends in the height and temperature of the tropopause and of fixed pressure levels in the lower stratosphere. Such trends, if they exist, could be the most sensitive indicators of tropical climate change, and the time period for which the data are available extends back roughly 40 years, allowing detection of decadal-scale changes. Preliminary results have shown a small but significant increase in tropopause heights, and a marked cooling in stratospheric temperatures that is especially pronounced in the years following 1980.

Trans-Pacific Profiler Network (TPPN)

The major objectives of the TPPN are to provide enhanced atmospheric monitoring of tropospheric winds over a data sparse region of the equatorial Pacific. Data from network stations provide long-term observations for climate diagnostics research and process studies of the climate system and its simulation in GCM's. They also provide data from under-sampled regions of the tropical atmosphere needed for the global analyses and forecasts made routinely by operational meteorological centers such as NCEP and ECMWF. Recent accomplishments include development and testing of merged profiler and OMEGA sounding data sets plus merged surface and profiler measurements. Scientific studies include analyses of diurnal wind cycles, circulations associated with the tropical annual cycle, and precipitation work aimed at development of schemes for classification and analysis of cloud microphysics and kinematics.

Space Weather

CIRES has been involved with the implementation, validation, and improvement of the Wang-Sheeley model: an empirical model that predicts the background solar wind speed and interplanetary magnetic field (IMF) polarity at Earth. Advance knowledge of these two parameters assist space weather forecasters in making predictions of the geomagnetic

environment. The model often reliably predicts these background parameters four days in advance. The Wang-Sheeley predictions are posted daily on a NOAA/SEC Web page located at http://solar.sec.noaa.gov/~narge/. The model uses magnetogram-derived synoptic maps and a potential coronal field model to make the predictions. Daily magnetograms are presently based on data from the Wilcox Solar Observatory, but Kitt Peak and Mount Wilson Solar Observatory data will soon be added as model input. The ability to use magnetograms from a number of solar observatories will help to minimize the gaps in data that result from bad weather, mechanical problems, and other perturbations.

Solid Earth

Groundwater contamination

Pursuing a long-term goal of detecting groundwater contamination, CIRES' scientists seek to understand the propagation of strain waves through porous rocks, partially saturated with fluids. Such an understanding should lead to the development of a ground water monitoring system for toxic and nuclear waste sites as well as for the study of two phase flow as also encountered in oil and gas recovery. The propagating strain wave interacts with the matrix and fluid by mainly compressing the matrix and moving the fluid. Our work extends previous research by including forces that act on the meniscus. Static as well as dynamic meniscus forces significantly influence the moduli and attenuation. Laboratory work determines the meniscus forces directly by measuring the drag exerted on surfaces as fluids move across them. We then measure the energy that is absorbed when single cracks are deformed sinusoidally and the liquid within them flows. By measuring the drag forces as a function of velocity and the absorbed energy over nearly five orders of magnitude in frequency (0.001 to 100 Hz), we are able to separate viscous effects from surface tension and kinetic effects. At present we are establishing the characteristics with which different contaminants affect the absorption spectrum of strain waves.

Crustal Observations

CIRES completed a major geochemical study of the origin and evolution of silicic magmas in the upper continental crust using exposed igneous rocks from southern New Mexico. Model assessment was done for the Precambrian tectonic evolution of the western U.S. using Nd isotope data from ancient sedimentary rocks in U.S. and Mexico. The sources of dissolved constituents (including As) in domestic drinking water in Fairbanks AK were determined and the initial work began on the development of lattice Boltzman automata modeling of water- rock interaction. They used Nd, Sr and Pb isotope data to investigate the nature of the lower continental crust beneath the Rocky Mountains and to study sediment distribution paths associated with Heinrich events in the North Atlantic and initiated radiogenic studies of Carlin-type gold deposits in Nevada and the Klondike gold deposits in the northern Yukon, Canada.

Satellite Gravity Mission

CIRES has been working to better understand the scientific potential of NASA's GRACE satellite gravity mission. GRACE, which has been approved for a 2001 launch, will map Earth's gravity field to unprecedented accuracy and spatial resolution every few weeks. The time-variable component of gravity reflects the effects of changes in mass within the earth and on and above its surface. It will be possible to use the GRACE gravity results to address problems in a wide variety of disciplines, from oceanography to hydrology to glaciology to solid earth geophysics. We and our collaborators have been addressing problems in all these disciplines, both to help define the capabilities of GRACE, and to develop methods of processing the gravity field data to help realize those capabilities.

Seismology

CIRES scientists led a data analysis team associated with the NSF-funded Mantle Electromagnetic and Tomographic (MELT) seismic experiment. The MELT experiment consisted of the deployment of over 40 ocean bottom seismometers in the southeastern Pacific Ocean. They analyzed seismic waves from distant earthquakes recorded at the MELT seismic stations to study the deep structure and dynamics of mid-ocean ridges. Their results indicate that mid-ocean ridges do not have a lower mantle or core-mantle boundary origin, but rather represent passive upper mantle upwelling in response to spreading oceanic plates. Other colleagues participated in deployment and operation of the Lodore real-time seismic array of a 34-stations in NW Colorado. The data was transmitted in real-time to CIRES and is being used to study crustal and mantle structure of the Cheyenne Belt Archaen/Proterozoic suture, local seismicity, and to develop array technology and processing capabilities.

Crustal Deformation Studies

GPS receivers and an FG5 absolute gravimeter were used in a number of studies in ice motion and glacial rebound collaboratively with JILA. CIRES scientists also re-measured GPS arrays across the SW Caribbean plate boundary, the Mexican/Cocos plate boundary, India relative to central Asia and Tibet, and the motion of the Somalia Plate relative to Africa. They maintained arrays of creepmeters across the Hayward fault in the Bay Area and a biaxial 500 m-long tiltmeter in the Long Valley caldera. Measurements to Aves Island determined the slip during the 1996 El Pillar earthquake and the motion of the Caribbean plate relative to N. America (22 mm/year west). Convergence across the Nepal Himalaya continues at 222 mm/year and we have added additional points in western Nepal to monitor the details of the convergence process. Some work was featured in the recent IMAX movie on Everest. Measurements across the Altyn Tagh fault on the northern margin of the Tibetan plateau indicate that its long-term slip velocity is moving approximately 17-25 mm/year absorbing 1/3rd of India's convergence with Asia. The African rift in northern Ethiopia is widening at 2.5-4.5 mm/year. Measurements of the amplitudes of tides across the rift reveal that these are not amplified suggesting that the strength of the rift at daily periods is no different from the surrounding continent.

Arctic Science

Greenland Ice Sheet

Mapping of the albedo of the Greenland ice sheet from satellite AVHRR and in-situ measurements has revealed that large seasonal changes occur due to snow melt near the coasts and lesser effects result from grain size characteristics elsewhere (see Annals of Glaciology 1997 and Remote Sensing of the Environment,1997).

Permafrost Data Now Available

Production of the first CD-ROM containing data and information on permafrost and seasonally frozen ground (including a digital Northern Hemispheric map of permafrost, a 12-language glossary of terminology, numerous data sets, and cumulative bibliography) was completed during the previous year.

Program for Arctic Regional Climate Assessment (PARCA)

Five new automatic weather stations were installed during the '97 field season to increase the GC-Net to a total of 14 AWS stations. Seven AWS maintenance jobs were carried out at Swiss Camp, JAR, Crawford Point-1, Summit, DYE2, GITS, NASA-W, and the AWS tower was extended by 2 m at GITS, NASA-W, Crawford Point-1, and JAR. GC-Net data set has been calibrated and quality control programs have been applied. This algorithm outputs cleaning statistics and methods used to ancillary data files for reference purposes. Documentation of the datasets and quality control methods are on-line. The mean annual temperature at the Swiss Camp increased by about 1° C per year from -16° C to -11° C between 1992 and 1997. During the same time period, the mean wind speed decreased by about 2 m/s. The data set collected at the Swiss Camp is presently the longest continuous climate record of the Greenland ice sheet. The katabatic outflow of cold, dense air from the top of the ice sheet is controlled by the location and strength of the Icelandic low pressure. The mid-winter air temperature pulsation at lower elevations of the ice sheet can now be parameterized using the National Center for Environmental Prediction (NCEP) pressure fields. The annual surface height change for the dry-snow regions of the ice sheet can be approximated with a linear model, with over 90% of the variance explained. Each AWS location however has a different slope for the linear approximation. Accumulation events in northwestern Greenland occur mainly during up-slope westerly wind conditions with wind speeds in the range 5-10 m/s. The formation of drainage of a melt lake was studied at the western slope of the ice sheet due to the "un"-fortunate placement of the JAR-AWS. A surface albedo decrease from 0.7 to 0.25 was observed from pre-melt to bare-ice conditions, with an additional albedo decrease from 0.25 to 0.15 during the formation and filling of the melt lake. A cloud amount parameterization was developed based on measured solar radiation and calculated effective cloud opacity. Compared with observations at the Swiss Camp, this approach has a mean monthly error of ±1.5 tenths in cloud amount. A mean cloud amount of 57% was derived for the Swiss Camp for a five-year data set during March and September. NCEP modeled atmospheric pressure compares within ±5 hPa with measured pressure values at three AWS locations in north and west Greenland. Larger variances occur in the winter months when deep cyclones are common over the Greenland ice sheet.

Surface Heat Budget of the Arctic Ocean (SHEBA)

NSIDC (National Snow and Ice Data Center) personnel participated in two elements of the *Surface Heat Budget of the Arctic (SHEBA)* during April, May, and July of 1998. They used a suite of sled-mounted instruments to collect spatially distributed observations of skin temperature, air temperature, and surface reflectance over a range of surface conditions including multi-year ice, first-year ice, young ice, and refreezing leads. Measurements were coordinated with satellite, aircraft overpasses and fixed-location instruments. The latter included a network of Portable Automated Mesonet (PAM) stations installed and maintained by NOAA and CIRES investigators. The objectives of this field component are to document the spatial variability of energy balance parameters in relation to ice and atmospheric conditions.

We also took part in NCAR C-130 flights over the SHEBA study area during July. Aircraft mapping instruments include a passive microwave radiometer, scanning visible- and thermal-band radiometer, and video cameras. In addition to extensive overflights of the SHEBA vicinity, the C-130 observed ice and atmospheric conditions during the entire flight route from Barrow to the research site (approximately 76° N and 163° W in late July). Combined aircraft data, satellite imagery and field observations will enable algorithm validation and mapping of the evolution of open water fraction and melt pond coverage.

Water in the Interior West

Susan Avery, CIRES Director, and Randy Dole, Director of NOAA-CDC, notified NOAA during Spring of 1998 that CIRES would be seeking support from NOAA for a new research initiative focusing on Water in the Interior West. The scope of the initiative, as conceived by a multi-disciplinary group of faculty and federal scientists, extends across the entire water cycle. For NOAA, a logical point of entry to the initiative is through climate variability. The CIRES Water Initiative encourages NOAA to support analysis of the connections between climate variation and hydrology, water management and water availability, aquatic ecosystem function, and water quality in the Interior West. Both Susan and Randy made multiple trips to Washington to confirm the general interest of NOAA in the Initiative.

During Spring of 1998, we prepared a concept document giving the scope and content of a long-term research effort that might be supported by NOAA and, ultimately, other agencies as well. The document entitled "A Water Research Initiative for the Interior Western United States" was prepared by representatives from the fields of climate research, hydrology, aquatic ecosystem studies, and social sciences. A copy of the text of the concept document is attached and will soon be available on the CIRES Website at http://cires.colorado.edu/.

The response from NOAA to the concept document was quite positive. While potentially any one of several branches of NOAA could sponsor the Western Water Initiative, it became apparent that NOAA OGP might be the most logical one to do so, at least for a

regional assessment effort. A proposal for a multi-year regional assessment to be supported by NOAA OGP was prepared and submitted to NOAA in mid-June. A hopeful sign for the Regional Assessment Proposal is some startup funding from NOAA that became available on 28 August 1998. While the amount of startup support is modest, it will allow CIRES and NOAA-CDC to immediately begin setting the groundwork for the Regional Assessment Program.

Yet to be decided is a much larger increment of funding for the full Western Water Initiative which extends beyond the boundaries of regional assessment and into the development of new analytical tools and measurement techniques, application of modeling to regional water balance, and numerous other topics. This higher level of support has received some encouragement through approval within NOAA and within the Department of Commerce. Generally, larger programs of this type evolve only over a period of years, and the rate of progress thus far is highly encouraging.