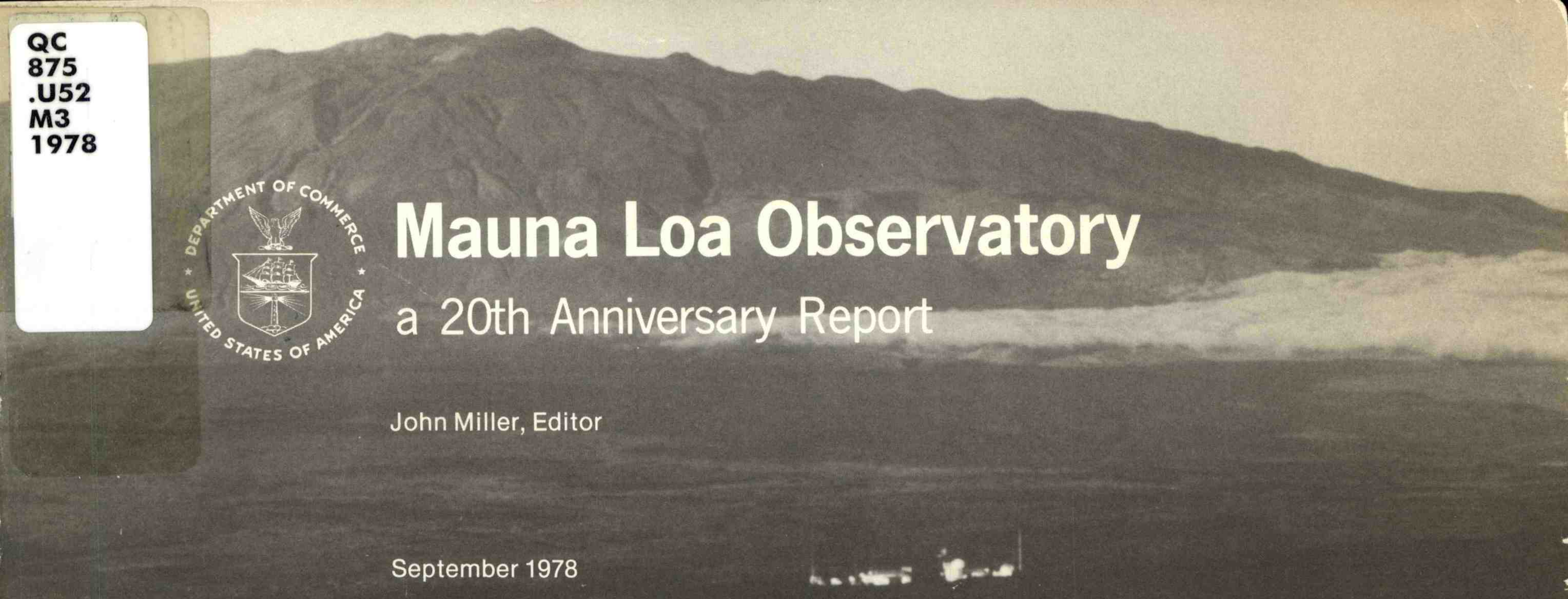

Mauna Loa Observatory

a 20th Anniversary Report

John Miller, Editor

September 1978

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

NOAA Special Report

MAUNA LOA OBSERVATORY
"A 20th Anniversary Report

John Miller, Editor

Air Resources Laboratories
Silver Spring, Maryland

September 1978

U.S. Department of Commerce
Juanita Kreps, Secretary

National Oceanic and Atmospheric Administration
Richard A. Frank, Administrator

Environmental Research Laboratories
Boulder, Colorado
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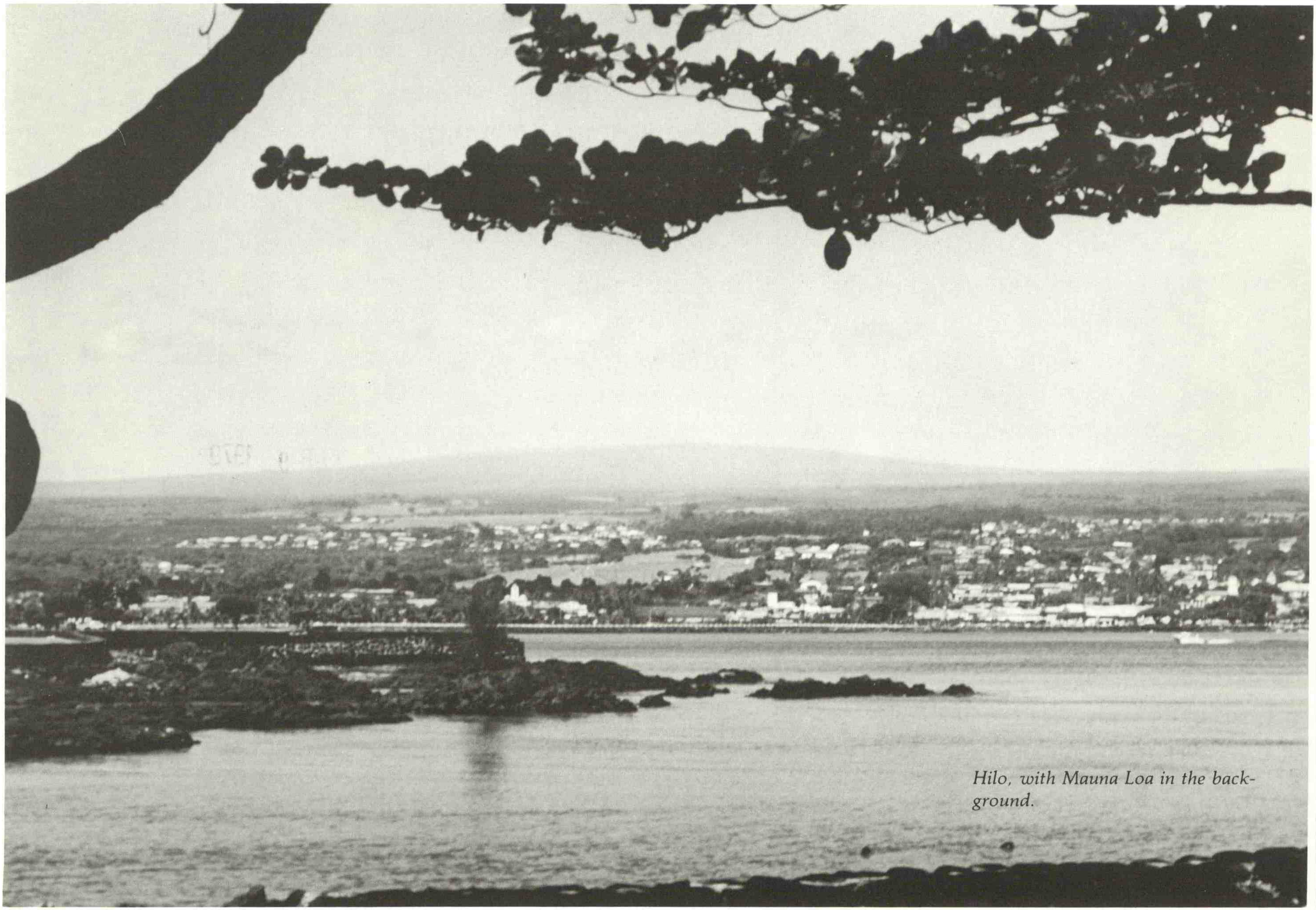
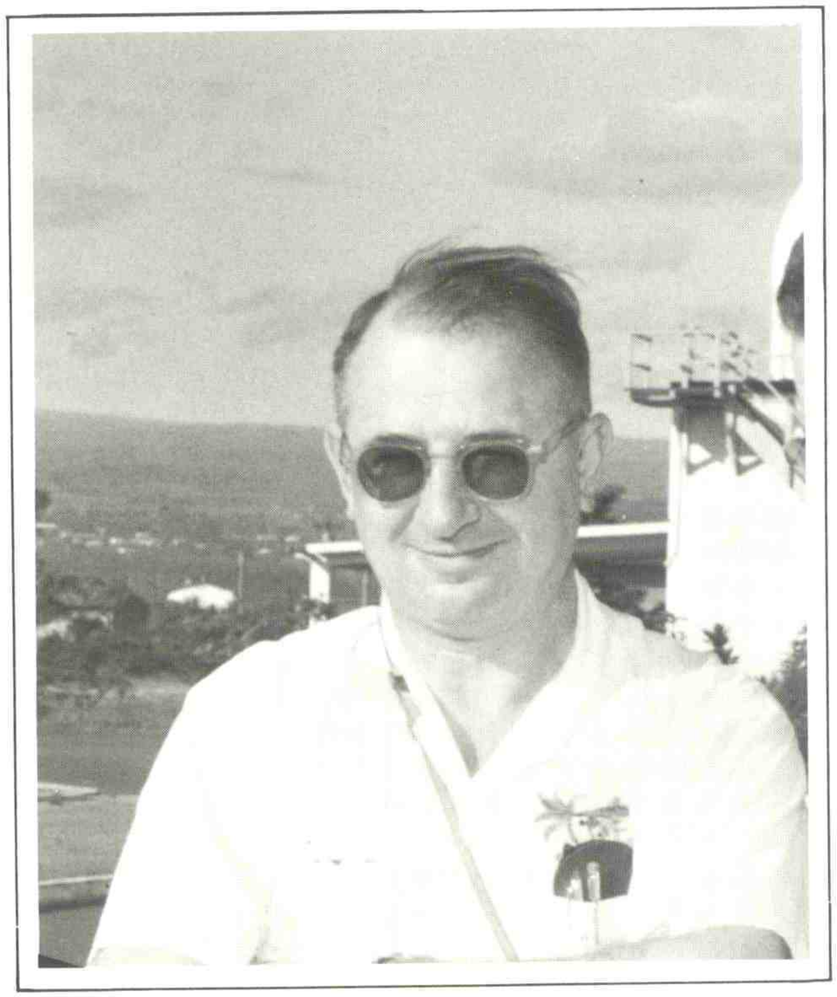
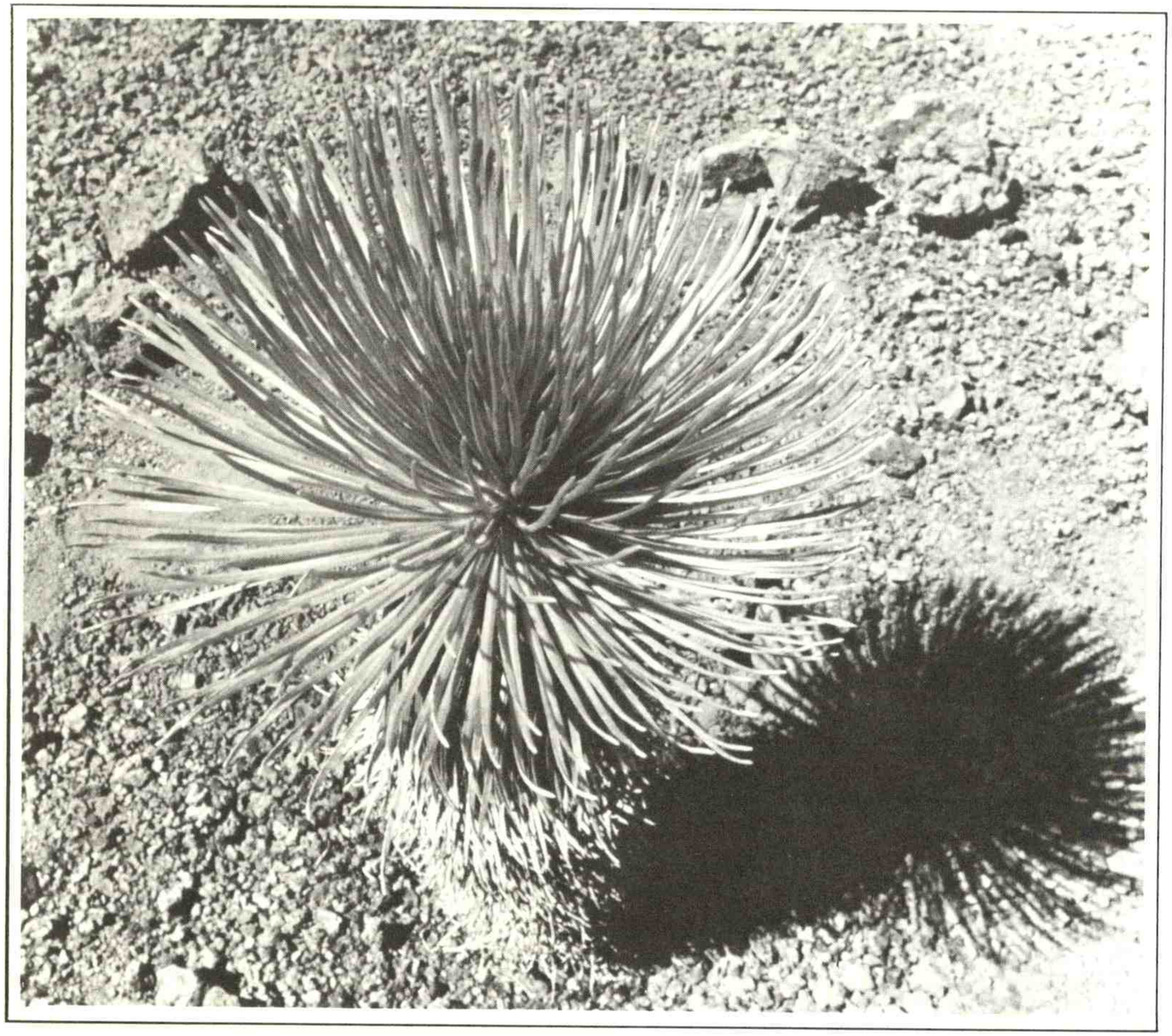


Hilo, with Mauna Loa in the background.



To the memory of Harry Wexler, a scientist with remarkable perception, breadth, and foresight; a man whose warmth, sincerity, and generosity set an enviable goal for those who were fortunate enough to know him; a research director with outstanding ability who had much to do with the establishment of Mauna Loa Observatory.



A single, rare silver-sword grows on the north slopes of Mauna Loa, protected by a fence and periodically visited and inspected.

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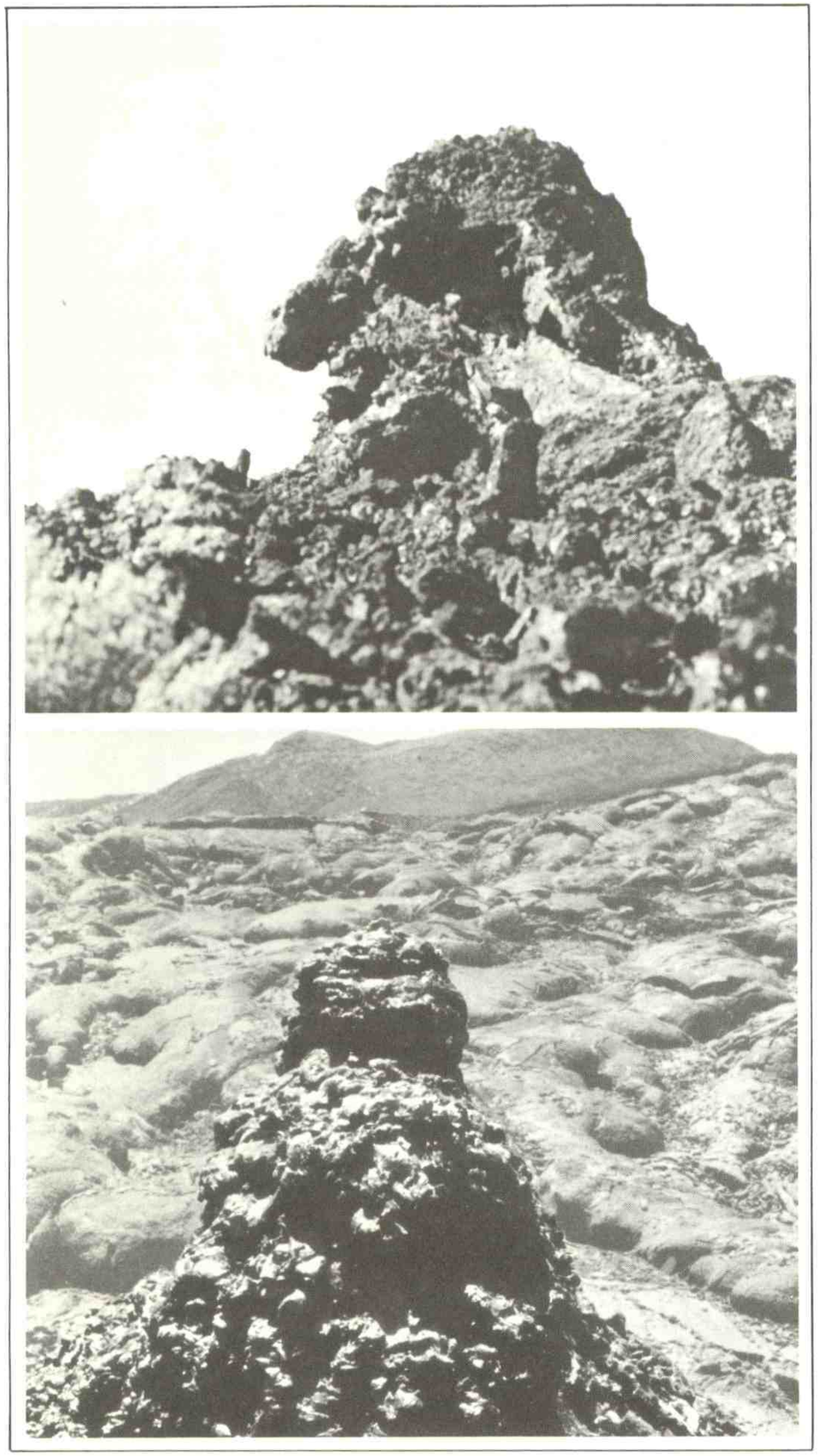

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Natural lava formations like "the head of Charles de Gaulle" and "a former keeper of the mountain" are the scenic features on the road to Mauna Loa Observatory.

FOREWORD

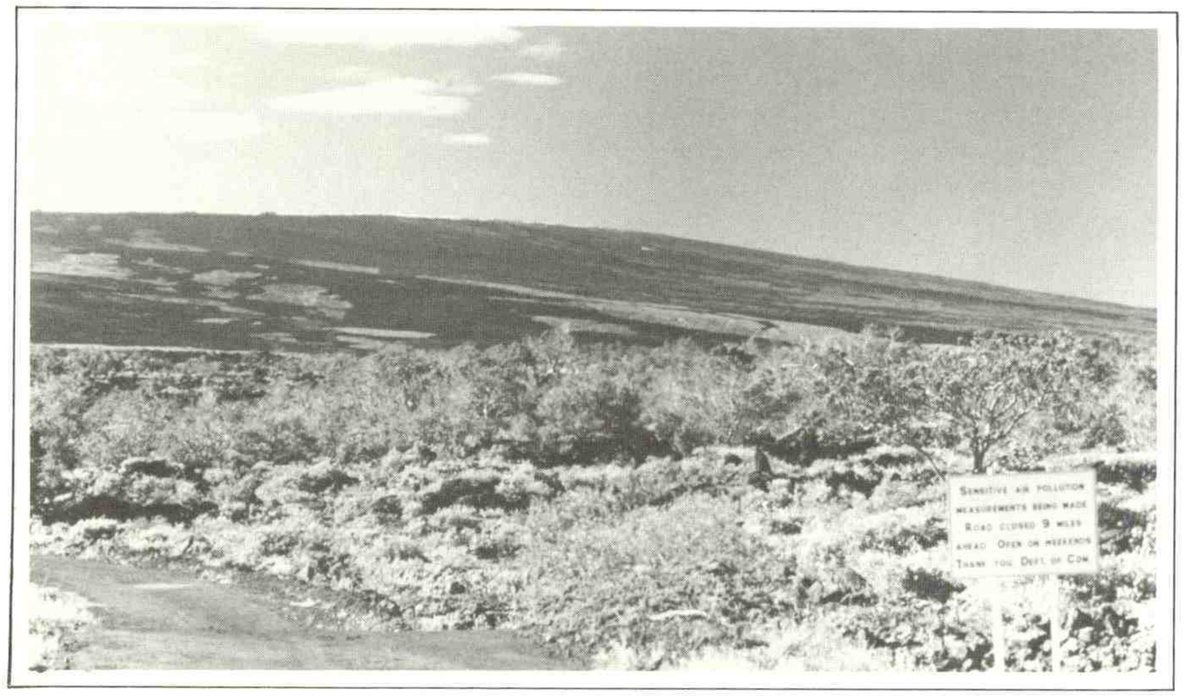
Man has always been an observer of his environment. Fragmentary observations and records were made even by prehistoric peoples as a matter of survival. With the advent of the scientific method the need for systematic observation of natural phenomena became apparent, and astronomical and geophysical observatories for that purpose were eventually established throughout the world.

Mauna Loa Observatory (MLO) started as a small meteorological station in the early 1950's. It is young in comparison with more established institutions such as Pic du Midi or Davos. But however young, MLO is distinctly set apart from all others by its location and purpose. Its location is unique—high on a mountain thousands of kilometers away from any continental landmass. The environment is one of the cleanest in the world, and thus is ideal for MLO's purpose, which is to monitor constituents in the atmosphere that could cause climatic change.

In the short time since its establishment, MLO has become a world-renowned institution, because of its measurements of trace gases and solar radiation, and because it is the only facility in the world that has been making continuous CO_2 measurements over the last two decades. MLO is now intended to become a model baseline station within the Global Monitoring for Climatic Change (GMCC) network, of which it is a part.

To mark the observatory's 20-year existence, this volume describes the milestones of its history, highlights work done in the past, and outlines its present purposes and goals.

Lester Machta
Director, Air Resources Laboratories
Silver Spring, Maryland



More than 18 miles ahead on the road, the observatory is barely visible (center) on the slope of snow-capped Mauna Loa.

As one of the people who originally climbed around Mauna Loa with Bob Simpson and Charles Woffinden, I am pleased to say hello on this twentieth anniversary celebration.

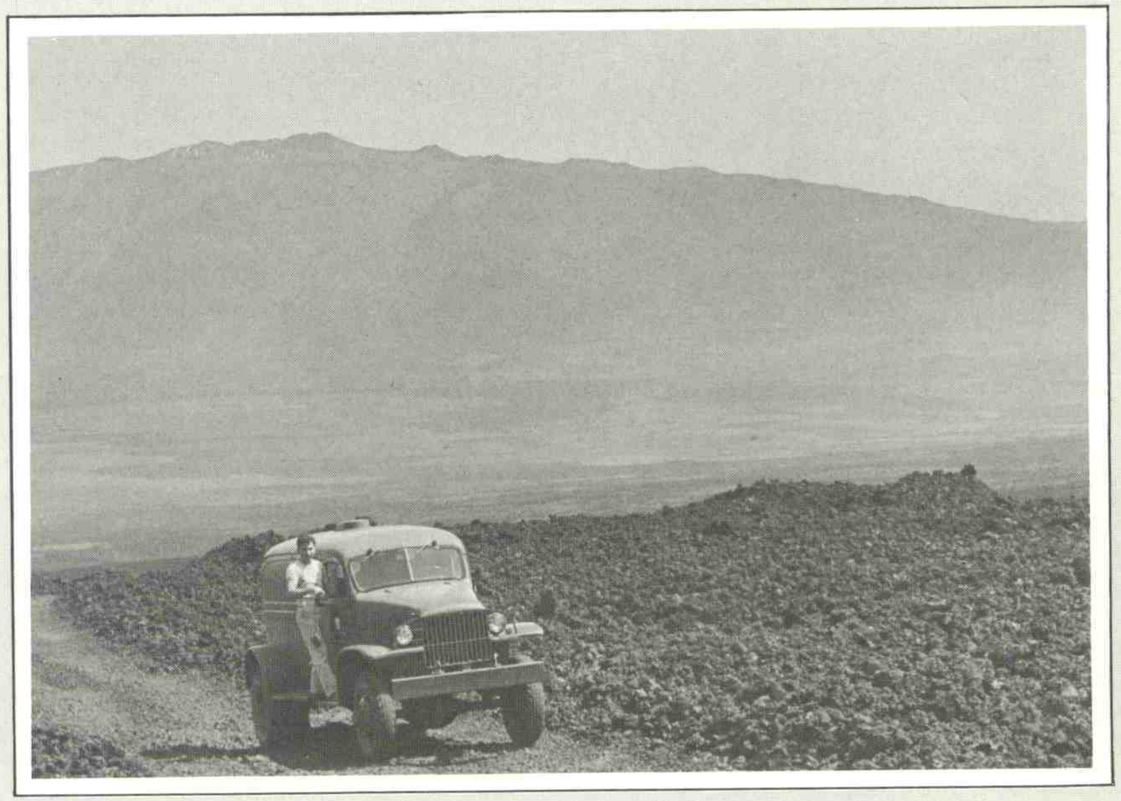
How well I recall the weekly torture of driving to the summit site in the early fifties. As I recall, the distance to the summit from Hilo was about 50 miles. It took 4 hours for the drive: 2 hours to the 11,000-ft level, and then 2 hours for the last 10 miles to the summit. First it was in a reclaimed WWII ambulance-type vehicle, then in a new Dodge power wagon. The impetus for the purchase of the new wagon was undoubtedly the fact that the old vehicle gave out near the summit when I was there with the director of what was then the Hawaii Aeronautics Commission. We walked for some seven hours — until about eight in the evening — before we were "rescued" by prisoners from Kulani prison at about the 6,000-ft level of the road.

The earliest efforts at data collection were simply to profile the temperature, humidity, pressure, and wind along the slope. Because of the arduous trip all the way to the summit, attempts were made to modify standard instruments for 30-day operation. Several Rube Goldberg contraptions were designed by me and my staff in Hilo, but none was effective. We returned to standard operation and made weekly trips. Even then there were problems. The diurnal lifting of the inversion layer and the influx of marine air caused the ink to blot, caused the paper to stretch, and in general, was a thorn in the side. I believe the first project at the slope observatory was conducted by C. C. Kiess and C. Corliss for the National Bureau of Standards and the National Geographic Society during the summer of 1956. Dr. Nakaya and a group from Hokkaido University were there when I left the Islands in January 1957.

My wife and I visited the observatory last June, just 2 weeks to the day short of the anniversary of dedication. I found some aspects of the observatory unchanged, but others quite different. The instrumentation and the vast array of projects are a far cry from our early beginnings. But the awesome beauty of the mountains remains the same.

I want you to know how I look forward to reading articles on GMCC and Mauna Loa's part in it. I swell with pride knowing I was there at the beginning. My congratulations to the observatory on this anniversary. I know there will be many more. After a 20-year marriage, Madam Pele has accepted you and will do you no harm.

James W. Steiner



A reclaimed World War II army vehicle provided a ride to MLO in the early fifties.

Best wishes on your twentieth anniversary. Your success has been due not just to instruments, buildings, and budgets. The most important factor in the observatory's history has been the people who have worked there. Their dedication, skill, and persistence have made this Pacific island mountain top unique.

Mauna Loa's founding marked both a beginning and an end: In 1956 the observatory's initiation was the beginning of organized surveillance of atmospheric chemical behavior. It also represented the end of an era during which mankind had behaved as though it could assault the air-ocean-land environment and leave no trace. Now, 20 years later, the information collected at Mauna Loa, by its staff and by scientists from all over the world, has shown that man is leaving marks on his environment. Carbon dioxide, chlorofluorocarbons, tritium, and carbon monoxide data all reflect human activity, even on this remote and still relatively clean atmosphere.

The observatory records also document the role of natural events. Its solar radiation data are a clear and quantitative indication of the effect of massive volcanic eruptions, such as the 1963 Mount Agung emissions.

Mauna Loa has played a vital role in the still incomplete understanding of the interlocking roles of trace gases and photochemistry. The interrelationships of ozone, nitrous oxide, methane, and carbon monoxide, documented over time, will assist in determining the extent to which human activity affects the atmosphere. The observatory's dominant role in assessing the growth of carbon dioxide needs no elaboration.

Fortunately, the observatory no longer stands alone. The three additional observatories in the NOAA Geophysical Monitoring for Climatic Change program now support and expand your role. Other nations have joined in similar programs in a truly global effort to measure important atmospheric constituents and document their changes over time.

Let me congratulate you on completing your second decade, and thank you for the Mauna Loa contributions — past, present, and future — to an understanding and appreciation of our environment.

Donald H. Pack

The two years that I spent working at the Mauna Loa Observatory (MLO) amount to a mere 10% of its existence. Although my time there was short it represents the most significant part of my professional career.

My involvement with the United Nations Environment Program over the past three years has brought me to many countries in Europe, Africa, and Central and South America. In talking to colleagues I find repeatedly not only that MLO is NOAA's most widely known field station but also that my work there is better known than all my work in Germany, California, Washington, and Colorado. It is sometimes difficult to explain why I am no longer involved with the observatory's operation.

The record shows that about 25% of my publications are related to work that was done at MLO during only 15% of my professional life. The paper on solar radiation trends at Mauna Loa that I had the pleasure to write with Howard Ellis is the one most frequently cited in the scientific literature in spite of the fact that solar radiation is outside my line of expertise. This is proof of the scientific creativity that MLO stimulates.

A relatively high scientific output can be explained partly by the geography and meteorology that surround Mauna Loa; these have often been described and praised and are very conducive to scientific work. Even more important for the success and satisfaction that I enjoyed at the observatory was the help from people. The constant flow of visitors who stopped in Hawaii on their travels between Asia or Australia and America made life very interesting. Visiting scientists such as Earl Barrett, Gerhard Langer, and Gote Ostlund provided lots of ideas, incentive, and cooperation.

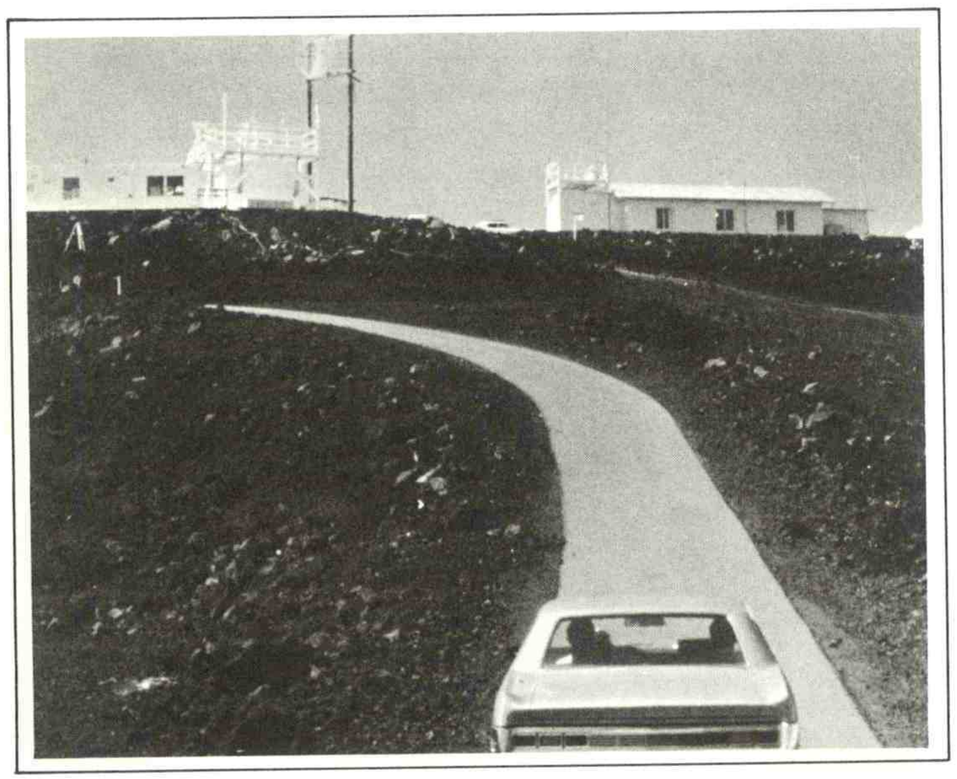
It is a particular pleasure to thank Helmut Weickmann for having created and Lester Machta for having extended the opportunity for me to work at MLO. I am most grateful to John Chin, Howard Ellis, Bernard Mendonca, Judy Pereira, Al Shibata, and Alan Yoshinaga for the loyalty, enthusiasm, and diligence with which they performed their tasks.

"Happy Birthday," MLO, and may your excellence long endure.

Rudolf F. Pueschel

ACKNOWLEDGMENTS

The editor is especially grateful to all those who made pictures available, including Rudy Pueschel, Earl Barrett, Barry Bodhaine, Bernard Mendonca, and Robert Pyle. Thanks are also due to Judy Pereira for retyping many of the papers, to the editor's wife, Sylvia, for compilation and pre-editing of the manuscipt, and to the staff of ERL Publication Services, Boulder, for beyond-the-ordinary help in designing and preparing this report.



Final steep approach to MLO, hard surfaced here, to minimize dust, but little more than one car wide.

INTRODUCTION

During MLO's first twenty years scientists have been attempting to gain only the simplest comprehension of the processes and mechanisms of climatic change. This book records the history and drama of MLO's contribution to that effort.

Our present knowledge is meager indeed. On the one hand, it is rather simple to list the various factors that are probably involved with climate change — some within the climate system itself, and some outside the system, which are not affected by climatic changes they produce. On the other hand, we are desperately lacking in an understanding of how these factors operate — that is, what are the processes and mechanisms of climate change?

Nature stores information on climate change in various ways. There are records in tree rings, in the layering of continental ice sheets, and in sediments of bogs and ocean bottoms. Interpretation of this stored information is a form of "monitoring," one that can evaluate in a short time changes in climate that have occurred over long periods of time. In addition, it may now be possible for man to copy nature's methods by "banking" air, water, soil, or biological samples in suitable containers and environments to provide information on long-lived constituents through laboratory analysis of the samples in future decades and centuries. This, too, is a form of "monitoring." However, many of the factors causing climate change cannot be captured in these ways but must be observed directly if their essence is to be monitored. It is in direct observation that MLO has made an important contribution.

Many people deserve thanks for their foresight and perseverence, which produced a valuable 20-year record of trace materials in the atmosphere. Many thanks are also due to John Miller, who conceived of this publication, and to those who gave valuable time to record their recollections of MLO.

Kirby J. Hanson
Director, Geophysical Monitoring
for Climatic Change
Boulder, Colorado

HISTORY OF MAUNA LOA

Scientific research on the slopes of Mauna Loa predated the present observatory by many years. Colin Ramage's account in this volume of Wilkes's expedition describes some of the early observations made on the mountain. Not only meteorologists but also geologists, botanists, and biologists claim to have found the slopes of Mauna Loa a fascinating place for scientific study, both in the past and in the present. Probably most interesting, however, is the effect of the mountain on the people who work there. The following articles present some of the personal remembrances of the people involved in establishing and maintaining the Mauna Loa Observatory.

Aerial view of MLO, looking to the northeast, in the early '60s before the HAO installation. The observatory was still using power from a generator (shed, lower left). The four CO_2 intakes are visible at the corners of the site.

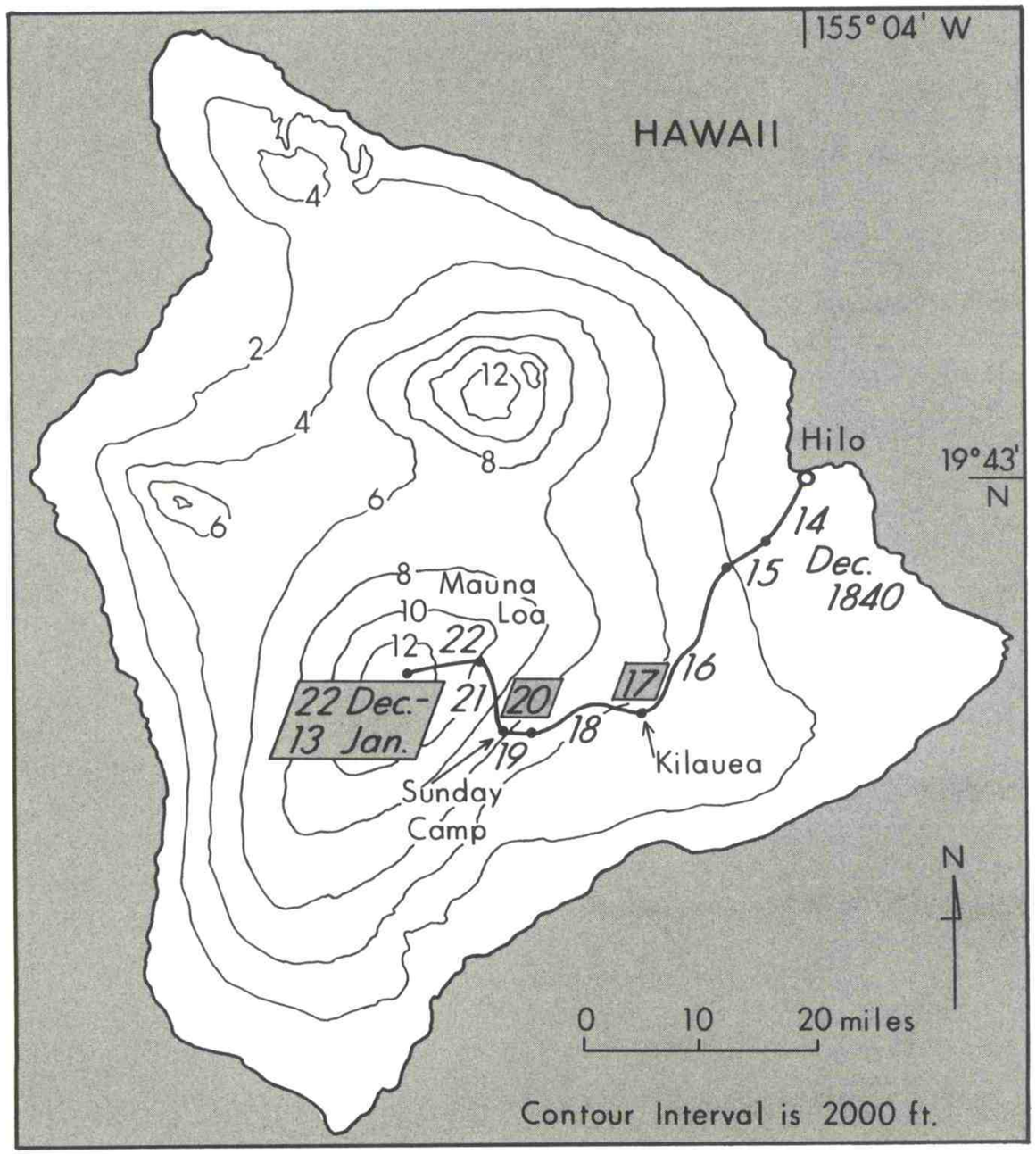


Figure 1. The island of Hawaii showing height contours (feet) and the route, dates, and camp sites of the expedition to Mauna Loa.

THE UNITED STATES EXPLORING EXPEDITION ON MAUNA LOA

C. S. Ramage
Department of Meteorology
University of Hawaii, Honolulu

Late on the afternoon of December 9, 1840, a dilatory sea breeze nudged the flagship of the first United States Exploring Expedition into Hilo harbor on the northeast coast of the island of Hawaii. Lieutenant Charles Wilkes, USN (1845, 1851), commanding from the sloop of war U.S.S. *Vincennes*, was personally responsible for the expedition's hydrographic and meteorological observations. His instructions from the United States Congress to "extend the bounds of science and promote the acquisition of knowledge" had led him to prepare a scientific foray to the top of the great volcano, Mauna Loa, which bulged 13,680 ft (4174 m) above sea level 40 mi (64 km) to the west-southwest (Fig. 1). On the authority of the King of Hawaii, Kamehameha III, 200 porters assembled, and early on December 14 they set out with a party of 16 from the ship. A distinguished member was Dr. Gerrit P. Judd, a medical missionary from Honolulu, who later became Prime Minister of Hawaii.

Lt. Wilkes had with him three mercurial barometers, thermometers, a Daniell silver cup hygrometer (Middleton, 1969), and a Pouillet capsule hygrometer. (The expedition volume on physics, which was to have included details of the instruments, was never published. A search of the original papers failed to unearth the information [Reichelderfer, 1940].) With them he measured "shade," temperature, and dewpoints but did not specify the method of exposure.

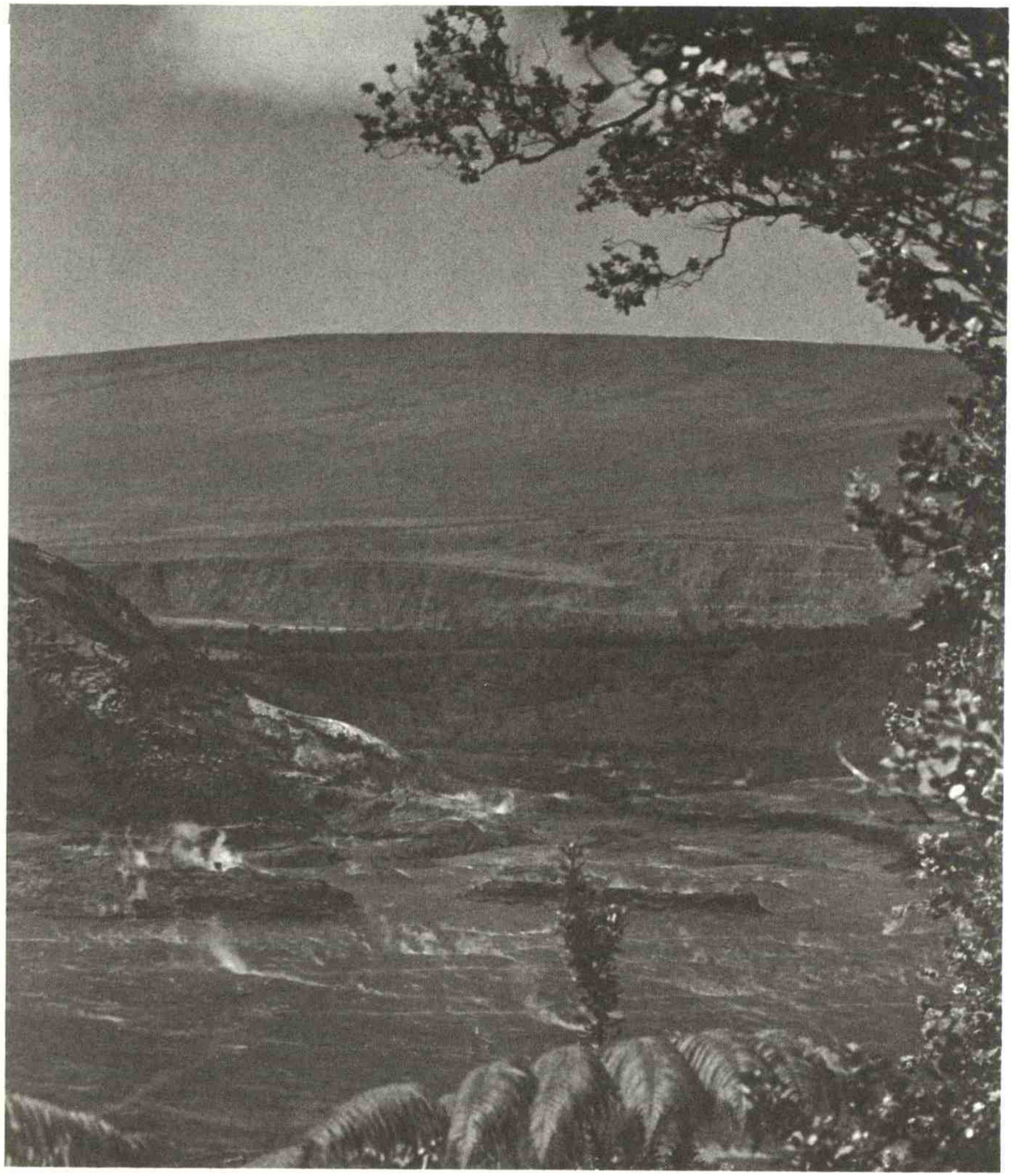


Figure 2. ". . . this immense dome rose before us. . . ." (Photo by D. J. Raymond.)

After the first day of the 9-day trip to the summit, the route lay pathless over rugged lava and was usually extremely difficult. Shoes rapidly wore out and were sometimes replaced by improvised sandals made from ti leaves. In the typically moderate trade wind weather, little rain fell. The small army reached Kilauea volcano, 4,000 ft above sea level, on the 16th, (Wilkes, 1845, 1851) and

> Mauna Loa burst upon us in all its grandeur. The day was extremely fine, the atmosphere pure and clear, except a few flying clouds, and this immense dome rose before us from a plain some twenty miles in breadth [Figure 2]. I had not, until then, formed any adequate idea of its magnitude and height. The whole dome appeared of a bronze colour, and its uninterrupted smooth outline was relieved against the deep blue of a tropical sky. Masses of clouds were floating around it, throwing their shadows distinctly on its sides. . . . I now, for the first time, felt the magnitude of the task I had undertaken.

After spending Dec. 17 inspecting the vigorous eruption taking place in Halemaumau fire pit, the entourage ascended about 1,000 ft on the 18th. Wilkes noted that "this part appeared to have suffered much from drought; for in passing along we came to several narrow and dry water-courses, but met with no water."

At 2:00 p.m. near 5,100 ft, the upper limit of the forest was reached, and "as the clouds began to pass over, and obscure the path, we determined to halt and encamp. . . . We were now for a long time enveloped in mist for we had reached the region of cloud [Fig. 3]." One dewpoint and three temperature observations were made at this camp (Fig. 4); during the night a cold westerly "mountain breeze" lowered the temperature to 43°F (6.1°C).

On the 19th, another 1,000 ft was climbed, during which "we lost all signs of trees, and were surrounded by low scraggy bushes." Soon after being enveloped in clouds between 2:00 and 3:00 p.m. the party made camp at about 6,100 ft, "at which we found ourselves above the region of clouds, and could look down upon them." That night, Wilkes first remarked what was to prove a commonplace phenomenon above this level: ". . . on pulling off my clothes, I noticed the quantity of electrical fluid elicited, which continued for

some time to affect the objects about me, particularly a large guanaco-robe I had to sleep in."

The group remained at "Sunday" Camp until early on the 21st. Wilkes made one dewpoint and seven temperature observations (Fig. 4). "Mountain-sickness" appeared, and "we all began to experience great soreness about the eyes, and a dryness of the skin." At noon on the 20th, "I found it impossible to obtain the dewpoint with one of Pouillet's hygrometers, but after the clouds reached us in the afternoon it was found at 10°." Wilkes now realized that "the want of water would prove the greatest difficulty I should have to encounter" and sent a party ahead to determine if snow was lying on the higher slopes.

> It was a most beautiful day: the atmosphere was mild, and the sun shone brightly on all above us. We enjoyed a clear and well-defined horizon, the clouds all floating below us in huge white masses (Fig. 5), of every variety of form, covering an area of a hundred or more miles; passing around as they entered the different currents, where some acquired a rotary motion that I had never before observed. The steam-cloud above the volcano was conspicuous, not only from its silvery hue, but by its standing firm, like an immense rock, while all around and beneath it were in motion. The vault overhead was of the most cerulean blue, extending to and blending with the greenish tint of the horizon; while beneath the clouds, the foreground and distant view of the island was of a dark green. The whole scene reminded me of the icy fields of the Southern Ocean; indeed the resemblance was so strong, that it seemed only to require the clouds to have angular instead of cumular shapes, to have made the similarity complete. It was perceived, that as masses of clouds met they appeared to rebound, and I seldom saw them intermingle; they would lie together with their forms somewhat compressed, and their outlines almost as well preserved as when separated and alone. After three o'clock, when the sun was retiring, the clouds advanced up the mountain-side, and finally we became immersed in them. This happened on both days at nearly the same hour. . . . After dark the mist cleared off, when we saw the majestic cloud of the volcano hanging as though illuminated in its position.

Figure 3. ". . . we had reached the region of cloud." (Photo by T. Takahashi.)

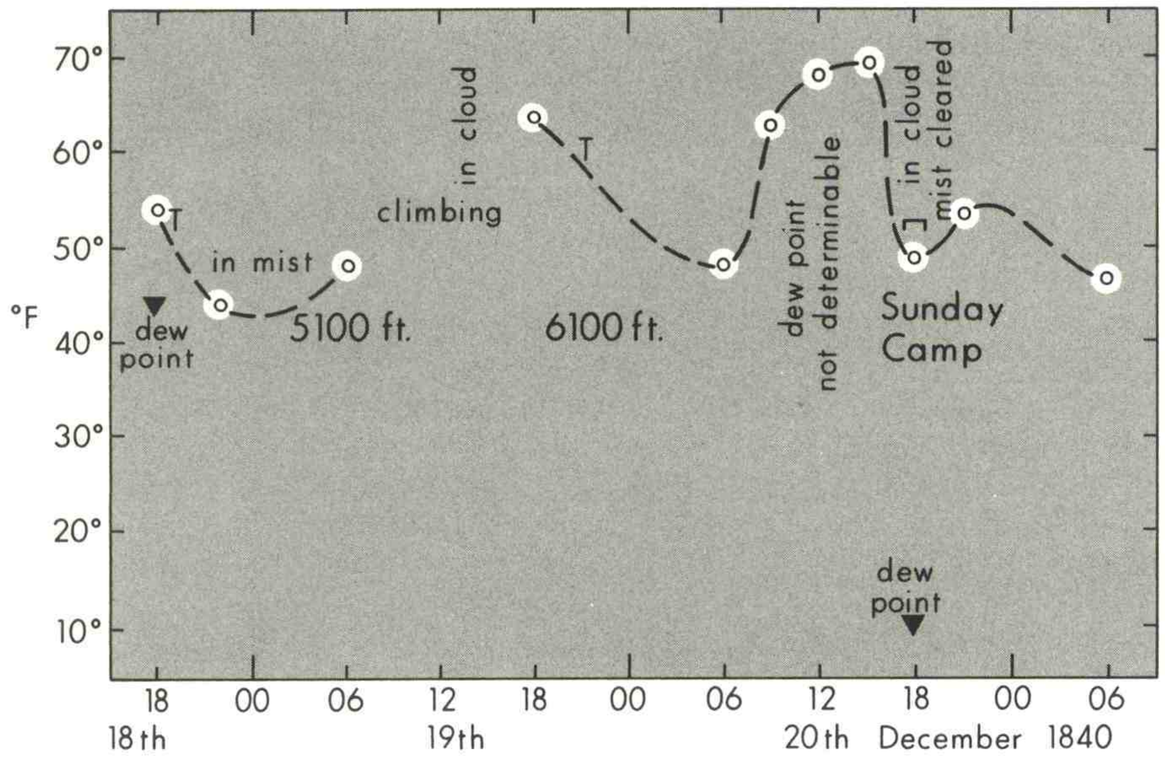


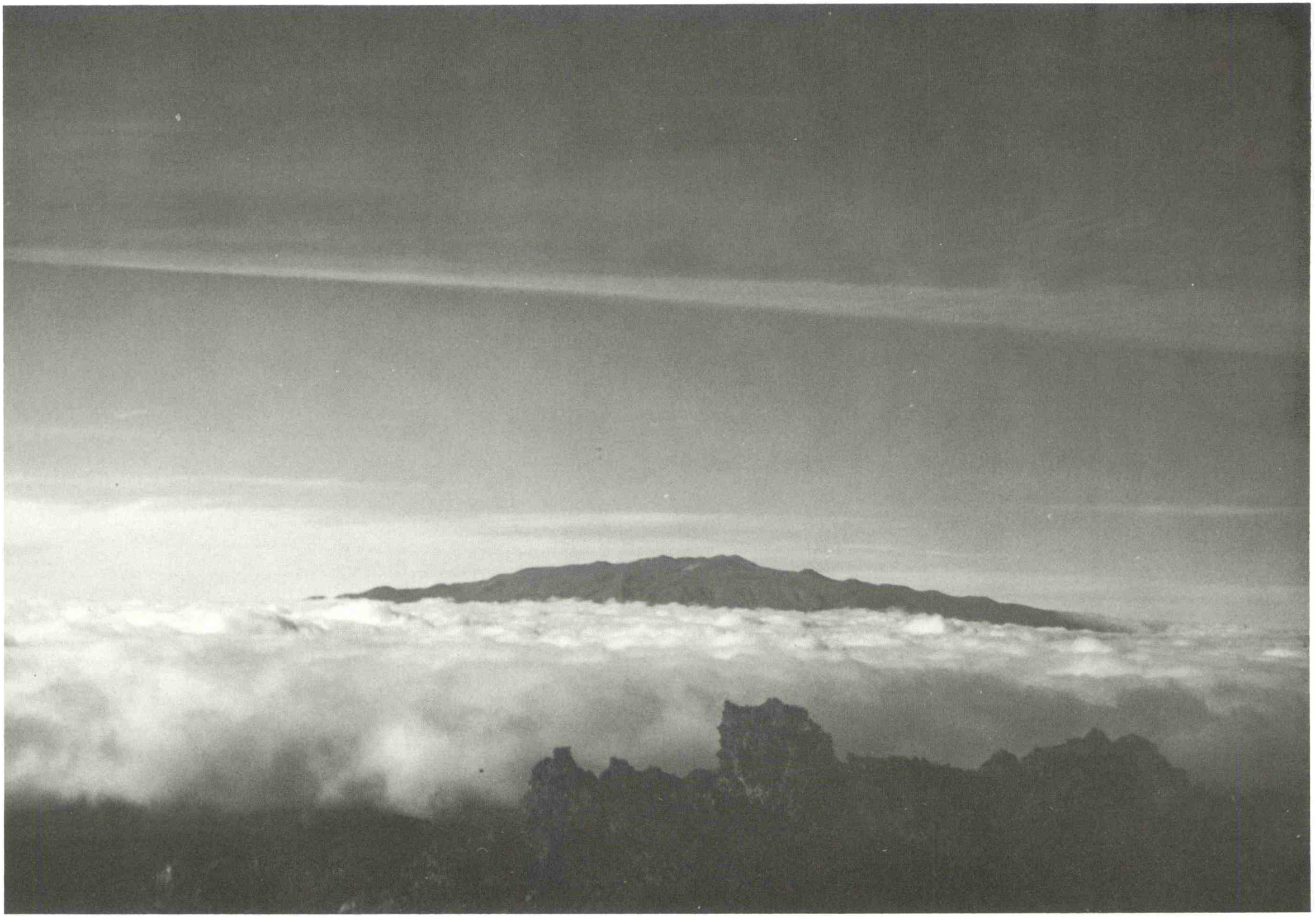
Figure 4. Temperatures, dew points, and weather at 5100- and 6100-ft levels.

From the 14th through the 21st the Hilo observations reflected a steady trade-wind regime. By sheer chance, the 5,100-ft camp lay just below the trade wind inversion and Sunday Camp just above. Wilkes made all the observations necessary to delineate the trade wind inversion—mist, cold, high dew-point, and scattered vegetation at the lower camp; extreme dryness ("around nothing but a dreary waste") and warmth at Sunday Camp, below which only the hot, moist venting from the volcano broke a flat cloud top. More than this, he described the diurnal variation of the inversion on the mountain—rising as the afternoon upslope winds lifted moisture and clouds to Sunday Camp, sinking as the nocturnal downslope winds took over. At the lower camp, the temperature fell between 6:00 p.m. and 9:00 p.m. but at Sunday Camp, as the clouds once more retreated below, it rose. Wilkes was puzzled by his observations but unaccountably advanced no hypothesis to explain them. This brilliant man had come within a whisker of discovering the trade wind inversion more than 15 years before Piazzi-Smyth (1858). (In August 1856, wet/dry bulb thermometers in an instrument shelter strapped to the back of a mule were read every few hundred feet of an ascent and descent of Pico de Teide in the Canary Islands. Piazzi-Smyth identified a sharp temperature inversion at 2,000 ft which coincided with a strong lapse in humidity and the top of a dense layer of clouds (see also Riehl, 1954). Ironically, Wilkes had already observed effects of the trade wind inversion not far from where Piazzi-Smyth made his discovery. "Whilst at Madeira [September 17-24, 1838] . . . we found the height of the vapour plain to be about 4,000 ft above the level of the sea . . . which corresponds to the highest point of cultivation. . . . There is little doubt that the vapour plain must have considerable influence upon the climate of Madeira.")

The group left Sunday Camp early on the 21st. "The ascent now became much steeper . . . for the whole face of the mountain consisted of one mass of lava, that had apparently flowed over in all directions from the summit. The sun shone brightly, and his rays seemed to fall with increased power on the black lava . . . many suffered from nausea and headache, and the desire for water redoubled. . . ."

Camp was made at about 9,700 ft, and although snow had been found farther up, water was still very short.

Figure 5. "We enjoyed a clear and well-defined horizon, the clouds all floating below us in huge white masses. . . ." (Photo by C. Garcia.)



Nearly 300 persons had occupied Sunday Camp, but by 3:00 p.m. on the 22nd the last of the porters could go no farther, and at 13,200 ft Wilkes found himself "with the guide and nine men, with nothing for a covering but the small tent used for the instrument. . . ." A southwest gale was blowing, snow began to fall, and the temperature dropped to 15°F (−9.4°C). A wall of clinkers helped keep the worst of the elements at bay, although at 4:00 a.m. on the 23rd the snow broke through the canvas roof. The storm continued, but even so, by 1:00 p.m. the last climb, through a foot of snow, was finished, and the small party stood on the edge of the summit crater.

As happens during winter in Hawaii, the trade winds had been disrupted by a "Kona storm," a middle tropospheric cyclone or a large-amplitude trough in the polar westerlies in the eastern half of which southerly or southwesterly winds and rising motion prevailed throughout the troposphere. The trade wind inversion disappeared, and deep, precipitating clouds extended far above the top of Mauna Loa. Wilkes subsequently learned that Hilo was on the protected lee side of the island with respect to the storm, but they had experienced at Honolulu, on the nights of the 23rd and 24th, "a very heavy storm from the southwest, simultaneously with the one that annoyed us on the mountain." A greater degree of cold was experienced there than they had had for years.

A wall of clinkers was built around living and instrument tents, and the party managed to survive a recurrence of violent southwest winds on the nights of the 25th and 26th.

Then the summit wind veered to the west, the trade wind regime was reestablished, and from December 28 to January 7, weather remained fine. Temperatures ranged from 15° to 20°F and reached 45° to 55°F in the afternoons. Wilkes was occupied making gravity and magnetic measurements but failed to coax the hygrometers into detecting atmospheric moisture.

> During our stay on the summit, we took much pleasure and interest in watching the various movements of the clouds; this day in particular they attracted our attention; the whole island beneath us was covered with a dense white mass, in the centre of which was the cloud of the volcano rising like an immense dome. All was motionless, until the hour arrived when the sea-breeze set in from the different sides of the island: a motion was then seen in the clouds at the opposite extremities, both of which seemed apparently moving towards the same centre, in undulations, until they became quite compact, and so contracted in space as to enable us to see a well-defined horizon; at the same time there was a wind from the mountain, at right angles, that was affecting the mass, and driving it asunder in the opposite direction. The play of these masses was at times in circular orbits, as they became influenced alternately by the different forces, until the whole was passing to and from the centre in every direction, assuming every variety of form, shape, and motion.
>
> On other days clouds would approach us from the southwest, when we had a strong northeast trade-wind blowing, coming up with their cumulous front, reaching the height of about eight thousand feet, spreading horizontally and then dissipating. At times they would be seen lying over the island in large horizontal sheets, as white as the purest snow, with a sky above of the deepest azure blue that fancy can depict.

Between January 8th and 10th, another storm passed over, repeating the sequence of southwesterly gales with snow, a shift to west with clearing, and then a slow decrease in force.

> These gales reminded me strongly of those we experienced among the ice on the Antarctic cruise. I regretted I had no anemometer, to ascertain the direction, changes and force of the wind. It is remarkable that these severe gales all occurred during the night, beginning in the evening and continuing until the next morning. I attempted to ascertain the velocity of the clouds by the rate of progress of their shadow across the crater, marking the time of the passage; and the greatest velocity in many trials of those from the southwest was about forty-seven miles an hour. It was, however, observed, in these experiments, that the swiftness of the clouds seemed to increase in passing over the apex of the cone or crater. Whether this was the effect of being able to compare their movements more nearly with fixed objects, I am not prepared to say; but I am inclined to believe that in some cases, as they touched the mountain-side,

they were forced upwards and over the summit, with a much greater velocity for the first half of the crater than the last. The shortness of the time that elapsed in passing the diameter of the crater, little more than a mile, precludes the supposition that they had changed their form sufficiently to alter the figure of their shadow. The wind was blowing what would be termed a strong gale, when the experiments were made.

The party quit the summit on the 13th and reached Sunday Camp at 5:00 p.m., where they were "soon enveloped in mist." The great observer remained unaware of his near miss. "The vapour plain, or the height at which the clouds usually remained, was about 5,000 feet above the sea. . . [They] were seldom seen above the height of 8,000 feet except during the stormy weather."

ACKNOWLEDGMENTS

I am grateful to my Hilo colleagues for taking the photographs used to illustrate this article.

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EARLY DAYS OF THE MAUNA LOA OBSERVATORY

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The site survey party on March 9, 1951, included (left to right) Charles M. Woffinden, U.S. Weather Bureau; W. P. Mordy, Head, Meteorology Div., Pineapple Research Co.; Tom Vance, County of Hawaii; Leon Sherman, UCLA; James Kealoha, Chairman, County of Hawaii; Mr. Youman, U.S. Weather Bureau; James Steiner, U.S. Weather Bureau, Hilo office.

Shortly after I arrived in Honolulu in the spring of 1948 and had benefited from an indoctrination tour of the Hawaiian Islands by Luna Leopold of the Pineapple Research Institute, I wrote an article published in the *Honolulu Advertiser* about the opportunities for research and in particular regarding Mauna Loa as an ideal natural laboratory for geophysical and atmospheric research. The potential benefits of establishing a summit weather observatory were stressed.

Much to my surprise several days later I received a call from Tom Vance, then Director of Institutions for the Territory of Hawaii, who offered to join me in seeking means of locating an observatory near the summit. His interest had been kindled because of the possibility of co-locating a ski lodge near the site which could be largely operated by and used as a means of progressively rehabilitating prisoners at the Kulani camp, a somewhat experimental facility on the slopes of Mauna Loa.

In the few weeks that followed, a plan of action was evolved for carrying out this joint venture. After a quick trip to Washington to obtain the endorsements of Francis Reichelderfer, then Chief of the U.S. Weather Bureau, and his Director of Research, Harry Wexler, Tom Vance and I set about the task of implementing the program, with the unfunded blessings of the Weather Bureau and with a preliminary endorsement of the Department of the Interior to enter National Park grounds for this purpose.

The first task was to determine a specific site for the structure and to survey the route of an access road that would minimize the risk to personnel at the site and provide egress in case of volcanic eruption. The aid of Gordon Macdonald, then Director of the Volcano Observatory at Halemaumau was enlisted for this task, and four survey trips were made to the summit before a satisfactory route was determined and a site for the structure pinpointed at the 13,453-ft (4100 m) level just below the upper rim of Mokuaweoweo crater.

I was able to obtain the loan of two giant road-building machines from the Navy at Pearl Harbor, which also supplied water transportation to Hilo and the necessary spare parts. The funds for fuel to operate these machines and to procure the materials for construction of a small building to house the autographic meteorological instruments were reprogrammed from the Weather Bureau Pacific Projects budget. The labor for road construction and

November 16, 1952, expedition to evaluate site locations.

supporting engineering services and for construction of the building was supplied by the Department of Institutions.

Month after month went by with discouragingly slow progress, in part because labor was available only sporadically and in part because of difficulties with the road routing. On a number of occasions one half mile of road bed would be roughed in only to encounter a giant lava tube that could not be bypassed or bridged with the funds available. Nevertheless, a road was completed to the summit, traversible by four-wheel-drive vehicles, and the frame observatory structure, built in sections at Kulani and trucked to the summit, was assembled at the selected site. While cinder cone materials were being spread to improve the road bed, meteorological instruments were installed at the site, and the observatory was equipped with the necessary facilities for overnight lodging and cooking by Weather Bureau personnel.

Little more than a year after construction began, the Mauna Loa summit observatory was officially opened and dedicated by Oren Long, Governor of the Territory of Hawaii, in the presence of more than 25 invited guests: distinguished scientists, administrators, politicians, and educators, from Washington, D.C., and half a dozen states as well as from the Territory. The open-air ceremony took place in a 20-knot wind, with light intermittent snow and a temperature in the upper twenties (°F). A barbequed beef dinner was served around a roaring bonfire following the ceremony. The excursion in four-wheel-drive vehicles to the summit, punctuated by frequent stops for rests, for accommodation to the thin air, and for a few deep breaths from the "walk-around" oxygen bottles borrowed from military supplies, was completed without incident.

Unfortunately, after the road-building equipment was returned to the Navy, the road began to deteriorate rapidly, and getting to the summit site to service equipment and collect records became progressively more arduous. Failure to obtain funds to improve the road so that a standard passenger car could reach the summit prevented Tom Vance from establishing a ski lodge. Finally, in 1953 it was necessary to discontinue trips to the summit observatory, and observations started in 1949 were discontinued.

Meanwhile, the studies of cold lows migrating westward across the Pacific, and questions raised by Clarence Palmer as to their origin, as well as

The Mauna Loa summit observatory structure prior to its opening at the 13,453-ft level. R. H. Simpson (left) and Joachim Kuettner (right).

studies of their influence on the weather of Hawaii and the role they might play in the formation of typhoons as they reached the western Pacific, led me to propose that local measurements of total-path ozone in Hawaii might provide useful inferences concerning the character of circulations in the upper troposphere and lower stratosphere and shed light on the evolution and development of these upper lows. However, no interest could be aroused or opportunities found to initiate such observations until 1955, when by a most remarkable coincidence while vacationing in the canyon country of the western United States I met a Bureau of Standards scientist, Ralph Stair, who was working on solar flare observations at Sacramento Peak Observatory. He complained of the protracted periods in which atmospheric conditions limited or completely curtailed his observations. I asked why he didn't arrange to make observations from a more ideal spot like Mauna Loa. This led to a discussion of our abortive venture at the summit site, my frustration in seeing observations there discontinued, and my new interest in having ozone measurements from a suitable Hawaii site.

The outcome of this encounter was a tentative agreement that we would work in our respective agencies to reestablish a Mauna Loa Observatory through a cooperative program in which the Bureau of Standards would do the engineering, let the contract, and supervise the construction, and the Weather Bureau would fund the construction, drawing upon funds recently appropriated for hurricane research at the newly established National Hurricane Research Project, to which I had just been assigned as the first director. The understanding was that a new site would be sought at which personnel could remain indefinitely and that the program would include not only meteorological observations but also facilities for solar coronagraph studies, a Dobson spectrophotometer for measuring total path ozone, and suitable instrumentation for measuring atmospheric particulates and carbon dioxide.

When I returned to Washington and presented the proposal to Harry Wexler with an indication of my willingness to divert hurricane research money to help reestablish the Mauna Loa Observatory, he was immediately enthusiastic and set about the task of assigning project leaders to coordinate the program. Ralph Stair was similarly successful, and the seeds were effectively sown from which ultimately the fine observatory at the 11,150-ft (3400 m) level was established.

THE CONSTRUCTION OF THE PRESENT OBSERVATORY

Ralph Stair
National Bureau of Standards

The Mauna Loa Observatory had been a dream of many for several decades. Although the U.S. Weather Bureau had from time to time set up temporary observation posts at a number of places along the trail leading to the summit of the mountain, the origin of the observatory came about in a rather peculiar manner differing greatly from any plans made or contemplated by those most interested in having a permanent weather station on the north slope of Mauna Loa.

The National Bureau of Standards (NBS) had been interested in the intensity of the ultraviolet solar radiation since about 1928. This interest grew with time and expanded in scope to include not only the total solar ultraviolet but also the spectral intensity through a wide region of the spectrum; the total amount and vertical distribution of ozone; and some information on water vapor, dust, and other pollutants in the atmosphere. In connection with this work, much effort was expended on the development of new instrumentation and standards of radiant energy. Much of this work was financed through non-Bureau sources, including the Army, Navy, Air Force, National Academy of Sciences, and Air Pollution Foundation, with assistance from others, such as the High Altitude Observatory, Upper Air Research Observatory, U.S. Weather Bureau, Lowell Observatory, and California Institute of Technology.

As the instrumentation and standards were improved through the years, the lack of atmospheric clearness remained the chief obstacle to obtaining high accuracy in the measurements of spectral solar energy. Measurements were made in various localities: Washington, D.C.; Mount Evans, Colorado; Climax, Colorado; San Juan, Puerto Rico; Flagstaff, Arizona; Pasadena, California; White Sands, New Mexico; and Sunspot, New Mexico.

The observatory building in June 1956.

It was at Sunspot, in June 1955, that we had the good fortune to receive a prominent visitor from the Florida Hurricane Center — none other than Dr. Robert H. Simpson himself. As there had been a dust storm of considerable magnitude over the adjacent New Mexico desert, the sky was very bright with the sun coming through weakly. Dr. Simpson was very sympathetic to our need for a clear sky with direct sunlight coming through at high intensity and for seeing Venus in the daytime and unobscured by clouds. (Venus was clearly visible in the daytime at Climax, Colorado, except when there were clouds.) We wanted a better location but knew not where to turn, since we had considered all possible locations within the continental United States and found no place superior to Sunspot.

Dr. Simpson had a suggestion that we agreed to consider. It was to set up our laboratory on one of the mountains in the Hawaiian Islands. Upon our return to Washington, a number of conferences at the NBS and at the Washington office of the U.S. Weather Bureau resulted in an agreement for NBS to use some $25,000, which would be transferred from the U.S. Weather Bureau to the Radiometry Laboratory of NBS, in the establishment of a laboratory for the joint use of the Weather Bureau and NBS. The amount of money available was insufficient for the construction of a permanent building through the normal construction channels, but for use in establishing a durable "shelter" for practical use in all kinds of weather expected on one of the Hawaiian mountains it was considered adequate if strict economies were followed throughout.

Following preliminary discussions and evaluations in Washington, it was decided that the best location for a solar radiation laboratory in the Hawaiian Islands would be on the north slope of Mauna Loa, where as a result of the shielding effect of Mauna Kea the atmosphere would be least turbulent and most free of clouds. Furthermore, a mountain cinder road was already in existence in this area. Accordingly, an arrangement was made for a conference (in December 1955) with the Honorable Samuel Wilder King, then Governor of Hawaii, for the purpose of transferring title to a suitable area on the north slope of Mauna Loa (within the Mauna Loa forest and game reserve) from the Territory of Hawaii to the Department of Commerce of the federal government. Mr. King agreed to the transfer, and it was accomplished through the proper Hawaiian channels, with survey by C. L. and D. J. Murray for an area of 4.05 acres (10 hectares) in the shape of a square 420 by 420 ft (tax map 4-4-16; C.S.F. No. 12333). The exact area was chosen previous to the survey by Ralph Stair, Roy L. Fox, and James W. Steiner, of NBS; Pacific Area, U.S. Weather Bureau; and Hilo office, U.S. Weather Bureau, respectively.

In picking the site for the observatory a number of considerations were taken into account. The site chosen was near the mountain cinder road at the upper terminus of its better condition, that is, at the highest elevation possible to be reached with two-wheel-drive vehicles. The elevation, approximately 3400 m, was considered near the limit for extended living and working for most individuals. The area was on a recent volcanic lava flow which, because of its elevation above adjacent areas to the right and left, offered promise of some protection from future flows on this side of the mountain.

The 4.05-acre area was marked at the northeast corner by a spike set in concrete which was labeled "Stair, 1955." The other three corners and the midpoints of the north and south sides were defined by ¾-in iron

Dedication ceremonies on June 28, 1956, marked the official beginning of the observatory.

pipes driven into the lava.

The transfer of this parcel of Mauna Loa to the Department of Commerce (of which NBS and the U.S. Weather Bureau were parts) having been arranged, numerous interviews were conducted with other government and business people within the Hilo area concerning the best procedures to follow in getting the most desirable building on the site at the least cost. A first thought was to construct the building of lava block, of which there was an abundance within the area. However, investigation showed this to be more expensive than the use of cast cinder block manufactured in Hilo. (The possibility of a lava block building was left open, however, for a time when more money might be available, through the incorporation of a concrete ledge on the building foundation.) Other interviews regarding available material resulted in the location of local overstocks of certain items and sizes (for example, aluminum sash and roofing sheets). The final specifications for the building included only materials available locally so as to permit construction without delay or extra cost. All possible contractors within the area were interviewed and made acquainted with the local supplies in stock.

The Hawaiian Kulani prison authorities were extremely helpful in the construction of the new observatory. They not only continued to keep the roadway in repair but volunteered to "level off" the 4-acre area ahead of the contractor and to deliver to him the water required during construction. The latter was a most important item as it relieved the contractor of all expenses that might be involved in obtaining and operating water tanks.

All developments in the specifications for the new building were handled by NBS, with consultations and interviews with U.S. Weather Bureau personnel. This work was performed primarily on regular Bureau schedule with no cost to the construction fund. As a matter of fact, to keep all costs to a minimum no drawings or blueprints were prepared, all work being performed from detailed specifications.

With the building specifications in order, the requests for bids on construction were handled through the offices of NBS in the usual official manner.

During construction, in order to keep costs down, all inspections and consultations with the contractor were handled by Hilo U.S. Weather Bureau personnel through occasional visits to the site followed by simple reports to NBS.

By June 1956 the building was essentially complete as described and illustrated in the September 1956 issue of *Weather Bureau Topics,* the October 1956 issue of *National Bureau of Standards Technical News Bulletin,* and the November 1956 issue of *Discovery.*

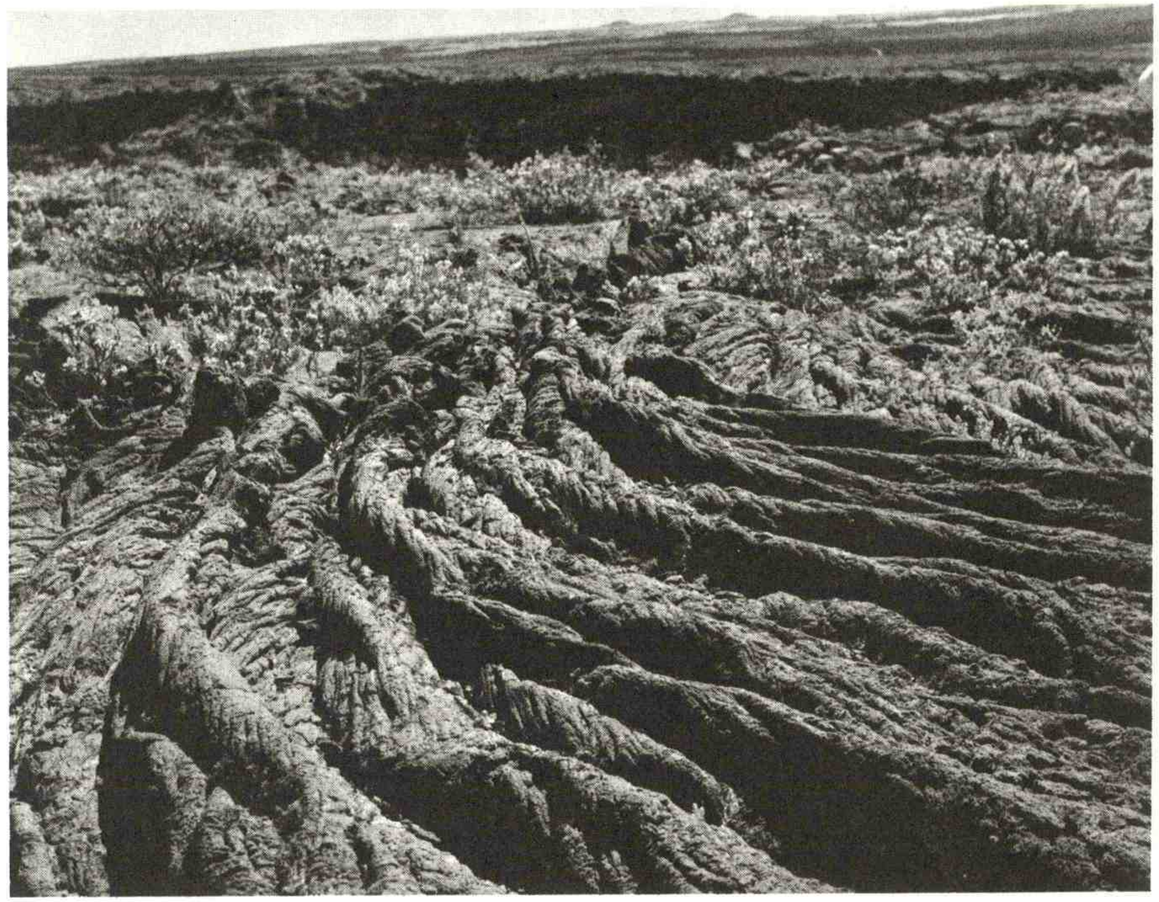
The construction of the observatory proceeded smoothly throughout. There were helping hands in all quarters with no dissidents anywhere. Donations came from several organizations. One, in the form of a radio transceiver, was supplied by the Radio Section of NBS. A small library was furnished by the Smithsonian Institution and the Department of Agriculture. Only minor problems developed, and those were primarily the result of "corner cutting" to get the job done at low cost. For example, the placing of the diesel electric generator near the building under the water tank required moving it later to a more distant location because of vibrations and noise that interfered with experiments inside or near the building. Although the construction of the observatory building

was carefully specified to contain steel rods to hold the structure securely attached to the foundation in case of a hurricane, no such forethought was included in the case of the "outhouse"; it went the ways of the winds upon the arrival of the first 100-mph hurricane.

In getting the "most possible for the least cost," one can run into real trouble. This happened in the case of the NBS project leader, who found it necessary to become plumber and janitor for a day to get the water running and the floors clean for the first scientific observing team to use the observatory (Dr. C. C. Kiess and associates of NBS for the National Geographic Society).

By dedication time, the building was completely furnished (down to bed sheets, kitchen utensils, dishes, and flatware) for comfortable living for six observers. Government inspection (by Ralph Stair) confirmed fulfillment of the contractor's obligation, although the observatory faced "magnetic south" rather than geographic south, which shows that one can never be too careful in writing a specification — the contractor used a compass. The building was duly accepted by NBS, the contractor paid, and the Mauna Loa Observatory dedicated on June 28, 1956, the introductory remarks being made by the Honorable Samuel Wilder King, Governor of Hawaii.

Lava formation at the 7000-ft level on Mauna Loa in December 1966.



THE FIRST TWENTY YEARS; AN UNSCIENTIFIC REMEMBRANCE

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I am sure that enough will be said in this 20-year commemorative about the scientific work done at Mauna Loa Observatory (MLO) and the uniqueness and suitability of its setting for atmospheric monitoring. Certainly, the observatory has served as a fountainhead for scientific studies and subsequent scientific publications on the atmospheric sciences. Without doubt it should also continue to do so for the next 20 years or more.

So instead of dwelling on the science at MLO I would like to recall briefly, for old times' sake, some of the people and events associated with the observatory that will never make the scientific publications and in the dimness of time will be forgotten. What is related is not complete, all-comprehensive, or plucked from an accurate chronology, but comes from memory with all its failings.

My first contact with MLO was in August of 1958 as a part-time government employee. To support myself while attending the University of Hawaii, I was working under Saul Price in the U.S. Weather Bureau Pacific Region Office in Honolulu. Saul Price, together with Jack Pales (the first director of MLO), was responsible for the operation of the observatory. At that time the observatory had a Honolulu branch, which consisted of Saul Price, Richard Sasaki, and myself. The observatory was officially 1 year old by then. Data flowed from Mauna Loa to the Honolulu branch for processing analysis and eventual publication in scientific journals. The International Geophysical Year (IGY) was winding down, but because of the high quality of measurements made at MLO during the IGY the observatory operation was continued in the succeeding years. Those were prosperous times. The staff expanded to a maximum of about 13 people (counting the Honolulu branch), and many came and went. A few names remain in mind: Jack Pales, director; Cliff Kutaka; Harry Arashiro; Colby "Doc" Foss; Bill Cobb; Howard Ellis; and John Chin. These people broke ground for those who followed. Their work was long, arduous, and often frustrating. Conveniences were minimal, and the daily travel over rough roads from Hilo to the observatory and back wore on the will of all.

People like "Doc" Foss, the first electrical technician and instrument man at MLO, made life interesting in the first trying years. His belief in 1960 in solar power, his pattern of a solar hot water heater, and his formation of a company to produce it in Hilo attested to his inventiveness and vision of things to come. He was a master of improvisation and modification of the scientific instrumentation at MLO and saved the day many a time by being able to adapt state-of-the-art instrumentation to the needs of the monitoring programs at MLO. Some of his other vocations were orchestra leader and druggist and drugstore owner, whence the name "Doc."

But even before the "official" opening of MLO in 1957–1958 during the IGY, preliminary meteorological measurements at test sites had been done at Mauna Loa. In 1956, Dr. Ralph Stair (solar physicist from the National Bureau of Standards) with the help of other people got the funding to build the first permanent building at the present site of the observatory for his solar and planetary studies (Mars).

As early as 1951 the first meteorological measurements on a routine basis were started at the summit of Mauna Loa. A wooden building was erected and maintained by the U.S. Weather Bureau rawinsonde crew at the Hilo airport under the official in charge, Ray Busniewski. Weekly trips were made by Howard Tatum, Roy Sodetani, George Nii, and others over a nearly impossible jeep trail to collect meteorological data at the summit. The beginnings of benchmark monitoring on Mauna Loa had its humble origin with this sturdy crew. They showed that it could be done routinely.

In 1959 the observatory proposed and obtained a 4-year contract supported by the Department of Defense to do spectral solar radiation measurements, with an emphasis on measurements of the upper tropospheric aerosols and their relation to the Bowen hypothesis of worldwide precipitation anomalies and meteor showers. The CO_2 and atmospheric ozone programs were also coming into their own, and so were benchmark measurements of atmospheric electricity parameters during this interval. Then, at the end of 1963, an austerity wave washed through all government agencies, the ripples extending to the MLO programs. There was serious talk and maneuvering to shut down the observatory permanently. Funds suddenly were not available, interest in long-term monitoring had lost its champions, and the expense and effort of running an observatory thousands of miles distant on a volcano in the middle of the Pacific was hard to justify. The staff dropped from a high of about 13 to 3. Personnel transferred to other jobs, and programs terminated one by one. In February 1964, Howard Ellis, Mike Keyes, and I were the only ones who remained on the official staff, mainly because we had pleaded desperately (with the help of others, all of whom I do not know) for the continuation of the observatory. I do know that Jack Pales; Saul Price; Nels Johnson, director of the Pacific Supervisory Office; and Dr. C. D. Keeling were involved. Later, Dr. Helmut Weickmann, director of the Atmospheric Physics and Chemistry Laboratory in ERL, took us under his wing after the reorganization of the U.S. Weather Bureau into the Environmental Science Services Administration. With his help the observatory survived the lean years.

As a result of the cutback during this austere time the Honolulu branch was closed, the staff was reduced to 3, the Hilo office was closed, and a starvation budget was given for salaries, gasoline to get to the mountain, and chart paper for the recorders, with a few dollars extra for the light bill. Under Howard Ellis, the director at the time, the basic programs were kept going, and we waited. For 2 years, nothing much changed, and the observatory hung in limbo.

By 1966, things began to pick up and continued for several years. Funding once again became available; a new director, Dr. Lother Ruhnke, obtained commercial power and a telephone to the observatory. Previously, diesel generators had provided power and a multitude of headaches to the staff who had to maintain them. An office in Hilo on the University of Hawaii campus was established with secretarial help and several new staff members. Soon the first part-time university student help were on the payroll, sharing in the program—an innovation that has lasted to the present. Things started to hum again!

The scientific community had expanded, and two other agencies joined the observatory on the mountain. The High Altitude Observatory (HAO), a section of NCAR in Boulder, had set up a solar coronascope observatory adjacent to the observatory in 1965. The Atomic Energy Commission (AEC) had set up a classified program on the mountain in 1963 for 2 years, which afterwards was continued intermittently for several years. The AEC program was classified, that is, it was classified until the newspaper, to everyone's dismay, flashed the headlines "Mauna Loa Station to Monitor 'N' Tests" on Friday the thirteenth, some months after the AEC had arrived. The HAO coronascope has stayed to the present.

Budgeting once again became hard, and there was a slight recession. Help from other agencies lessened the slack, and the observatory endured. The next big push came in 1971. Under the directorship of Rudolf Pueschel several significant papers were published, the Mauna Loa data showing the worthiness

The road to MLO in June 1966.

of benchmark monitoring for climatic change. MLO was incorporated as the principal geophysical monitoring station of a new section in the Air Resources Laboratories (ARL) of the Environmental Research Laboratories in NOAA. This section was designated Geophysical Monitoring for Climatic Change (GMCC) and started under the directorship of Donald H. Pack and Lester Machta, Director of ARL. For the first time, MLO was part of an agency set up to do the kind of atmospheric research that the observatory had been involved in for the past 13 years. It has remained so to the present. Now, three other observatories have been added, and a central office in Boulder, Colorado, coordinates the network.

However, in the evolution of such an observatory there are many adventures, milestones, and passing interests that are as integral a part of the history of the observatory as the scientific work that it was set up for. To attempt to comment on them all is of course impossible, but I'd like to mention a few:

ROAD AND TRAVEL

A major nemesis to the operation of the observatory over the years has been the roads used for access to the observatory. The standing joke for those who have worked there is that the access road is the only road on the island that no one will lay claim to for fear of being obligated for its maintenance. The first road was laid out (by some sweet-talking and creative accounting and financing of several government agencies) with prison labor from the Kulani honor camp. As it is jokingly retold, an inmate was set on a bulldozer and told to cut a road to the summit of Mauna Loa. When funds ran out, the observatory was built at the end of the road.

The first route used for access began at the Kulani honor camp turnoff on the belt highway. This preexisting road was called the Stainback Highway and very soon was corrupted to "strainback" highway by those who made the weekly trips to the observatory. It terminated at the Kulani honor camp (elevation 7,000 ft). The daily search and shakedowns of people and vehicles by the guards at the camp were an unbelievable experience for first-time travelers to the observatory. Later the guards got to know the staff and waved them through the camp unless something was amiss. Above the camp the road ran along the northeast ridge and required four-wheel-drive vehicles. A good trip with no breakdowns required 2½ hours for the 40 miles. It took a hard head, resilient behind, and cast-iron stomach to make the journey and keep one's breakfast. Maintenance of the road was virtually nonexistent, and the gravel surface deteriorated rapidly with the heavy tropical rains. It was not unusual to come across wild boar rooting among wild orchids on the shoulder of the road in the early morning and later to see wild goats eating ohelo berries along the road above the camp.

In 1963, with the establishment of the AEC project at Mauna Loa, funds became available for upgrading the road. Howard Ellis, who was director at the time, diverted funds and equipment and convinced the road crew to cut two sections of the new road north from the 8,300-ft elevation to connect with an old isolated hunters' road and the saddle road. The event was hailed as the opening of the highest road in the Pacific by the press, who also noted that only the state of Colorado had a higher road. To the observatory staff it meant welcome relief that driving on the rugged road through the Kulani honor camp was over and that the new saddle route was now paved for half the trip to the observatory. Everyone was happy.

By 1965 the road to the observatory had again fallen into disrepair and taken a heavy toll on vehicles. With the AEC, HAO, NOAA, and the county government all contributing, another major upgrading was begun, and this time most of it was oiled to a smooth hard surface. Again the road repair was done by prison inmates.

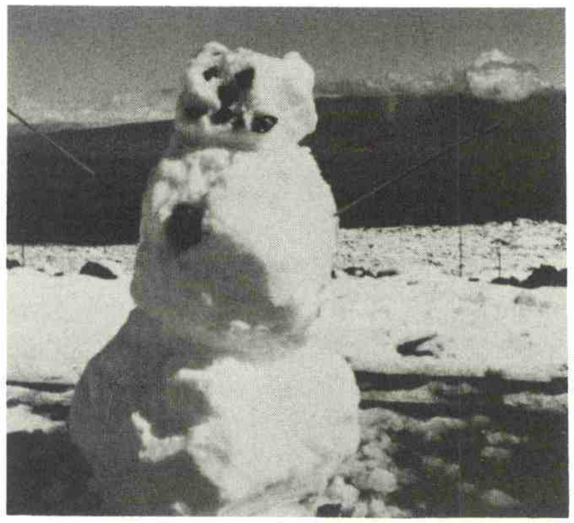
During this period the HAO staff championed the upkeep of the road. Dick Hansen and Charles Garcia were instrumental in organizing the work done on the road. After each major project the staff members of HAO and MLO would prepare a Hawaiian luau for the inmates, and feasting was the order of the day.

During the periods when the road fell into disrepair, the vehicles used for travel to the observatory suffered drastically. Punctured brake lines, broken springs, busted shocks, sheared-off wheels, and ruptured oil pans were not unusual but routine monthly maintenance. It didn't take long before the word was out to the local garages in Hilo to avoid the MLO GSA-vehicle contract like the plague. Car rental agencies in Hilo started to attach clauses to their standard contracts that forbade trips to MLO.

When the observatory was at its wit's end in finding suitable repair garages, an agreement was made with a garage in upper Kaumana, the last one before the saddle road. The proprietor, Noburo Yamanouchi, who quietly ran the garage in the local community, accepted the maintenance of our vehicles as a personal challenge. He was a master mechanic and through his personal efforts kept our vehicles on the road through the most adverse conditions from 1964 to 1972, when he retired. His dedication would often result in midnight repairs to get a car ready for the morning trip. He was so familiar with our vehicles that he could identify the arrival of the observatory cars approaching his garage by their characteristic rattles before he saw them. He delighted in being able to tell the current customers to their surprise that

the observatory boys were approaching the garage before they were seen. Mr. Yamanouchi would certainly have qualified as an honorary member of the MLO staff.

The road and daily travel to the observatory are still part of the rugged, rustic appeal of the observatory's setting.

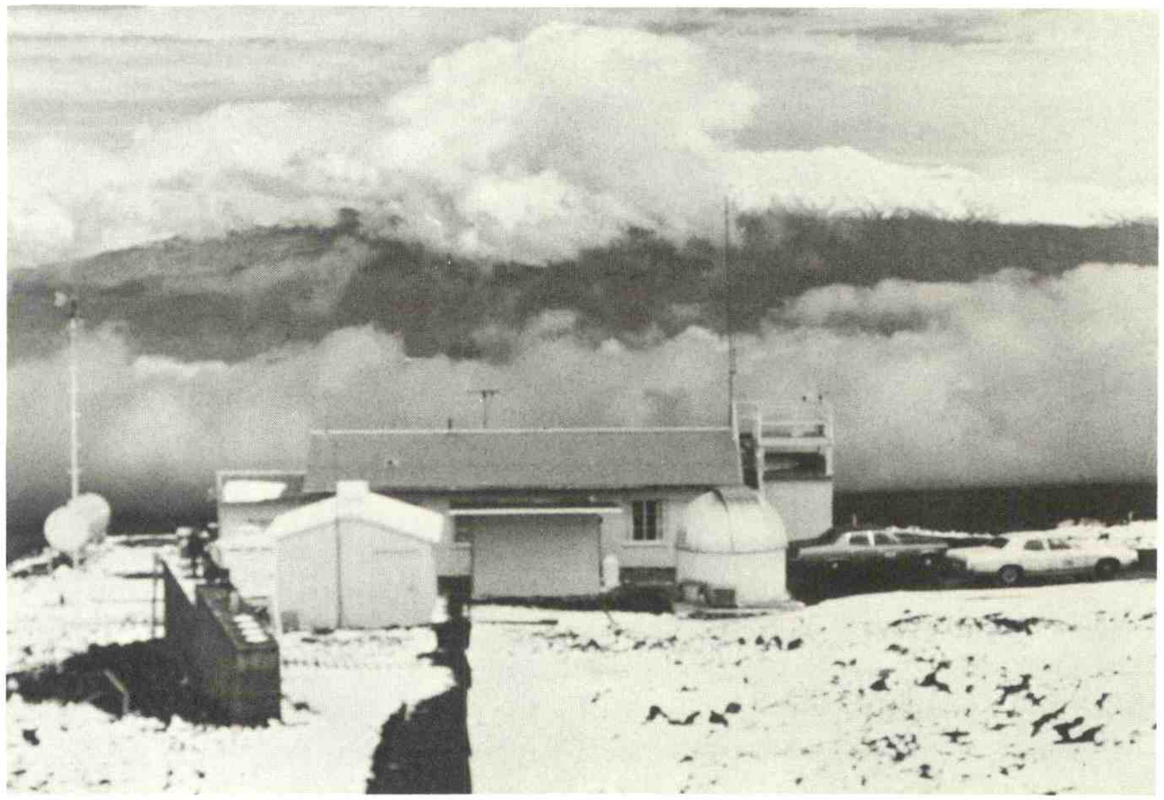


Snow time at MLO.

VISITORS

To anyone who has spent time at remote observatories, visitors are a way of life. Over the years, MLO has had more than its share. Visitors have been a mixed blessing: the visiting scientists generally are a welcome and refreshing contact with the outside world, a source of fresh ideas, and an update of events occurring in one's field of interest. The casual visitor, on the other hand, could make the observatory staff practice their virtues to the limit. The sign-in guest book maintained at the observatory contains a virtual who's who of visitors over the last 20 years. The visitors can arbitrarily be classified into several categories: (1) the visiting scientist; (2) the visiting VIP; (3) the outdoorsperson (hiker); and (4) the casual inquisitive walk-on, the prearranged tours and the snow people.

The snow people were a phenomenon that no one anticipated at the observatory. With the opening of the saddle route access road to the observatory, a typical family passenger car with some strain was able to ascend the mountain to the 3.4-km altitude of the observatory for the first time in the island's history. The significance of the elevation was that in the winter the snow line of the mountain often descended to about 2.8-km elevation. The stage was set to permit the people of the island to drive up to freshly fallen snow after a winter cold front passage and experience for the

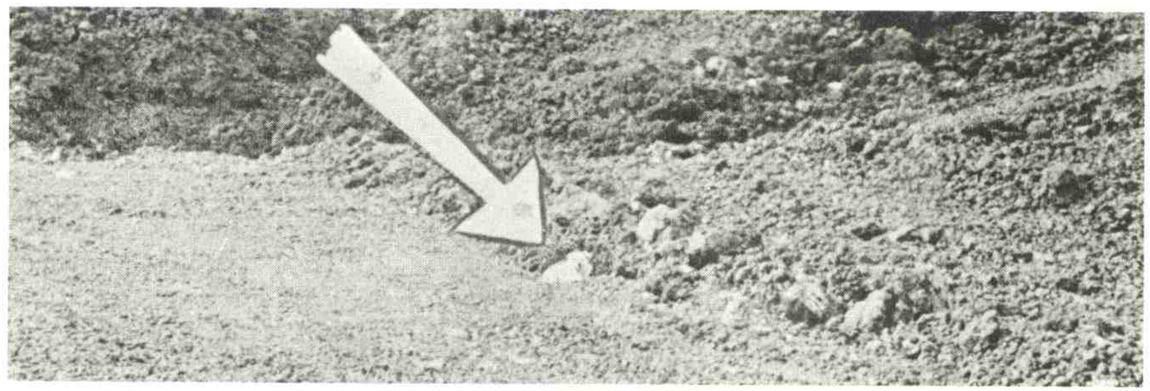


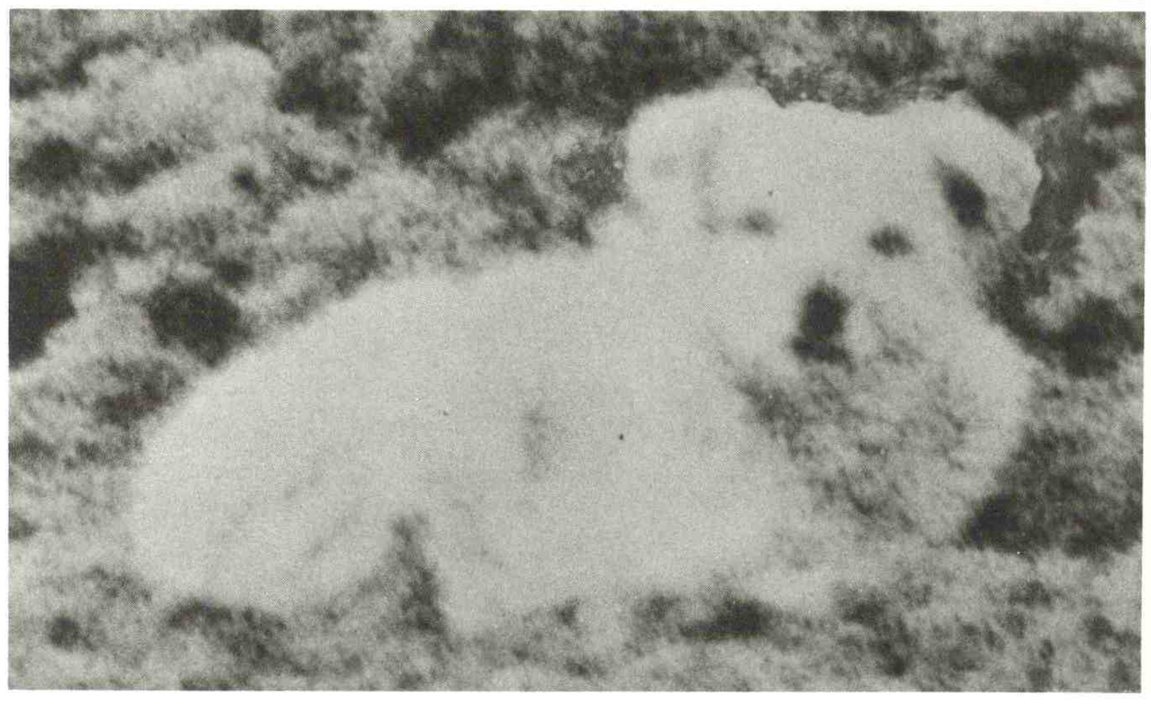
first time in their lives snowman building, snowball throwing, sledding, and all sorts of winter sports. Once the word got out that this could be done, the result was mayhem on the slopes of the mountain after each snowfall in the winter. A good weekend would bring more than 500 cars a day packed with people, hot Thermoses, picnic lunches, makeshift sleds, and every possible adaptation of Hawaiian wear into winter fashions. The upper reaches of the mountain turned into an instant winter carnival land. The effect on the observatory staff driving to work was bewilderment. The net effect was that the local community was accepting the establishment of a scientific observatory on Mauna Loa. To this day, to a lesser degree, the arrival of the snow people every winter is a Mauna Loa phenomenon.

THE WHITE DOG

No reminiscence of MLO would be complete without mentioning the white dog of Mauna Loa. Much has been told about the mysterious phantom dog that would appear on the mountain to forewarn of a volcanic eruption. Hawaiian legend relates a tale of Pele, who is the fiery goddess of the volcanoes on Mauna Loa, and her companion dog, whom she would send as a messenger to alert the people whenever an eruption was imminent.

The white dog was first noticed by the observatory staff during the latter part of 1959. At that time the staff were living on site for up to a week at a time on rotating shifts. Because of this housekeeping, a rubbish dump was soon developed to the west of the observatory. The contention of the staff was that a stray white dog had discovered the dump and foraged it for food. Attempts by the staff to befriend it and later to capture it, no matter how persistent or devious, failed. The dog for some reason would have nothing to





do with the observatory staff. Soon the dog disappeared and was presumed to have found its way back to the populated regions of the island. In December 1959, Kilauea Iki erupted.

To the amazement of the staff the dog reappeared at the observatory several months later and again was spotted intermittently for a month or so and then disappeared. This pattern of appearances and disappearances continued until 1966. Since then, to my knowledge, no one has seen the dog. Its appearances or disappearances were never regular, and at times it was seen at the summit as well as farther down the access road to the observatory. It would never have anything to do with anyone and whenever pursued would always easily outdistance its pursuers over the rough lava and run to the top of the mountain. The staff could never determine where it obtained food when it was not at the dump (months at a time) in the desolate environment of the mountain nor why, if it did descend the mountain when it was not seen, it did return to roam the mountain top for months at a time. This was especially puzzling in view of the fact that the staff sometimes discovered lost hunters' dogs wandering close to the observatory, always in the most pitiful condition. In every case, starvation and exposure to the elements had just about done in these hunters' dogs.

Concerning the belief that the white dog was a messenger of pending eruptions, it is true that it was sighted sometimes before an eruption, but it was also sighted many other times when no eruption occurred. The dog did create a problem for the staff in that when a staff member would describe the appearances of the dog to visiting scientists or to the public the response would invariably be looks of worry and discomfort or of concern and a fear that this staff member had finally gone stark crazy. The story of the dog was definitely out of place among scientific endeavors at the observatory, and soon the staff members were hesitant to talk about it to anyone they did not know. To this day the mystery of the white dog is just that—a mystery.

In any remembrance such as this there is an irresistible urge to list names and events to recall the life and scientific history at the observatory over the years. One consequence of such listings of course is to omit inadvertently someone deserving or some significant event from the litany. Therefore I will abandon my strongest desires to list and leave it to someone else. However, I would be remiss if I did not mention two names. The first is Harry Wexler. Dr. Wexler's belief in MLO showed a vision in ground-based baseline monitoring that was far ahead of its time, and his support for the observatory was indispensible for its establishment. The other is Charles D. Keeling, whose CO_2 monitoring at MLO is the textbook case of proper monitoring for climatic change. Through his tenacious effort and strictest attention to measurement technique the atmospheric CO_2 measurements at MLO constitute the best continuous CO_2 record in the scientific community.

I am fortunate to have had even a small part in the program at MLO over the past 19 years. Knowing the people and being associated with the program at the observatory during its growing years, contributing to the work and seeing it mature into a worthwhile endeavor have been gratifying. On this twentieth anniversary I'd like to congratulate the long line of people who have participated in MLO's history and the many more who will be involved in its future.

THE OBSERVATORY

Howard T. Ellis
Mauna Loa Observatory
Hilo, Hawaii

As I remember, I first heard about Mauna Loa Observatory (MLO), where I came to spend a large part of my career, in September 1957 through an article in *Topics*, an official monthly publication for U.S. Weather Bureau employees. Even though I had no intention of going there, I kept hearing about MLO from Jack Pales, who shortly before I joined the Physical Science Laboratory in Washington, D.C., had left that institution to become the first physicist-in-charge at MLO, then an IGY station under the administration of Dr. H. Wexler. Jack's frequent calls and letters asking for advice and equipment procurement kept us informed about the place.

In 1960 I received an urgent call from Charles Lee, of the U.S. Weather Bureau personnel office, asking me to take the position of principal assistant at MLO. At that time I was also attending graduate school at American University, and naturally the decision was a difficult one. Eventually, I accepted the job and left for Hawaii in February 1961 with Dr. Wexler's instructions to concentrate on the interpretation of ozone and carbon dioxide measurements.

My first days on the mountain were quite a shock, since my expectations of job conditions had been quite different. I was strongly tempted to ask for a reassignment on the mainland, but after longer deliberations I decided to stay and do my best at the observatory and also to adjust completely to the local culture, an easy task thanks to the friendliness of Hilo people and their apparent fondness for newcomers.

Work routine on the mountain in those days consisted of manning the facility 24 hours a day. Generally, five people, but never fewer than two, stayed at the observatory on a staggered schedule. We were all working a 6-day week, since observations were also made at a site at the Hilo airport 12 hours a day. The mountain instrumentation, with the exception of a continuous carbon dioxide analyzer, was duplicated at the Hilo site. Data reduction was done on a day-by-day basis, thus insuring good-quality data.

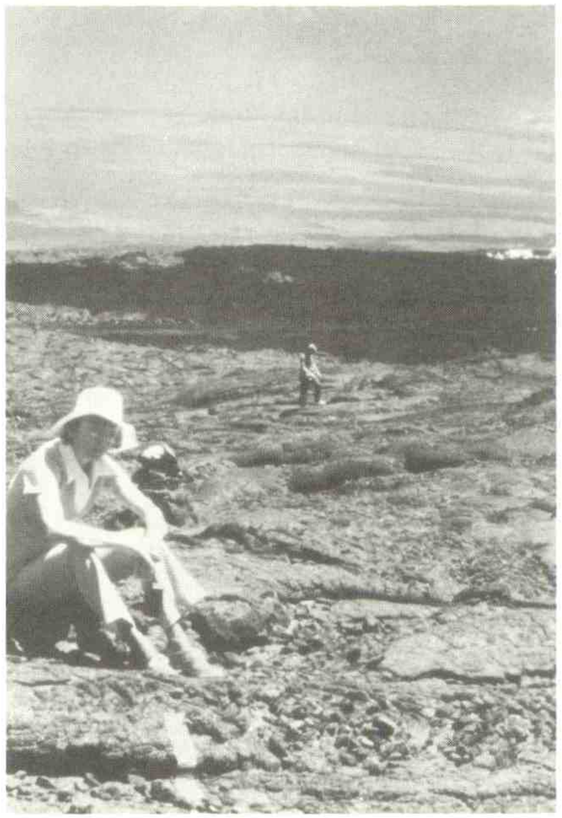
There was little change concerning the work on the mountain until January 1963, when Jack Pales, then director, suffered a heart attack, and I took on more responsibilities. My first project was to improve access to the observatory. Until that time we had to use the Kulani road, which was in very poor condition. I decided to have a 4-mile road built that linked the Kulani road to the saddle road; when completed it made the drive to MLO much easier and shorter.

In November 1963, word reached us from the U.S. Weather Bureau that the observatory would probably have to be closed down because of lack of funds and that everybody would be transferred. Despite this grim outlook I was determined to continue anyway and stated that I would find my own funds for running the place if it came to that extreme. In February 1964, Jack Pales left for a new job in Las Vegas, and the administration of the observatory was turned over to me. To save money, I immediately closed the administrative office in Hilo and personally hauled all the equipment to the mountain. The staff had been reduced to three including myself, and I tried to accomplish as much as I could by frequently staying on the mountain overnight and working 7-day weeks. On the whole I remember these 2 years as a peak of personal accomplishments and good relations with the Hilo community.

In March 1966, Lothar Ruhnke took over the leadership of the observatory until 1968, when another austerity period set in with his departure. Again I was in charge of the facility until 1970, when new funds became available through the increased interest in air pollution and environmental problems.

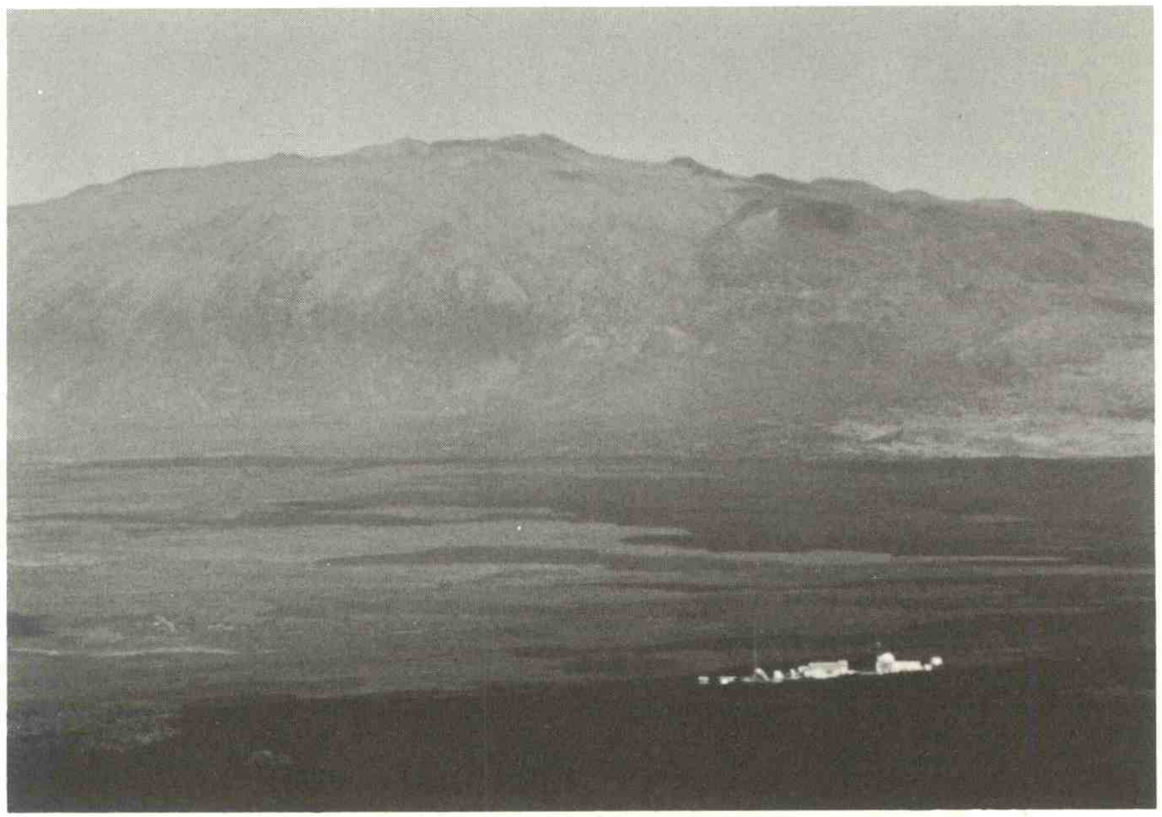
Fortunately, since then, MLO has not had to face any serious financial problems, and I hope that this situation will continue many more years.

Hikers ascend Mauna Loa, starting at the observatory.



Higher on the trail, a hiker rests by the trail marker, yellow paint on the lava. The observatory is visible (center right).

From even higher, the observatory is still visible (right).



MAUNA LOA OBSERVATORY — 1968

Lothar H. Ruhnke
Naval Research Laboratory
Washington, D.C.

It was an exciting period. The observatory had struggled through 10 years of uncertainties in regard to being recognized as a permanent research station despite a well-established record of fine observations unique to the high-altitude tropical environment. But the national awareness of the importance of watching and maintaining our natural atmospheric environment had just begun. Slowly but definitely the idea began to form that there was really a national need for the Mauna Loa Observatory (MLO), that its existence should not depend on occasional support by short expeditions or sporadic investigations of the mountain climate. We started to believe that there always would be a Mauna Loa Observatory, and we began to work with confidence on the future of this installation.

Ten years ago, diesel generators were replaced by permanent commercial power, telephone service was installed, jeeps and trucks were replaced by sedans, and the long road to the observatory was covered with blacktop to decrease dust contamination of our aerosol and pollution measurements. And what a job it was just to organize such work. Whose job was it anyway to improve the road? Federal agencies supported the observatory but felt no responsibility for the road. The state judged priorities in road construction in terms of economic returns on investment and asked how many more federal employees would be hired if better roads were available and when would their state taxes pay for the construction (I estimated 723 years but kept the answer confidential). However, there was also the county, with little funds but a big heart to help, and last but not least we had the Hilo Chamber of Commerce, which helped with publicity and an open eye on all developments at the observatory. And then it happened somehow. Research projects paid for materials, the Federal Highway Department took over construction and supervision, the State of Hawaii provided free labor through the Kulani honor prison camp, and the county provided vehicles and machines free of charge. Even private donations (e.g., $5.00 from Mr. Pete Beamer) helped. For the 10-year anniversary celebration we could invite the public to drive over a stretch of newly paved road to MLO for an open house. More than 300 guests viewed the facilities, heard lectures on the problem of man-made contamination of our natural environment, and saw NCAR's coronascope and a movie on the sun's eclipse.

But there were also more subtle changes at the observatory, not easily visible to the public. Usually observatory personnel were busy taking scientific readings and repairing research gear, whereas data evaluation and data interpretations were done by other research agencies and universities. The change came when observatory personnel discovered that they themselves were most able to process their own data and publish their own research results without outside help. I remember the joy and surprise we all had when Bernard Mendonca's first paper on Mauna Loa's wind circulation was accepted by the *Journal of Applied Meteorology*. Where did we find the time for this additional research and still maintain all routine observations? We established a base office in Hilo at the university campus and limited visits to the mountain observatory to essential observatory duties. This gave us time at sea level to discuss our measurement results.

The remaining problem was how to eliminate administrative work. Fortunately, permission was granted to hire a secretary. The first applicant was Judy Bright and I hired her. And what luck we had with Judy. No more letter writing while driving up the mountain in an old jeep; no more trouble with our private filing systems; no more missed appointments; and finally, someone to answer the telephone with a genuine aloha spirit.

The Hilo office gave us also other advantages. Because of its location at

the Cloud Physics Observatory, we were induced to use this research environment to our benefit. We formed a common research association with regular seminars to discuss our research and to have a forum for visiting scientists to give lectures. Besides that we shared a scientific library and some laboratory and shop space. It became a period of learning that helped all of us to appreciate the unique research opportunities at MLO. While it is customary for researchers in the environmental sciences to organize expeditions and field experiments far from home, we practically lived inside a scientific gold mine. The tropical inversion below the observatory level keeps surface-produced contaminants well away from the observatory, so that it is possible to study large-scale tropospheric characteristics. The tropical weather regime of Hawaii and the local circulation are predictable with a high degree of accuracy, and certain weather situations repeat themselves with great regularity. Solar radiation and nocturnal radiational cooling are very pronounced and lead to easy experiments on the atmospheric radiation budget. I wish the national energy crisis had occurred 10 years ago; then I would have urged Howard Ellis to start research on solar energy. Conditions are ideal at MLO for research on photovoltaics and thermoelectric power conversion. Most solar energy conversion systems increase in efficiency with increasing temperature differentials. High insolation coupled with very low radiational sky temperatures is very favorable for such research.

But even 10 years ago, research subjects were plentiful, and many temporary as well as permanent researchers were attracted to MLO. I remember well a research expedition to the top of Mauna Loa not only to celebrate our tenth anniversary but also to celebrate the first anniversary of NCAR's solar coronascope. This tenth anniversary expedition showed us clearly that the 13,000-ft-high top of the mountain was not necessarily the best place for an observatory. A local circulation transports and accumulates insects at the mountain top, which inhibit accurate sky observations through foreward-scattered sunlight.

I wish MLO continued success in the coming decades and I am very sorry that I cannot personally thank all my friends in Hawaii for the wonderful time I had with them 10 years ago.

THE VOLCANIC ENVIRONMENT OF MAUNA LOA OBSERVATORY, HAWAII HISTORY AND PROSPECTS

John P. Lockwood*
U.S. Geological Survey
Hawaiian Volcano Observatory, Hawaii

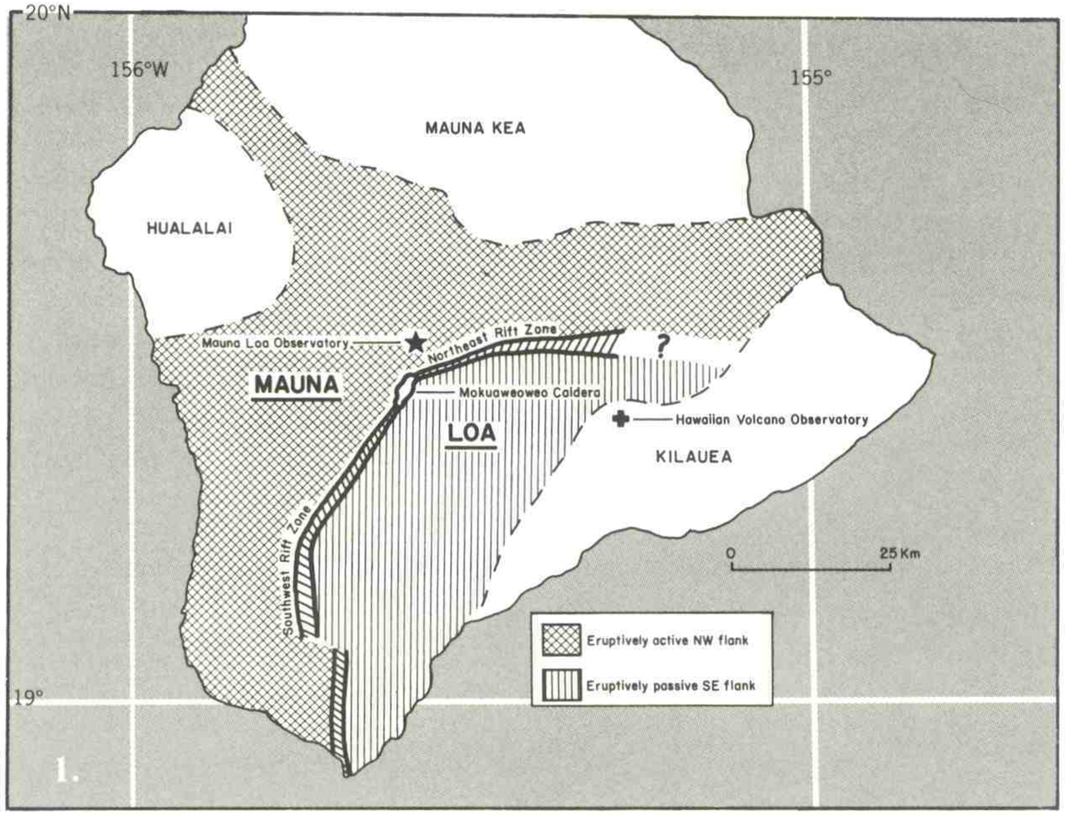
INTRODUCTION

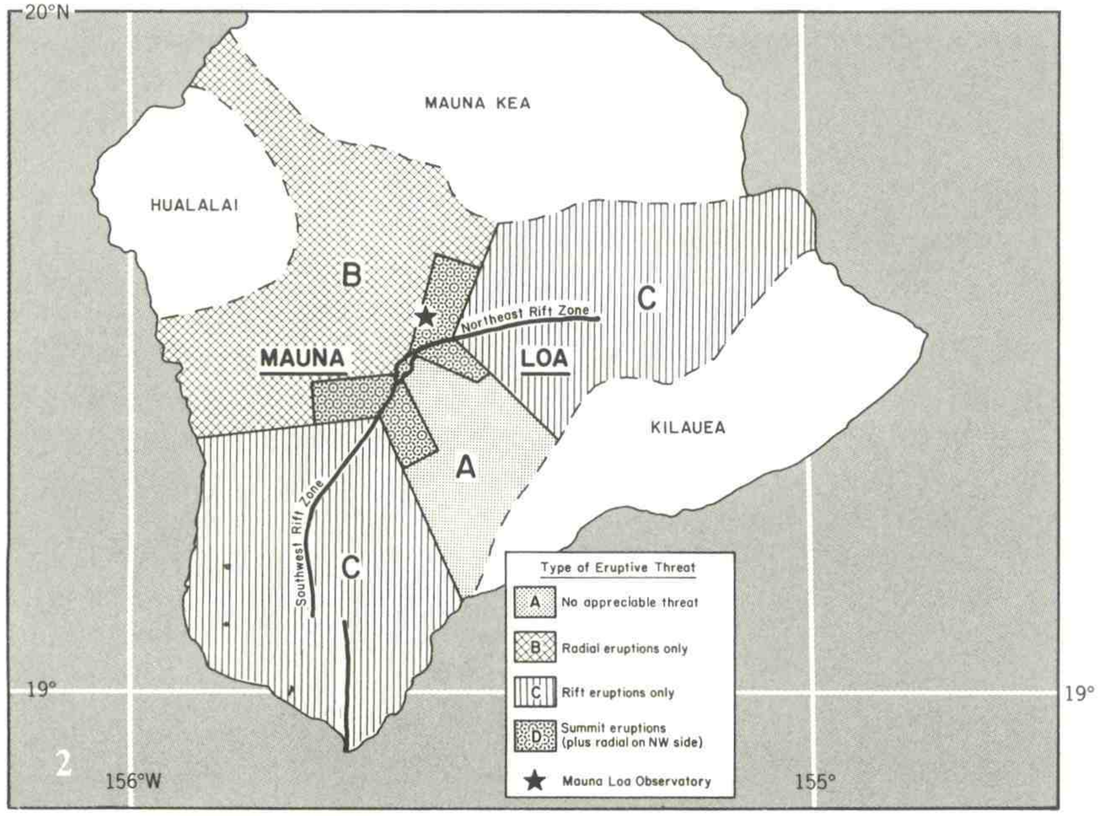
Mauna Loa Observatory (MLO) is located near the summit of one of the largest and historically most active volcanoes in the world. During 118 years of written history, between 1832 and 1950, Mauna Loa volcano erupted on an average of once every 3½ years. Then, after the large eruption of June 1950, the volcano began a period of inactivity that lasted 24 years. During this anomalously long period of inactivity, the U.S. Geological Survey's Hawaiian Volcano Observatory (HVO) installed a seismometer at the volcano's summit to monitor small earthquakes (1964) and established a small geodetic network to monitor deformation at the mountain's top (1965). However, no significant activity was noted until 1974 when a sharp increase in microseismic activity was accompanied by marked swelling of the summit region. This summit expansion has continued to the present and, coupled with the summit eruption of July 1975, has suggested that a large eruption may occur on Mauna Loa within a few years (Lockwood et al., 1976).

The renewed activity necessitated a dramatic increase in HVO's monitoring capability, and observatory crews began to make frequent trips to the volcano summit. Throughout this build-up of activity and in the years before, HVO

*Publication approved by the Director, U.S. Geological Survey

Aerial view of MLO in the mid-'70s. Faintly visible above the observatory site is the signal cable to the seismograph in the caldera.





scientists and technicians stayed hundreds of person-nights at MLO to prepare for predawn treks to Mauna Loa's summit. Thus nearly every HVO staff member since MLO's founding in 1956 has been a recipient of MLO hospitality. A feeling of closeness exists between MLO and HVO, partly because of mutual courtesies extended over the years and partly because of the realization at HVO that the MLO staff is at the "cutting edge" of Pele's sword while working at MLO, that the MLO staff is vulnerable to certain types of Mauna Loa eruptions, and that HVO has a responsibility to MLO to offer the best possible advice on the eruptive threat to Mauna Loa Observatory. For all these reasons I am happy to contribute a few words to this volume celebrating MLO's twentieth anniversary.

GEOLOGIC BACKGROUND

Mauna Loa can be divided into two parts: an eruptively active north and northwest side, and an eruptively inactive southeast side (Fig. 1). The two parts are separated by the southwest and northeast rift zones. At Mauna Loa's apex is Mokuaweoweo caldera, the geologic heart of the volcano.

Eruptions on Mauna Loa are of two different types: summit and flank. Summit eruptions are here defined as those originating within Mokuaweoweo caldera, whereas flank eruptions occur in the rift zones or north and northwest flanks of the volcano. Summit eruptions typically do not occur below about 3,700 m; flank eruptions typically occur below this elevation. Although more numerous than flank eruptions, summit eruptions produce considerably less lava and tend to be of shorter duration.

Flank eruptions are themselves separable into two categories: rift and radial eruptions. Rift eruptions constitute more than 90% of the flank outbreaks and are limited to Mauna Loa's two rift zones. Radial eruptions occur only on the northwest side of Mauna Loa, on eruptive fissures radial to Mokuaweoweo caldera, or inclined at high angles to the rift zones.

These different types of eruptions pose potential threats to different parts of Mauna Loa, and the volcano can be divided into four areas to indicate relative activity (Fig. 2). MLO is situated on the area exposed to the threat of summit eruptions or radial flank eruptions. It is not, however, directly threatened by the high-volume rift-type flank eruptions.

Figure 1. Map showing principal structural features of Mauna Loa volcano.

Figure 2. Map showing approximate areas of Mauna Loa susceptible to damage by different types of eruptions.

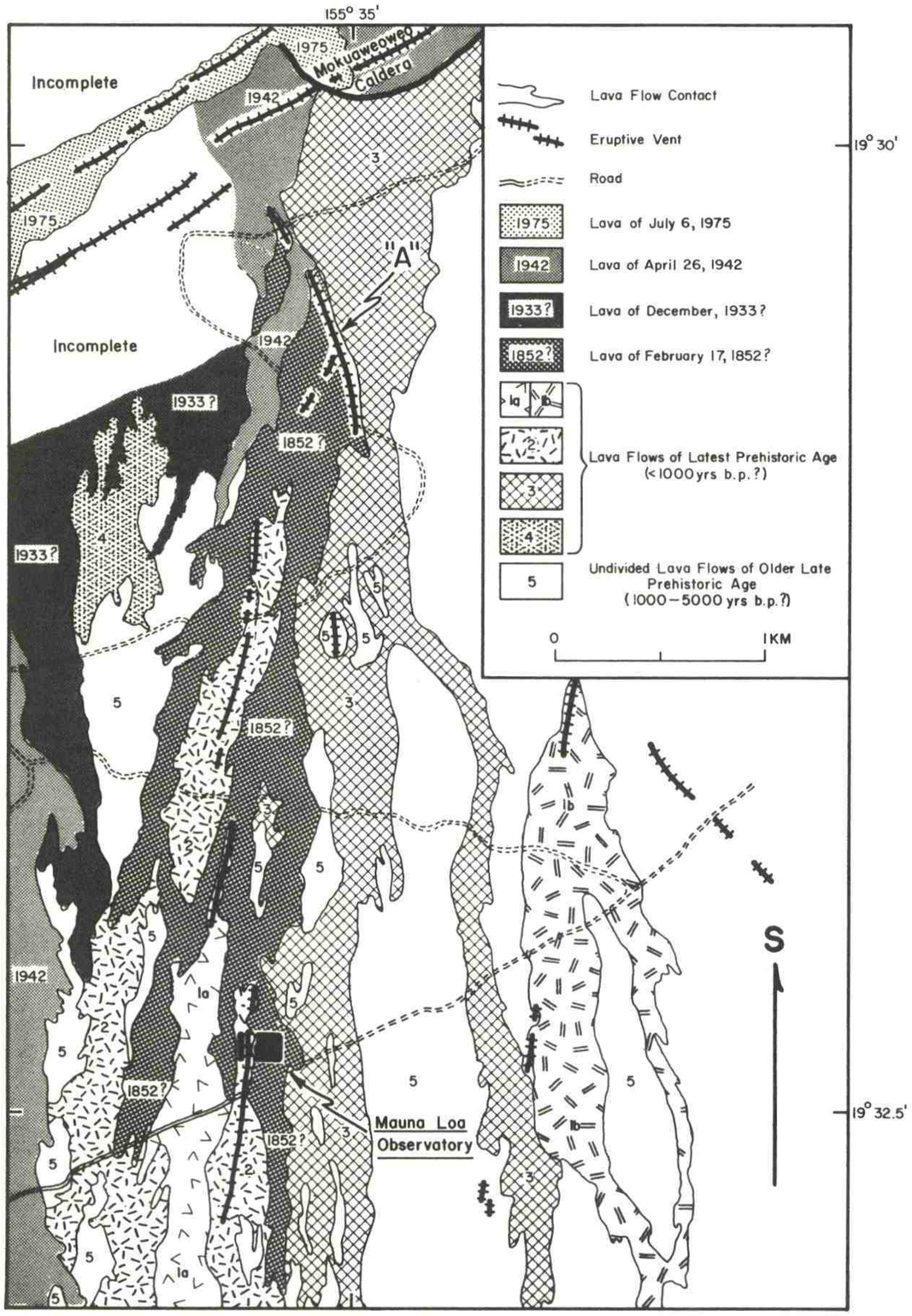


Figure 3. Generalized geologic map of the area surrounding MLO.

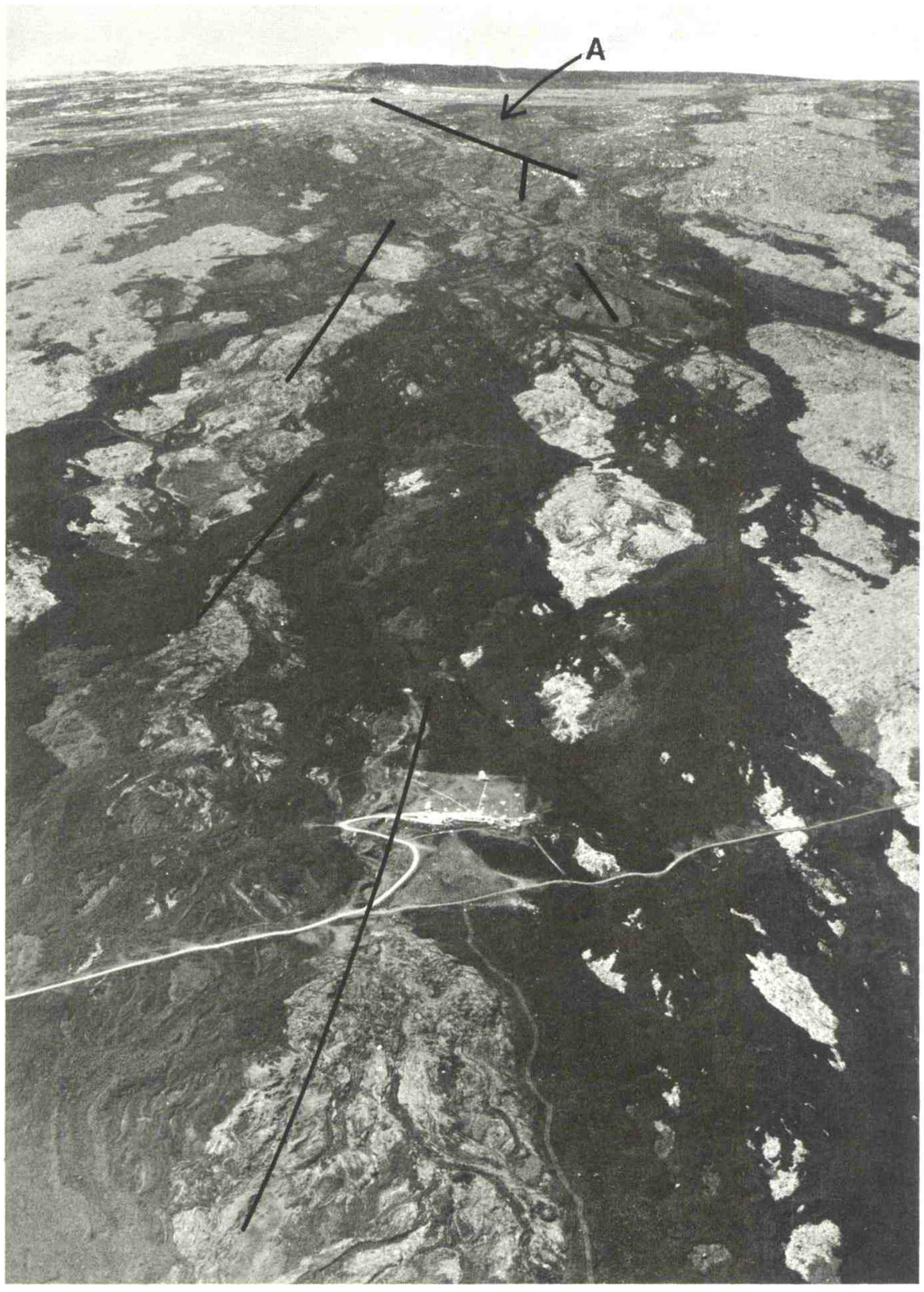
VOLCANIC GEOLOGY OF AREA AROUND MLO

MLO is located directly downslope from Mokuaweoweo caldera and is completely surrounded by lavas that were erupted from vents either within or radial to the caldera (Fig. 3). On Fig. 3 these lavas have been divided into nine age groups: four historic flows, four groups of latest prehistoric age (including five flows), and an undivided group of older prehistoric lavas that includes many separate flows. The division of the prehistoric lavas into "latest prehistoric" and "older prehistoric" age groups at 1,000 years is a best guess based on the amount of weathering compared with weathering of historic flows. However, the division point probably does fall somewhere between 600 and 2,000 years. Lavas of the younger eight groups consist predominantly of the aa form (blocky lava rubble); lavas of the older group consists predominantly of pahoehoe (smooth-surfaced lava).

Within the area shown in Fig. 3, six eruptive fissures radial to Mokuaweoweo caldera have been identified (Fig. 4), all of them prehistoric. One of these eruptive vents cuts across the east end of the MLO compound, at the entrance hairpin curve. The age of this vent is estimated to be 200 to 400 years on the basis of its lavas compared with historic lavas in the area.

ORIGIN OF THE FLOW UNDERLYING MLO

The MLO buildings are constructed on a very fresh blocky aa flow, typically with the following modal composition: 22% clinopyroxene, 12% plagioclase, 5% olivine, and 61% very fine grained matrix of pyroxene, plagioclase, and olivine crystallites set in dark brown glass clouded by opaque minerals. This lava was erupted from a 1.2-km-long vent located 3.5 km upslope from MLO. The vent consists of an acruate fissure (A on Fig. 3) oriented perpendicular to the northeast rift zone. A spatter and reticulite (pumice) rampart, 3–8 m high, along the fissure attests to a "curtain of fire" lava fountain that probably reached heights of 20–40 m. Lava was erupted as frothy pahoehoe at the vent but changed to aa as it moved rapidly downslope. Farther than 1 km below the vent, only aa is found.



The age of this flow is not known. It is included with lavas of late prehistoric age on the reconnaissance geologic map of Hawaii (Stearns and Macdonald, 1946, Plate 1) and yet shows no more weathering than known nineteenth century lava flows in the same climatic area on Mauna Loa. Specifically, it shows no more weathering than the 1843 aa flow that crosses similar climatic zones 7 km to the east. In mapping this flow the question arose whether this lava could have formed during historic time but not have been recognized owing to its then inaccessible location.

When the written accounts of witnesses to nineteenth century Mauna Loa eruptions are reviewed, one eruption is notable because its site has not been previously recognized. At 3:30 a.m. on February 17, 1852, citizens of Hilo were awakened by a Mauna Loa summit eruption. Reverend Titus Coan, Hilo's precise chronicler of Hawaii's volcanic eruptions from 1840 to 1881, wrote (Coan, 1852, pp. 219-220) that

> immense columns of burning lava shot up heavenward to the height of 300 or 400 feet, flooding the summit of the mountain with light, and gilding the firmament with its radiance. Streams of light came pouring down the mountain, flashing through our windows, and lighting up our apartments so that we could see to read large print. . . . In two hours the molten stream had rolled, as we judged, about fifteen miles down the side of the mountain. The eruption was one of terrible activity and surpassing splendor. But it was short. In about twenty-four hours all traces of it seemed to be extinguished.

However, in his autobiography (Coan, 1884, pp. 270–280) Coan stated that the eruption lasted 40 hours and flowed at the apparent rate of 15–20 mph.

Three days later a much larger and well-documented flank eruption followed at the 2,600-m level on the northeast rift zone (Coan, 1852, pp. 220–224). The earlier eruption of February 17 was generally forgotten, and the only information as to its location are the words of Coan (1852, p. 219) that "it was from the same point, and it flowed in the same line, as the great eruption which I visited in March, 1843."

Figure 4. Aerial photograph of MLO showing relation to Mokuaweoweo caldera and young lava flows. The lines mark locations of eruptive vents. The lava underlying MLO was erupted from the vent labeled A.

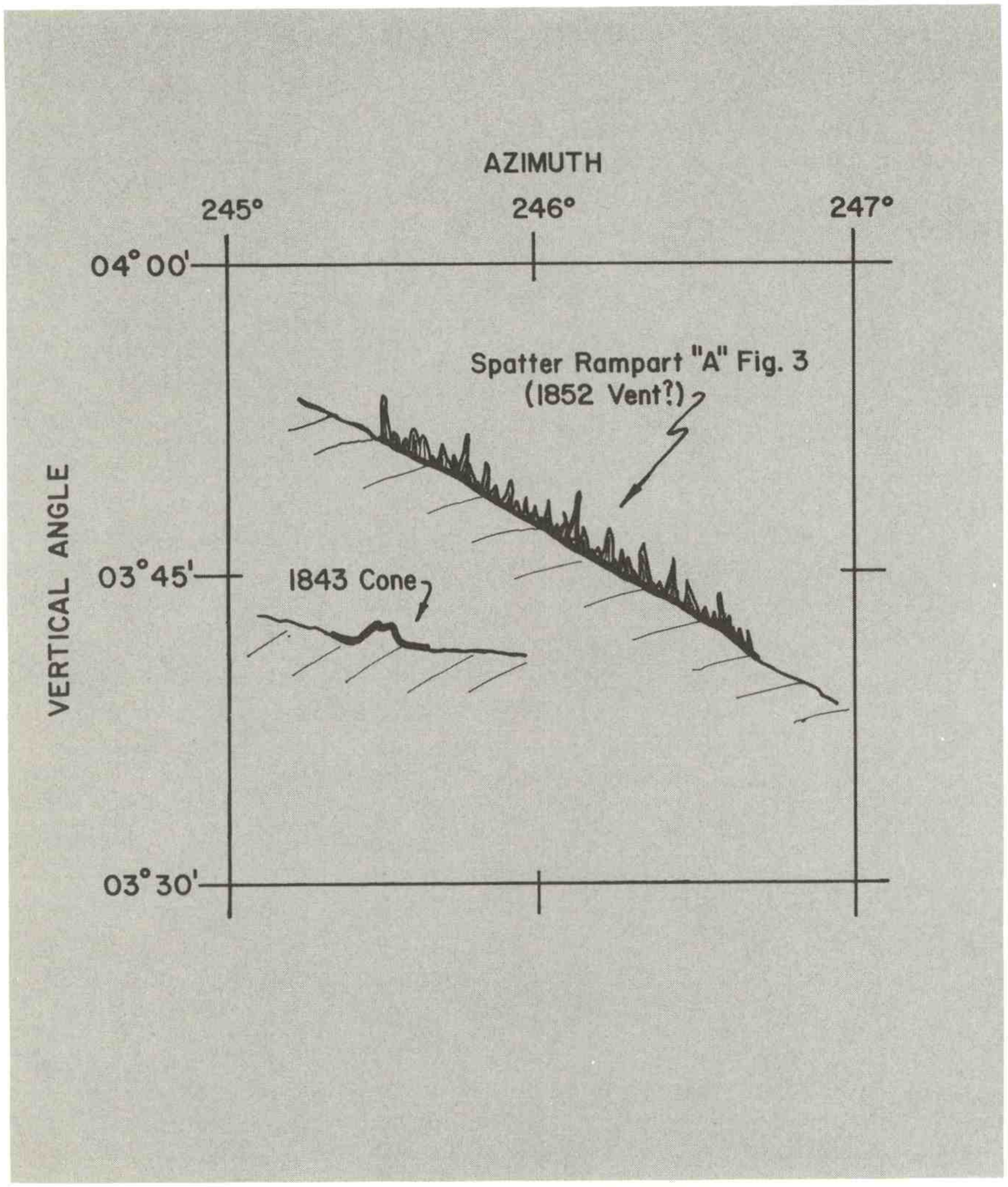
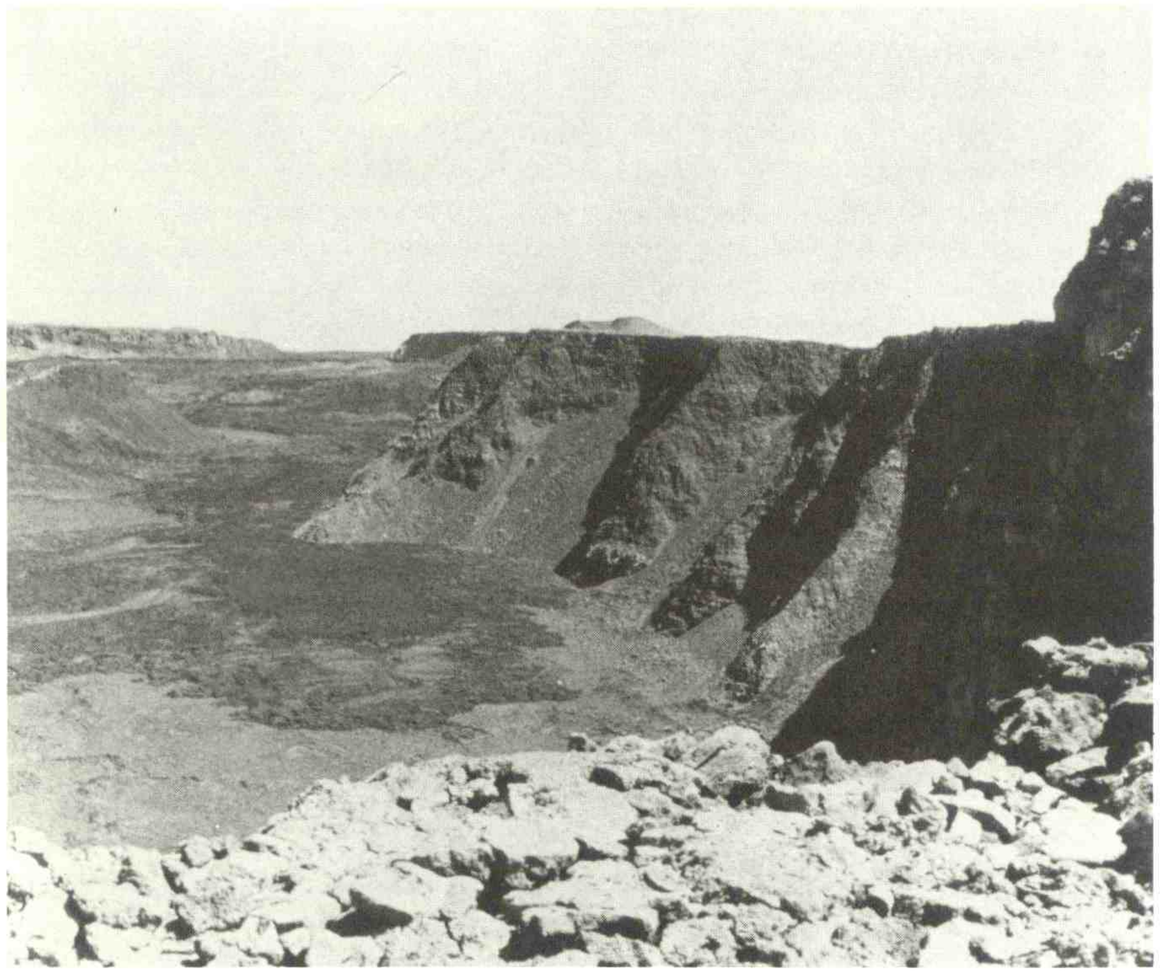


Figure 5. Diagram of possible view from downtown Hilo at 4:00 a.m. on February 17, 1852 (azimuths and vertical angles are from the site of the home of Reverend Titus Coan).

There are two 1843 eruptive vents, but only the upper one could have been seen from Hilo. The upper 1843 vent had not previously been designated on any map, but from Coan's lucid description (Coan, 1844, p. 47) the vent was identified during current studies on the northeast rift zone as hill 11,427 (lat. 19°31.6'N., long. 155°31.8'W.). A subsequent ground visit confirmed that this was indeed the upper 1843 vent known to Coan. (It was later discovered that Howard Powers had reached the same conclusion many years before [T. L. Wright, 1976, personal communication].) To reconstruct Reverend Coan's 1852 view, it was then necessary to find where he had lived. His house, since demolished, had been located in Hilo on Haili Street just below the present Haili Church (O. Lyman, 1977, personal communication). Lines of sight were projected from the site of Coan's home to the upper 1843 vent and to the source vent for the flow on which MLO is constructed (vent A, Figs. 3 and 4). From the perspective of Coan's home the MLO vent was indeed nearly coincident with the 1843 cone (Fig. 5), even though the cone is located 6 km to the east and 430 m lower in elevation than vent A. The vertical scale is exaggerated four times in Fig. 5, so that the visual coincidence of the two vents is even closer than this figure indicates.

The MLO flow is only 5 km long, however, so that if the reconstruction is correct, Coan's estimate of a "fifteen mile" length is in error. There are no known young flows 15 miles long on the northeast rift that could fit the 1852 description. Furthermore, a 15-mile-long flow would indicate an anomalously high 12-km/hr flow rate if Coan's 2-hour flow duration is correct. Assuming a 5-km length gives a 2.5-km/hr flow rate—much more reasonable in view of historically observed flow rates in this area.

It thus seems likely, all considered, that the aa lavas underlying MLO may be the products of the eruption viewed by Reverend Coan on the early morning of February 17, 1852. For those interested, a dramatic summary description of the 1852 eruptions was published in the *Hilo Tribune Herald* (Allan, 1929).



Mauna Loa's caldera, Mokuaweoweo, is about two miles wide, at an elevation of 13,650 ft.

THE PROSPECTIVE VOLCANIC HAZARD AT MLO

MLO is located in an area that is exposed to a serious volcanic threat, as shown by Figs. 3 and 4. Mullineaux and Peterson (1974, Plate I) placed the area encompassing MLO in their zone of highest volcanic risk, zone F. They divided the volcanic hazards contributing directly to this risk as lava flows, falling rock fragments, gases, and particle and gas clouds (Mullineaux and Peterson, 1974, pp. 29–40). The risk related to the last three phenomena is considered negligible at MLO, and lava flows are considered the only hazard that seriously threatens the MLO facilities. Some perspective can be placed on the threat of lava flows by studying the area's history, as recorded by flows near the observatory.

The area shown in Fig. 3 encompasses approximately 18 km-. Within this mapped area, 21% of the surface rocks are of historic age (on the assumption that the year of the MLO flow was 1852), 23% were erupted in later prehistoric time, and 56% were erupted in earlier prehistoric time. Thus, 21% of the surface rocks were erupted within the 140-year period of written observation. The 140-year historic record (since about 1837) is very short and may well not be typical of the future. Several lines of evidence now suggest that Mauna Loa may have been more active during this period than in the late prehistoric past, but even so, the conclusion is inescapable that MLO is located in an area of high volcanic risk. Firm statistical limitations cannot be assigned to this risk because of the lack of knowledge about the prehistoric record and because of potential variability in the future.

This then is the unfortunate state of our ability to quantify the volcanic risk to MLO. Researchers at MLO can, however, take comfort in two facts: (1) the risk to life at MLO is very slight, and (2) MLO is situated on relatively high ground provided by the 1852(?) lava. Future flows will tend to flow around the observatory.

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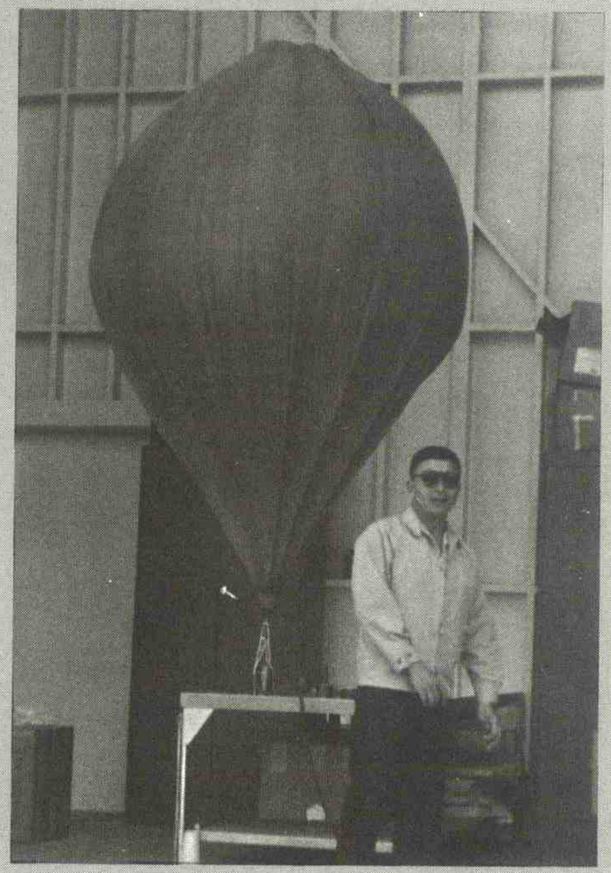
Gas measurements

CO_2 instruments (left) in the new observatory building 1978, with meteorological and solar radiation strip charts (right).



John Chin with ozonesonde at the National Weather Service airport station, Hilo, in March 1970. The MLO balloon-supported instrument used the standard Weather Bureau radiosonde transmitter and receiver at the airport.

THE INFLUENCE OF MAUNA LOA OBSERVATORY ON THE DEVELOPMENT OF ATMOSPHERIC CO_2 RESEARCH

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INTRODUCTION

The increasing amount of CO_2 in the atmosphere from the burning of fossil fuels has become a serious environmental concern. Central to this concern is the question whether a rise in CO_2 constitutes a peril to man by raising world temperatures, as many scientists now claim. That a rise in CO_2 is occurring is unquestionable, however. Mauna Loa Observatory (MLO) data are providing dramatic evidence of that: they show amounts more than 10% over amounts recorded before the Industrial Revolution, and a rise of 6% in the last 19 years alone.

Ninety-seven percent of the energy demand of the industrial world is met today by burning fossil fuels. Even if the industrialized world were to decide to shift to other energy sources as rapidly as possible, the annual consumption of fossil fuels would double before the shift was complete. Without such a shift, a peak annual rate ten or even twenty times today's rate may occur before fuel reserves, especially coal reserves, are exhausted. Thus a large additional increase in atmospheric CO_2 is likely in the next few decades. As Revelle and Suess (1957) wrote, "Through his worldwide industrialized civilization, man is unwittingly conducting a vast geophysical experiment. Within a few generations he is burning the fossil fuels that slowly accumulated in the earth over the past 500 million years."

The idea that CO_2 from fossil fuel burning might accumulate in air and cause a warming of the lower atmosphere was speculated upon as early as the latter half of the nineteenth century (Arrhenius, 1903). At that time the use of fossil fuel was too slight to expect a rise in atmospheric CO_2 to be detectable. The idea was again convincingly expressed by Callendar (1938, 1940) but still without solid evidence of a rise in CO_2.

The first unmistakable evidence of atmospheric CO_2 increase was furnished by continuous measurements made at MLO and by measurements of flask samples collected periodically at the South Pole. These data, obtained in connection with the International Geophysical Year (IGY), were precise enough to indicate a rise in concentration in 1959 when compared with the results of the previous year (Keeling, 1960). Further measurements have shown a persistent year-to-year increase.

Along with new observations have come increasingly refined calculations of the heating effect of increased atmospheric CO_2. One of the most widely accepted climate models emerging from this effort indicates that the earth's surface would warm by 4°C above the present average global temperature for a fourfold increase in CO_2, by 6°C for an eightfold increase (Geophysics Study Committee, 1977). A rise in CO_2 as great as eightfold before coal reserves are exhausted has been predicted using a geochemical model calibrated by the Mauna Loa and South Pole trends (Keeling and Bacastow, 1977).

Such a high average global temperature has probably not occurred for tens of millions of years. Accompanying such warming may be shifts in rainfall patterns and in agricultural zones. Polar ice may melt or break up and lead to coastal flooding (Geophysics Study Committee, 1977). These problems, once upon us, will not be easily overcome. Once high CO_2 levels are reached, they will probably decrease only slowly as deep ocean water gradually absorbs the excess CO_2. Concentrations well above preindustrial levels are likely to persist for at least 1,000 years, along with attending climatic problems (Keeling and Bacastow, 1977).

Whether or not a large CO_2 increase will occur and persist depends on the natural carbon cycle, about which we still know too little. How much CO_2 from fossil fuel will remain in the air during the next centuries? How much will be taken up by the oceans and by vegetation on land? These questions cannot be answered from present knowledge. Sustained monitoring of CO_2 at sites such as MLO is an indispensable aid to validate predictions stemming from calculations of the behavior of the carbon cycle.

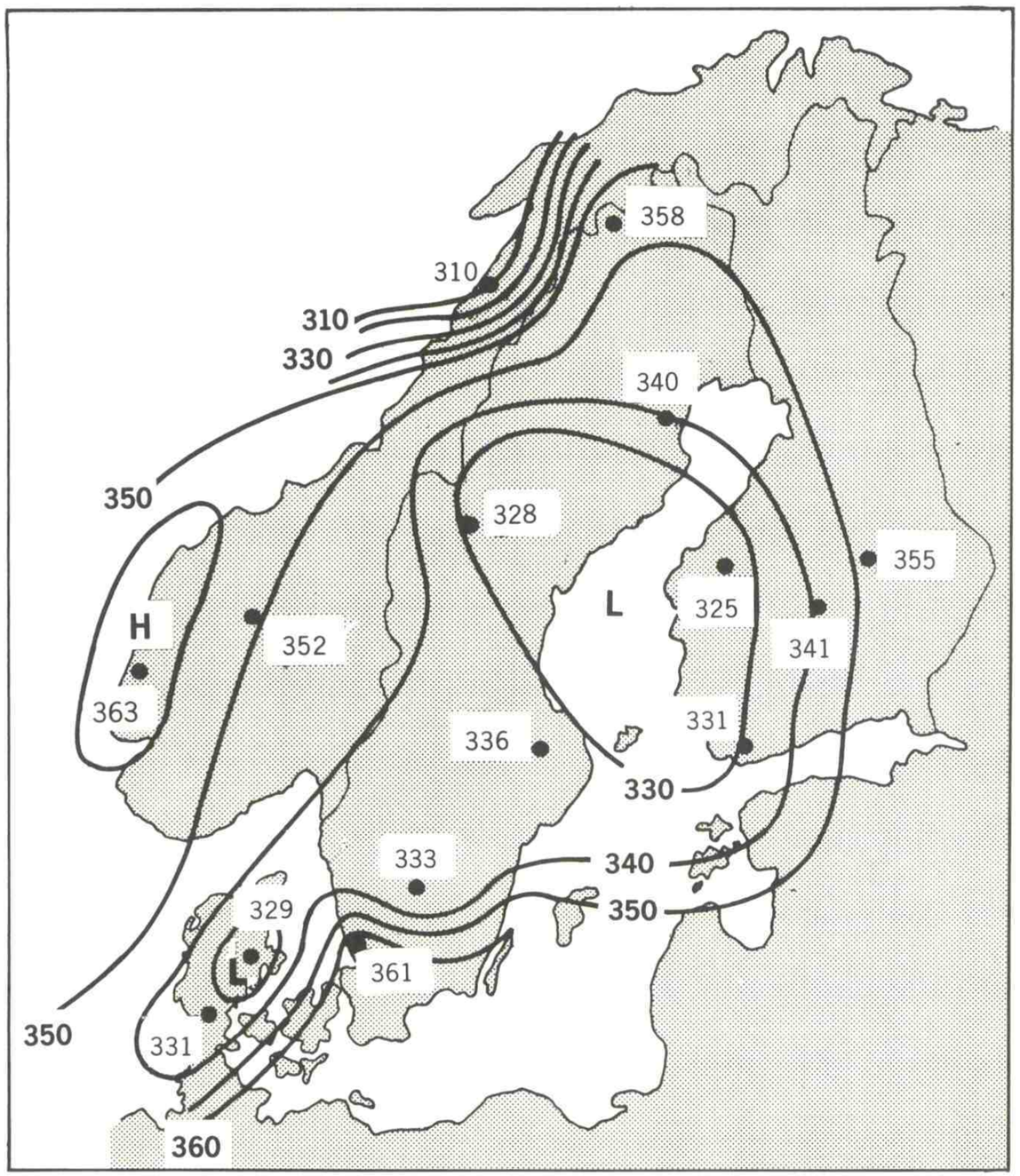


Figure 1. Concentrations of atmospheric CO_2 over Scandinavia (ppm) on February 20, 1955. The approximate pattern is shown by contour lines in a manner similar to Bischof's (1960, Fig. 6). Concentrations were determined by absorption of CO_2 in barium hydroxide solution.

Viewed in this context, the reasons for measuring atmospheric CO_2 at Mauna Loa seem compelling. A few of us remember, however, that the original decision to study CO_2 at this remote site was not easily made. Because the story is closely involved with MLO being established in the first place, it seems appropriate to recount here some of the human aspects of this story and its scientific perspective.

HISTORY

The IGY, which began in 1957, offered scientists for the first time an organizational setting for study of atmospheric CO_2 on a global scale. In view of the importance of knowing whether airborne CO_2 was rising worldwide, such a study was long overdue. The data published before the IGY led to a general belief that CO_2 concentrations depended greatly on location with no clear time trend (Bray, 1959). Observations varied from under 200 parts per million (ppm) near the North Pole to over 350 ppm in continental air and air near the equator (Buch, 1948). Owing to this apparent spatial variability, a whole network of stations was deemed necessary to detect any significant global trend.

In the early 1950's, Carl G. Rossby suggested that Stockholm University's Meteorological Institute, which he directed, should participate in an extensive investigation of trace chemicals in the atmosphere as a prelude to the IGY. At a conference held on the subject in 1954, participants decided to plan for a worldwide network of CO_2 monitoring stations, possibly including a site in the Hawaiian islands (Eriksson, 1954). Responsibility for setting up stations in the Pacific region fell to Wendel Mordy, a conference member and chief meteorologist of the Pineapple Research Institute in Honolulu.

When I learned that Mordy was interested in measuring atmospheric CO_2 in the Pacific region, I informed him of CO_2 studies I had begun in 1955 while at the California Institute of Technology. In contrast to previous studies, I had found practically constant atmospheric CO_2 in turbulent air near midday.

Meanwhile, CO_2 monitoring had just begun in Scandinavia under the general direction of Kurt Buch of Finland. The Scandinavian data (Fig. 1) resembled past work, with greatly varying CO_2 concentrations — even though

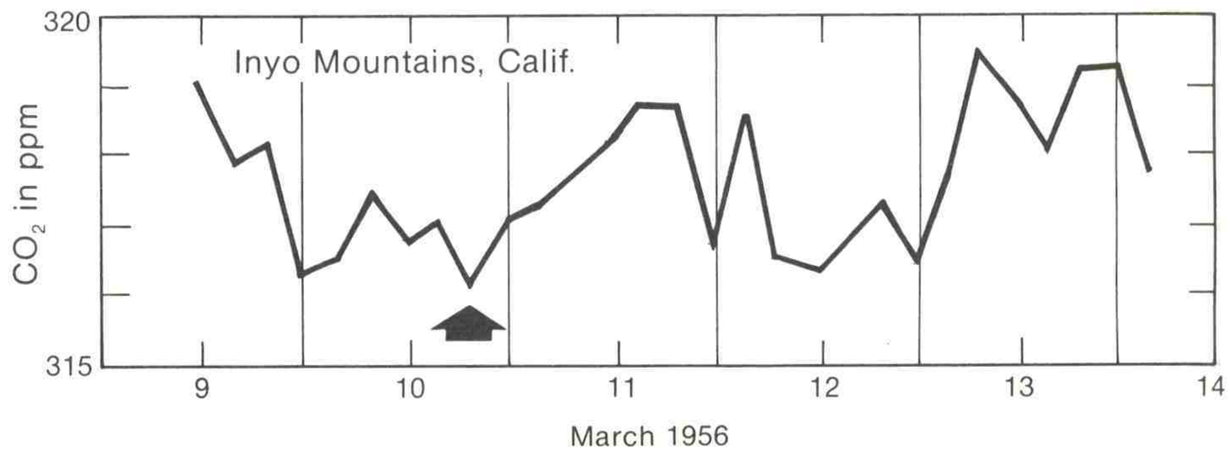
special care was being taken to sample in open areas away from local influences (Fonselius et al., 1955). My daytime CO_2 results were close to the Scandinavian means, but the variability was far less — even though I had taken special care to sample in densely vegetated areas where local influences would predominate. Specifically, I had found that everywhere I went the air a few tens of meters from the plants on sunny days tended to reach a nearly constant CO_2 level of about 315 ppm (Keeling, 1958). In an attempt to understand why, I took measurements in some exposed windy areas away from plants: at high elevation in the White Mountains (Fig. 2) and Sierra Nevada of California, on ocean beaches, and over ocean water near the equator (Keeling, 1961). All these data were also near 315 ppm. I concluded that the CO_2 in air had a characteristic background concentration, at least near the west coast of the United States and Central America where I had sampled. Evidently, on sunny days this background level prevailed even near plants.

Thus I became concerned that the proposed measurements in Hawaii and elsewhere might not be accurate enough to establish this background CO_2 level. Although Mordy soon decided not to participate in CO_2 studies, my concerns reached the attention of Harry Wexler, Director of Research for the U.S. Weather Bureau. Wexler was a friend of Rossby and an ardent supporter of broadly based meteorological studies. He invited me to Washington early in 1956.

The Weather Bureau already had a small wood frame hut near the summit of Mauna Loa where some simple automatic instruments were housed. In 1955, at Wexler's urging, plans were underway to construct a larger, more permanent structure where people would live and tend more complicated instruments. During my interview with Wexler, which I recall began promptly at 8:00 a.m., I talked to him about the possibility of setting up a continuous recording CO_2 gas analyzer on Mauna Loa since it would be possible to live there and tend the analyzer as necessary. As far as I knew, no one had ever before suggested measuring atmospheric CO_2 continuously. Wexler asked a number of questions in rapid-fire, covering both the scientific and the practical. He was especially interested in costs. We went so far as to discuss setting up a second continuous CO_2 analyzer in Antarctica. Then the interview was over. Altogether it took almost exactly 15 minutes, as scheduled. Wexler had made up his mind to press for CO_2 measurements at Mauna Loa using monies which he hoped would be made available by the participation of the United States in the IGY.

During this same spring of 1956 the oceanographic community was making plans to participate in the IGY. Roger Revelle, as director of the Scripps Institution of Oceanography, was a leader in this effort. Revelle had an intimate knowledge of the natural CO_2 cycle going back to his student days, and he wanted to make sure that man's "vast geophysical experiment" would be properly monitored and its results analyzed. Revelle believed that a CO_2 program should include ocean water studies as well as atmospheric measurements. With this in mind and with Wexler's concurrence, he arranged funding for a laboratory for CO_2 measurements at Scripps, and I was invited to run it. Although it had not been decided precisely what kind of CO_2 program should be implemented as part of the United States IGY effort, I accepted his offer.

Wexler's support of continuous measurements of atmospheric CO_2 at MLO was a bold decision not widely accepted at the time. Wexler knew that I had located a manufacturer of nondispersive infrared CO_2 gas analyzers, but he also knew that I had not yet been able to test such an analyzer. Even the firm itself did not claim that its infrared analyzer was accurate enough for the task.



It had been designed principally for industrial uses which did not demand high accuracy. I was relying on the judgment of one of the firm's engineers that the device was inherently very sensitive and stable. The firm couldn't even lend me one to test. The basic instrument was expensive and required costly additional equipment to operate as an air monitor at a remote field station. Reference gases to calibrate the instrument did not exist.

To most of the IGY planners who heard about the CO_2 infrared analyzer scheme in 1956, such expensive and complicated equipment seemed unnecessary. Both the earlier published data and the new Scandinavian data, appearing in print every 3 months, proved that atmospheric CO_2 variations were so large that traditional methods of chemical analysis would always remain adequate. I distrusted these variable data, but my distrust was based on no more than a few hints from my own data. The most important of these was the near constancy of CO_2 over five days for samples taken at 3,500 m in the White Mountains. Wexler had been especially impressed by the White Mountains record (reproduced in Fig. 2). He felt that if this record was typical of background air, high measurement accuracy at a site on Mauna Loa just might pay off in the IGY program.

Revelle soon agreed to the new infrared analyzer method, but he preferred a network of measuring locations in which such analyzers would be used to analyze air collected in flasks, from ships and aircraft for example.

Rossby remained dubious. I had a chance to meet him just once at an IGY planning meeting at Scripps during 1956. Someone pointed me out to him across a grass lawn during a recess. As he walked up to greet me, he remarked for the benefit of some nearby acquaintances, "Ah . . . za yong man wiz za machine." He seemed upset at this abrupt new American plan to buy expensive gadgetry to measure CO_2. His skepticism became obvious as we talked about plans for an ambitious instrument-based United States program.

Ironically, I had so far obtained CO_2 data using quite inexpensive devices — glass sampling flasks, a liquid nitrogen cooled freeze-out trap, a mercury column manometer. But my manometric method could not be used for a large program because a single sample took over an hour to analyze. The infrared gas analyzer was needed to speed up the work without sacrificing high accuracy.

Late in the summer of 1956 I arrived at Scripps to begin implementing the new U.S. atmospheric CO_2 program. In all, four gas analyzers were purchased. One was hastily outfitted for Antarctic field work. Shipment to Little America couldn't be delayed. This first venture turned out, in fact, to be too hasty. No useful data were obtained at Little America until the second Antarctic field year in 1958.

As soon as the Antarctic shipment was off — on the same vessel that was to have carried Admiral Byrd to Antarctica, had he been able to go — I began systematically to test the new analyzers. In March 1957, continuous measurements of air began at Scripps. Soon afterward I assembled another apparatus for Mauna Loa. But there were numerous delays and problems with the aircraft and shipboard programs. These delays were especially bothersome because the IGY had already begun. Soon it would be over, and ships and aircraft would not be available.

As it turned out, when the equipment for Mauna Loa was ready, I couldn't install it. Revelle insisted that I give first attention to aircraft and shipboard sampling, and the aircraft program was not yet underway. He reinforced his view of the matter by refraining from signing my travel orders to visit Mauna Loa. As the IGY approached its July 1958 ending date, Wexler became very anxious about Mauna Loa. At length he took action himself and

Figure 2. Variation in atmospheric CO_2 over barren ground near White Mountain Research Station in the Inyo Mountains of California during March 1956 (adapted from Fig. 2 of Keeling, 1961). Concentrations were determined manometrically from liquid nitrogen temperature condensates. The arrow identifies the minimum concentration plotted in Fig. 4, accepted as representative of west coast U.S. air.

sent to me Ben Harlin, the meteorologist who had operated the CO_2 equipment at Little America in 1957. With help from Jack Pales, the first director of MLO, Harlin installed the analyzer at MLO in March 1958 without my assistance. To our great surprise, on the first day of operation it delivered within 1 ppm the CO_2 concentration that I had told Harlin to expect on the basis of my earlier manometric data and preliminary test data obtained at Scripps.

Of course this agreement was an accident. The mean of the daytime manometric and Scripps data just happened to be close to the value typical for the month of March. Indeed, the next month's data did not agree — the concentration rose by over one ppm. The following month's mean concentration was still higher. Electrical power failures then shut down the equipment for several weeks. When measuring resumed in July, the concentration had fallen below the March value. I became anxious that the concentration was going to be hopelessly erratic, especially when the computed concentration fell again in late August. Then there were more power shutdowns.

Finally, after my first visit to Mauna Loa in November, the concentration started to climb steadily month by month. Gradually a regular seasonal pattern began to emerge: we were witnessing for the first time nature's borrowing of CO_2 for plant growth during the summer and returning the loan each succeeding winter. Earlier published data for Europe also showed a seasonal trend of sorts (Bray, 1959), but the maximum concentration, arrived at statistically from a highly irregular pattern, was in January, a time of year when CO_2 from burning is likely to accumulate near the ground because of winter temperature inversions. The maximum at Mauna Loa occurred in May just before temperate and boreal plants add new leaves. The seasonal pattern was highly regular and almost exactly repeated itself during the second year of measurements at Mauna Loa. Thus there was no need to wait for statistical studies to prove the reality of the oscillation as would have been required had less exact chemical methods been used. I soon reviewed my 1955–1956 manometric data and discovered that they showed a similar seasonal variation (Bolin and Keeling, 1963).

No one had expected to determine the long-term rate of rise in CO_2 during the IGY even though establishing the rise was the principal purpose of the program. Revelle and others had expected that the IGY program at best would furnish a reliable "baseline" CO_2 level which could be checked 10 or 20 years later, after the rise in CO_2 was large enough to stand out against local variability. But because of the regularity of the seasonal variation at Mauna Loa a rough estimate of the long-term rise was possible after only two years (Bolin and Keeling, 1963).

Fortunately, funding for CO_2 measurements at MLO was continued after the IGY. By early 1962 it was possible to deduce that approximately half of the CO_2 from fossil fuel was accumulating in the air and that a sink must be carrying a substantial fraction away (Keeling, 1960). Revelle and Suess (1957) had predicted that much of the CO_2 from fossil fuel would be absorbed by the oceans. The earlier published CO_2 data had argued against their view, however, because the rise in CO_2 seemed to be close to that predicted if all of the CO_2 from fossil fuel accumulated in the air. This latter conclusion was reinforced in 1958 after several years of the Scandinavian network data became available (Callendar, 1958). But after four years of measurement at Mauna Loa the question was settled in favor of the Revelle-Suess prediction.

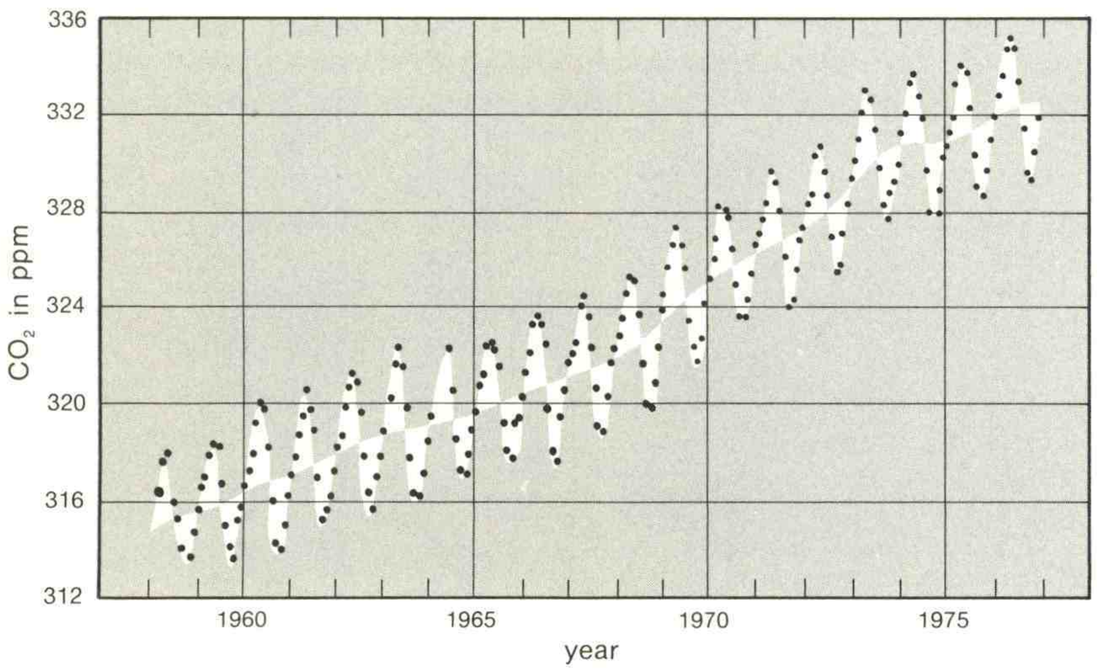


Figure 3. Monthly average concentrations of atmospheric CO_2 at MLO since the beginning of monitoring in 1958. Concentrations were determined with a nondispersive infrared gas analyzer as described by Keeling et al. (1976a), p. 539.

As the Mauna Loa record has been further extended, additional interesting features of the long-term trend have revealed themselves. These include perturbations that appear to correlate with the trade winds and with sea surface temperature (Bacastow, 1976; Machta et al., 1976; Newell and Weare, 1977). The seasonal pattern has also been scrutinized to see if variations in amplitude from year to year are meaningful. So far the pattern is too regular to reveal significant variations (Hall et al., 1975). Now after nearly 20 years of measurements, the Mauna Loa record (Fig. 3) appears as a natural yearly cycle gradually being dwarfed by a long-term rise — a dramatic example of inadvertent influence by man on his environment.

THE WEST COAST DATA

Even though the manometric CO_2 data obtained shortly before the IGY played a prominent role in deciding the strategy of the United States CO_2 program, they had never been compared with the infrared CO_2 data for Mauna Loa. Until a pressure broadening correction was recently applied to the latter data (Keeling et al., 1976a), a precise comparison was not possible. It seems worthwhile now to review these earlier measurements and to reconstruct, as closely as possible, the global concentrations of CO_2 back to 1955.

This reconstruction is greatly aided by additional infrared measurements of CO_2 obtained between 1957 and 1962 at La Jolla, California. Although these data were obtained as a by-product of instrument testing, they are nevertheless a useful record of air from the same general geographic area as the earlier manometric data. Except for a few days when air was sampled from a laboratory window, all measurements were made near the end of a 1,000-foot ocean pier where the air was often free of local disturbances, at least during sea breezes. The CO_2 record was twice interrupted for several months when oceanographic work was in progress, but a nearly unbroken continuous record exists from April 1958 to June 1960. Since the Mauna Loa analyzer was operating during this period, these data, and a few more in 1962, are useful in adjusting the La Jolla record to a common basis with Mauna Loa.

Most of the 1955–1956 manometric data reflect local CO_2 emanating from plants and soil. The minimum values for each location, occurring typically near midday, as already noted, may not have been markedly influenced by plant activity, however. A plausible reason for this is that the sampling locations I had chosen were in wild areas which had never been disturbed very much by humans. In wild areas the photosynthetic withdrawal of atmospheric CO_2 by the plants and the release of CO_2 by plant respiration and decomposition should not differ greatly. The net change in the CO_2 concentration of the local air should therefore be relatively small, especially if air turbulence, typically maximal at midday, further diminishes the net effect.

At several control sites on ocean beaches and barren mountains, where I also sampled during 1955 and 1956, the CO_2 concentrations usually agreed with the minimum values found near plants. For example, in Yosemite National Park in June 1955, the lowest value found for forest air was 316.2 ppm; a few miles away over barren terrain near Lake Tenaya, I found 315.9 ppm (Eriksson, 1954).

The minimum CO_2 concentrations for all CO_2 sites in the western United States are listed in Table 1 and plotted in Fig. 4, except that data have been omitted if the humidity was not measured, since for these data it is impossible to determine the CO_2 concentration versus dry air. Most of the measurements were obtained in California, but a few were obtained farther north in the state of Washington and several from Arizona.

Table 1. Minimum atmospheric carbon dioxide concentrations (relative to dry air) by direct manometric analysis, for various sites near the west coast of the United States and Central America

Location	Elevation (above sea level)	Date	Local Time	Minimum CO_2 Concentration (ppm)	Type of Site
1955					
Big Sur State Park (36 °N., 122 °W.)	70 m	May 18	12:15	319.3	forest
Yosemite National Park (38 °N., 119 °W.)	2500 m	June 2	12:30	316.2	forest
	3000 m	June 3	10:00	315.9	barren ground
Olympic National Park (48 °N., 124 °W.)	170 m	Sept. 7	13:30	312.6	forest
	0 m	Sept. 7	15:15	313.8	ocean beach
Gulf of Tehuantepec (9 °N., 89 °W.)	10 m	Dec. 1	5:30	314.4 314.9*	over ocean
1956					
Borrego Valley, California (33 °N., 116 °W.)	340 m	Feb. 1	10:30	314.1	barren desert
Inyo Mountains, California (37 °N., 118 °W.)	3800 m	Mar. 10	20:00	316.2	barren snow field
Organ Pipe Cactus National Monument (32 °N., 113 °W.)	550 m	Apr. 22	0:00	316.1	desert brush
Howard Pocket, Arizona (35 °N., 112 °W.)	2100 m	May 16	15:30	317.4	forest
Telephone Hill, Arizona (37 °N., 112 °W.)	2600 m	May 18	15:00	320.0	forest
Big Sur State Park (36 °N., 122 °W.)	70 m	June 6	12:00	318.4	forest
Yosemite National Park (38 °N., 119 °W.)	2500 m	June 11	12:00	316.4	forest

*Adjusted to 33 °N.

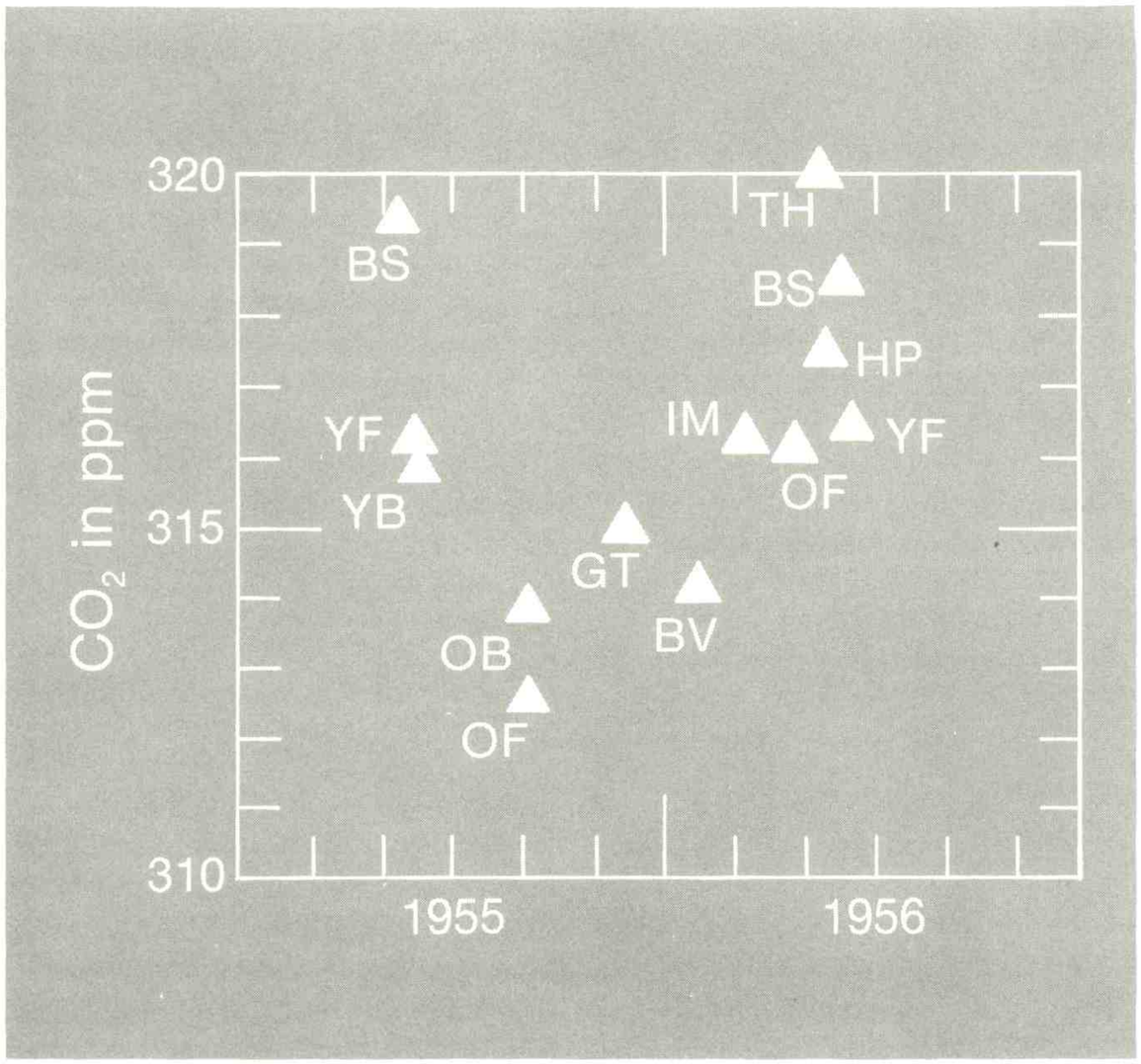


Figure 4. Minimum concentrations of atmospheric CO_2 at various sites near the west coast of the United States during 1955 and 1956. Concentrations were determined manometrically from liquid nitrogen temperature condensates. Sites are identified as follows: BS, Big Sur; YF, Yosemite forest; YB, Yosemite barren ground; OF, Olympic forest; OB, Olympic beach; GT, Gulf of Tehuantepec; BV, Borrego Valley; IM, Inyo Mountains; OP, Organ Pipe; HP, Howard Pocket; TH, Telephone Hill.

Also, as a single exception to the above site distribution, Table 1 includes the minimum CO_2 concentration from a suite of samples collected aboard ship off the coast of Nicaragua near 9°N, in 1955. This minimum has been adjusted upward by 0.5 ppm on the basis of the average latitudinal gradient found by Bolin and Keeling (1963) between 9° and 33°N for the appropriate month of sampling.

The continuous measurements obtained at La Jolla from 1957 to 1962 are highly contaminated by local and regional urban sources of CO_2. Even the daily minima, which usually occurred during sea breezes, vary considerably depending on the history of the air. Highest values typically occurred when the air had previously passed near the city of Los Angeles to the northwest. To reduce further the influence of contamination, the daily minima were arranged into calendar weeks, and weekly minima were identified. As noted already in 1960 (Keeling, 1961), these weekly minima scatter much less than the dailies. Also, unlike the dailies their monthly means show a consistent trend suggestive of uncontaminated air.

These monthly means are listed in Table 2 and plotted in Fig. 5. One entry, for June 1958, is omitted from further consideration because only one weekly minimum was obtained that month. Also, as indicated in the table, a few obviously contaminated minima were omitted in assembling the monthly means. The means for April 1958 through March 1960 have been published (Keeling, 1961). These, and previously unpublished data for 1957, 1960, and 1962, are here reported according to the 1974 manometric CO_2 mole fraction scale, using formulas for conversion from an adjusted index scale (Keeling et al., 1976a).

The manometric and infrared data (Figs. 4 and 5) display a seasonal variation similar to but of greater amplitude than that for Mauna Loa. The

Table 2. Mean of weekly minimum concentration of atmospheric carbon dioxide (relative to dry air) by infrared gas analysis, for Scripps pier, La Jolla, California, at 33°N, 117°W, elevation 8 m

Average date	No. of weekly minima included	Average observed CO_2 concentration (ppm)
1957–Mar. 24		
Apr. 17	4	315.91
May 16	4	315.92
June 16	4	315.43
Sept. 12	5	310.16
Oct. 4	2	311.15
1958–Apr. 21	3*	316.72
May 16	3	317.71
June 22	1	319.08*
July 17	5	313.52
Aug. 18	4	310.83
Sept. 13	4	311.08
Oct. 19	3*	313.17
Nov. 20	5	315.64
Dec. 20	4	316.76
1959–Jan. 19	3*	317.38
Feb. 14	4	316.89
Mar. 18	5	317.89
Apr. 18	4	317.52
May 17	4	317.52
June 14	4	317.65
July 14	5	313.95
Aug. 16	4	310.52
Sept. 12	4	311.14
Oct. 13	5	314.58
Nov. 8	2*	316.19
Dec. 16	5	315.95
1960–Jan. 16	3*	317.19
Feb. 14	4	317.94
Mar. 17	5	317.95
Apr. 16	4	319.82
May 12	3	320.57
June 12	2	318.58
1962–Mar. 25	2	320.43
Apr. 13	4	320.06
May 6	2	321.07

*One weekly minimum omitted from average.

Figure 5. Monthly averages of the weekly minimum atmospheric CO_2 concentration at La Jolla, California. Concentrations were determined with a nondispersive infrared gas analyzer.

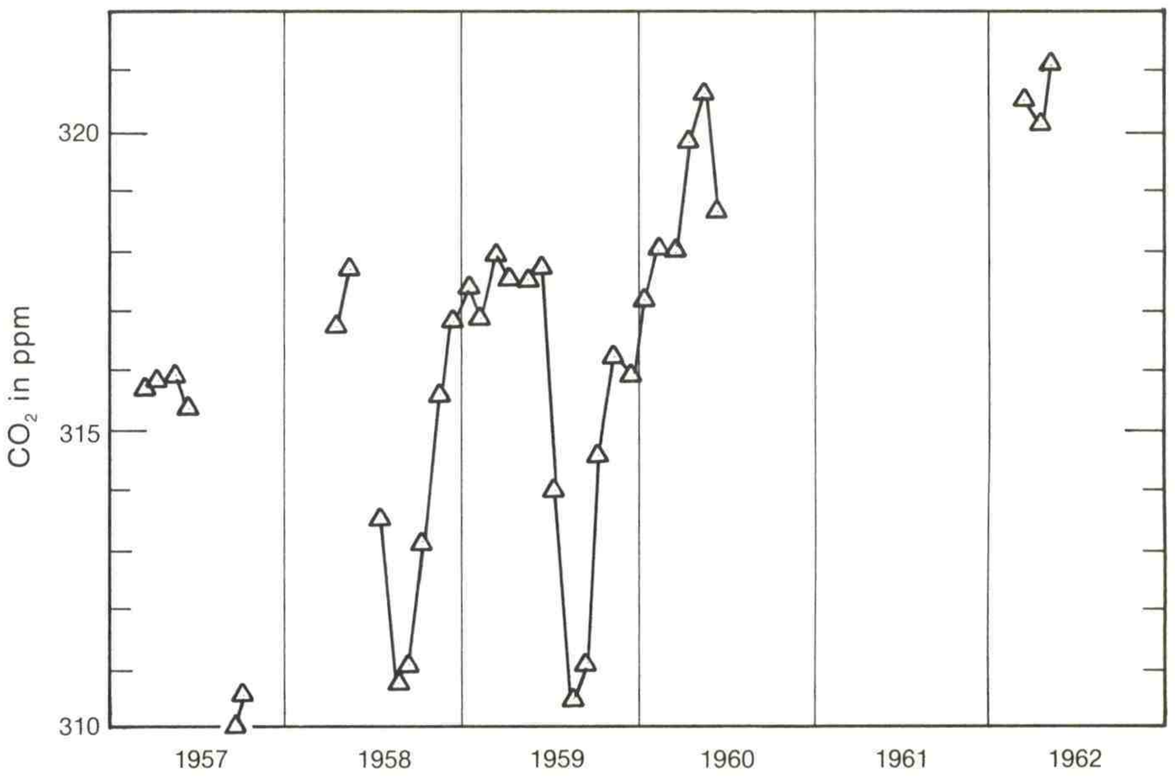


Table 3. Adjusted manometric data, 1955–1956, and infrared gas analyzer data, 1957

Location	Month and Year	Concentration (ppm)		Departure from linear trend
		Adjusted to 15th of the month	Adjusted for seasonal variation	
Big Sur State Park	May 1955	319.36*	316.40	3.46
Yosemite National Park at 3000 m	June	315.05	313.72	.72
Olympic National Park at 170 m	Sept.	312.81*	317.16	3.98
Gulf of Tehuantepec	Dec.	315.36	313.94	0.59
Borrego Valley	Feb. 1956	314.06	312.92	−0.55
Inyo Mountains	Mar.	316.35	314.75	1.23
Organ Pipe Cactus National Monument	Apr.	315.91	313.23	−0.35
Howard Pocket	May	317.42	314.46	0.82
Telephone Hill	May	320.06*	317.10	3.46
Big Sur State Park	June	317.74*	316.41	2.71
Yosemite National Park at 2500 m	June	316.08	314.75	1.05
La Jolla	Mar. 1957	315.46	313.86	−0.36
La Jolla	Apr.	315.85	313.17	−1.11
La Jolla	May	315.94	312.98	−1.35
La Jolla	June	315.51	314.18	−0.21
La Jolla	Sept.	310.26	314.61	0.16
La Jolla	Oct.	312.03	314.47	−0.04

*Judged to be contaminated.

seasonal variation, however, is clearly evident only for the La Jolla data because the 1955–1956 manometric data involve so many missing months and extend over less than two years.

Several of the manometric data appear to be inconsistent with the seasonal trend. That the two CO_2 minima for Big Sur State Park may be too high, both in 1955 and 1956, is not surprising because sampling was done in a public campground where daytime automobile traffic may have produced several ppm of contamination. Also, the CO_2 minimum for Telephone Hill, Arizona, seems too high relative to Howard Pocket, but there is no obvious reason, since the site was in a remote forest north of the Grand Canyon. Finally, the pair of CO_2 minima for the Olympic National Park agree with each other but are both considerably higher than had been expected for the month of sampling on the basis of the La Jolla data, again for no obvious reason.

Before deciding on the disposition of these possibly contaminated values, an adjustment of the data was made to the 15th of the month of sampling in order to reduce scatter resulting from uneven spacing in time. The adjustments were made following a procedure described previously (Keeling et al., 1976b). Specifically, the individual monthly concentrations $X(t)$, in ppm, where t denotes the time in years after January 1, 1955, were fit by the method of least squares to an oscillatory-linear trend function:

$$X(t) = Q_1 \sin 2\pi t + Q_2 \cos 2\pi t + Q_3 \sin 4\pi t + Q_4 \cos 4\pi t + Q_5 + Q_6 t \quad (1)$$

The four possibly contaminated data mentioned above were tentatively omitted from the computation. The parameters of best fit were found to have the values:

$$\begin{aligned} Q_1 &= 2.86883 \text{ ppm} & Q_4 &= 6.64806 \text{ ppm} \\ Q_2 &= 0.879716 \text{ ppm} & Q_5 &= 312.684 \text{ ppm} \\ Q_3 &= -1.51123 \text{ ppm} & Q_6 &= 0.6954 \text{ ppm yr}^{-1} \end{aligned} \quad (2)$$

On the basis of equations (1) and (2), the data, including the tentatively rejected values, were adjusted to the 15th of the month as listed in Tables 3 and 4. Next, the data were seasonally adjusted using the first four terms of

Table 4. Comparison of atmospheric carbon dioxide concentrations at La Jolla with the long-term trend in concentration at MLO

Month	Concentration at La Jolla*	Trend at Mauna Loa**	Difference
Apr. 1958	316.54	315.34	1.20
May	317.73	315.40	2.33
June	—	315.47	—
July	313.72	315.53	−1.81
Aug.	310.96	315.59	−4.63
Sept.	311.15	315.64	−4.49
Oct.	312.82	315.69	−2.87
Nov.	315.30	315.74	−0.44
Dec.	316.67	315.78	0.89
Jan. 1959	317.42	315.83	1.59
Feb.	316.89	315.88	1.01
Mar.	317.79	315.93	1.86
Apr.	317.43	315.99	1.44
May	317.56	316.05	1.51
June	317.57	316.13	1.44
July	313.85	316.20	−2.35
Aug.	310.57	316.29	−5.72
Sept.	311.24	316.38	−5.14
Oct.	314.75	316.46	−1.71
Nov.	316.72	316.55	0.17
Dec.	315.93	316.63	−0.70
Jan. 1960	317.20	316.70	0.50
Feb.	317.94	316.77	1.17
Mar.	317.88	316.84	1.04
Apr.	319.79	316.90	2.89
May	320.52	316.96	3.56
June	318.34	317.01	1.33
Mar. 1962	320.08	318.37	1.71
Apr.	320.13	318.43	1.70
May	321.02	318.49	2.53

*Adjusted to the 15th of the month.
**Determined for the 15th of the month from a spline fit of the seasonally adjusted monthly means for 1958–1976, inclusive.

equation (1), and the resulting trend data were plotted as shown in Fig. 6. From this plot it becomes clear that the questionable values, shown as crosses, should be rejected. A statistical computation bears this out: the four values differ by factors of 3.4 to 4.9 times the root mean square departure of the remaining 13 data points for 1955–1957 with respect to equations (1) and (2).

The next step was to establish from overlapping data the difference in seasonal variation and long-term trend for Mauna Loa and La Jolla. First, from the entire Mauna Loa record of monthly averages from March 1958 through December 1976, the average seasonal variation and seasonally adjusted trend for that station were established.

Several methods have been used previously to separate the long-term trend at Mauna Loa from the associated seasonal variation (Bacastow, 1977). Here I have chosen to express the trend by a cubic spline function (Reinsch, 1967) and the seasonal variation as an average of the monthly mean concentrations after subtracting the trend. Since the two features are not uniquely separable, an iterative procedure was used. First, an estimate of the long-term trend was found assuming a linear increase with time, and a preliminary estimate of the seasonal variation was obtained. Then consistent with this seasonal variation, the original monthly values were seasonally adjusted, and a cubic spline function was passed through the adjusted data points. Further iterations were carried out until the adjusted values approached constancy. This convergence was rapid, and because of the high regularity of the seasonal variation, the seasonal variation found was similar to that found by using a least squares fit based on equation (1).

Next, as shown in Table 4, the long-term trend for Mauna Loa, expressed as a spline function, was compared with the La Jolla data adjusted to the 15th of each month. For the relatively short period of the comparison it seems reasonable to assume that the long-term trends for Mauna Loa and La Jolla differ by only a constant. On the basis of the monthly differences between the Mauna Loa trend and the La Jolla data (last column of Table 4), mean differences between stations were determined for each month. The sum of these differences is −0.42 ppm; that is, the La Jolla weekly minima, on average, are lower by that amount than the Mauna Loa trend. Since the expected latitudinal difference between stations according to aircraft and shipboard data analyzed by Bolin and Keeling (1963) is −0.20 ppm, the weekly minima agree closely with expectations in spite of the high degree of selection involved in obtaining them. Evidently, the large irregular variations in the original La Jolla record are almost solely owing to high values, probably produced by urban sources.

Next, from the west coast data, 1955–1962, a long-term trend and an average seasonal variation were found in the same manner as that just

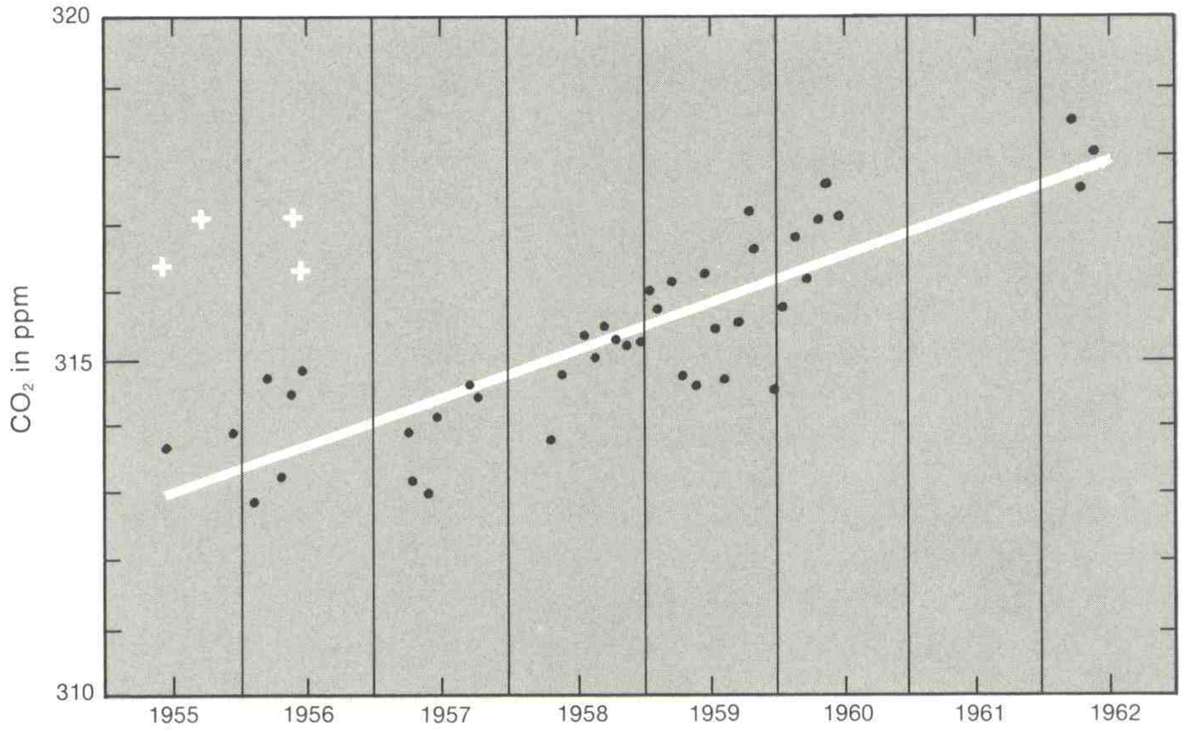


Figure 6. Long-term trend in the minimum concentration of atmospheric CO_2 near the west coast of the United States based on the data of Figs. 4 and 5 after adjustment of each point to the 15th of the month of observation. The seasonal variation, expressed by the first four terms of equation (1) as a harmonic function with 6- and 12-month terms, was subtracted to obtain seasonally adjusted concentrations shown as dots. Possibly contaminated data are indicated by crosses. The straight line is a least-squares best fit through the plotted points.

described for the Mauna Loa record. Because of the considerable gaps in the data, the trend in all iterations was assumed to be a straight line. The final trend, shown in Fig. 7, obeys the relation

$$X(t)_{\text{seasonally adjusted}} = Q_5 + Q_6 t \tag{3}$$

where

$$Q_5 = 312.592,\ Q_6 = 0.7167 \text{ ppm yr}^{-1} \tag{4}$$

and, again, $t = 0$ for January 1, 1955.

The corresponding seasonal variation, shown in the third column of Table 5, agrees closely with that obtained (see the second column) by comparing the La Jolla data for 1958–1962 with the Mauna Loa spline function trend. The only month where the agreement is possibly unsatisfactory is December which includes the data point from 9°N. This discrepancy does not appear to be significant, however, in view of the scatter of the other 1955–1956 data.

Evidently it makes little difference which seasonal variation is used in further analysis. Since the seasonal variation based on the entire data set from 1955 to 1962 results in slightly lower scatter, I chose this representation.

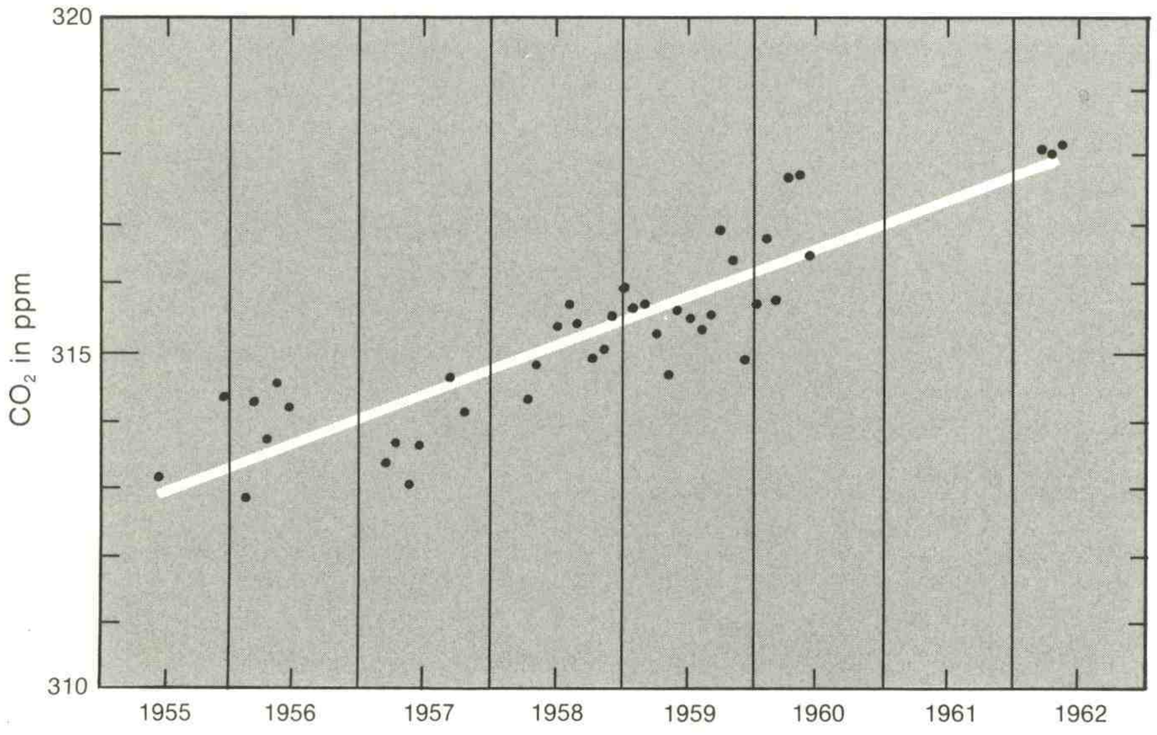
To express the comparison of the pre-1958 U.S. data with the Mauna Loa record, I have devised what I call "proxy" data. My goal is to produce, with the least interpretive adjustment, a set of monthly values valid for Mauna Loa for 1955 through 1957. On the basis of the difference between the seasonal variations for Mauna Loa and the west coast U.S. data for 1955–1962, with due regard for the average difference of 0.42 ppm between locations (Table 6 and Fig. 8), the west coast U.S. data were converted to equivalent Mauna Loa monthly means. In this way the scatter is included, and no judgment of the long-term trend is placed on these early measurements. The results are listed in Table 7 and plotted in Fig. 9. Finally, a long-term trend line was established for the seasonally adjusted Mauna Loa record including these proxy data (Table 8 and Fig. 10). The previous iterative method was again used to separate the trend from the seasonal variation. Since the Mauna Loa record already includes 19 years of direct data, the new data have a negligible effect on the computed seasonal variation for Mauna Loa, shown in the third column of Table 6. Also, since the spline function at any part of the record is

Table 5. Seasonal variation in atmospheric carbon dioxide near U.S. west coast determined by summing monthly concentrations with the long-term trend removed

Month	La Jolla 1958–1962*	West Coast 1955–1962**	Difference
Jan.	1.47	1.46	.01
Feb.	1.51	1.22	.29
Mar.	1.96	2.05	−.09
Apr.	2.23	2.18	.05
May	2.90	2.87	.03
June	1.81	1.87	−.06
July	−1.66	−1.70	.04
Aug.	−4.76	−4.79	.03
Sept.	−4.40	−4.37	−.03
Oct.	−1.87	−2.11	.24
Nov.	0.28	0.28	.00
Dec.	0.52	1.04	−.52
			$\sigma =$ .20

*Monthly means of the fourth column entries of Table 4 normalized by adding 0.42 ppm to each value.

**Based on comparison with the linear trend for the west coast of the United States, expressed by equation (3).



sensitive only to nearby data, the inclusion of the early data affects the trend line only near its former beginning in 1958.

The small difference of 0.42 ppm between the La Jolla and Mauna Loa trends where they overlap suggests that the La Jolla weekly minima are not biased, but actually one need not make this assumption in accepting the proxy data, provided that the original west coast minima for 1955–1957 have the same bias as those for 1958–1962. This appears reasonable for 1957 because the data are for the same location as the 1958–1962 data and were selected in the same way. Indeed, as can be seen from Fig. 10, the seasonally adjusted proxy data for 1957 appear to be consistent with the direct data (1958 and later) both as to scatter and trend. Thus one is encouraged to accept the 1957 proxy data as reliable.

One is less confident that the 1955–1956 proxy data are unbiased. Their scatter is greater, and a backward extrapolation of the relatively steep trend line for 1958 suggests that they could be too high by as much as 1.0 ppm. On the other hand, the rise and fall in trend indicated by the spline function for 1955–1956 (Fig. 10) is similar to abrupt changes in trend that have occurred more recently, for example in 1973. Thus one cannot easily decide that the proxy data for 1955–1956 are wrong.

We are probably expecting too much to consider that these early data might tell us something about a change in the long-term trend. These data are better regarded as the kind of "baseline" data which Revelle had in mind to obtain during the IGY. At least they add evidence that no very unusual circumstances influenced the atmospheric CO_2 record immediately before systematic data collecting began during the IGY.

Figure 7. Long-term trend in atmospheric CO_2 for the west coast of the United States, as in Fig. 6 except that the seasonal variation was determined as an average of the monthly average concentrations after subtracting a linear estimate of the trend. Data identified in Fig. 6 as possibly contaminated are not shown.

Month	West Coast*	Mauna Loa	Difference
Jan.	1.02	–0.15	–1.17
Feb.	0.80	0.53	–0.27
Mar.	1.63	1.21	–0.42
Apr.	1.76	2.27	0.51
May	2.45	2.74	0.29
June	1.45	2.24	0.79
July	–2.12	0.87	2.99
Aug.	–5.12	–1.12	4.09
Sept.	–4.79	–2.68	2.11
Oct.	–2.53	–2.99	–0.46
Nov.	–0.14	–1.96	–1.82
Dec.	0.62	–0.97	–1.59

*Third column of Table 5 reduced by 0.42 ppm.

Table 6. Seasonal variation in atmospheric carbon dioxide — comparison of west coast United States, 1955–1962, with MLO, 1958–1975

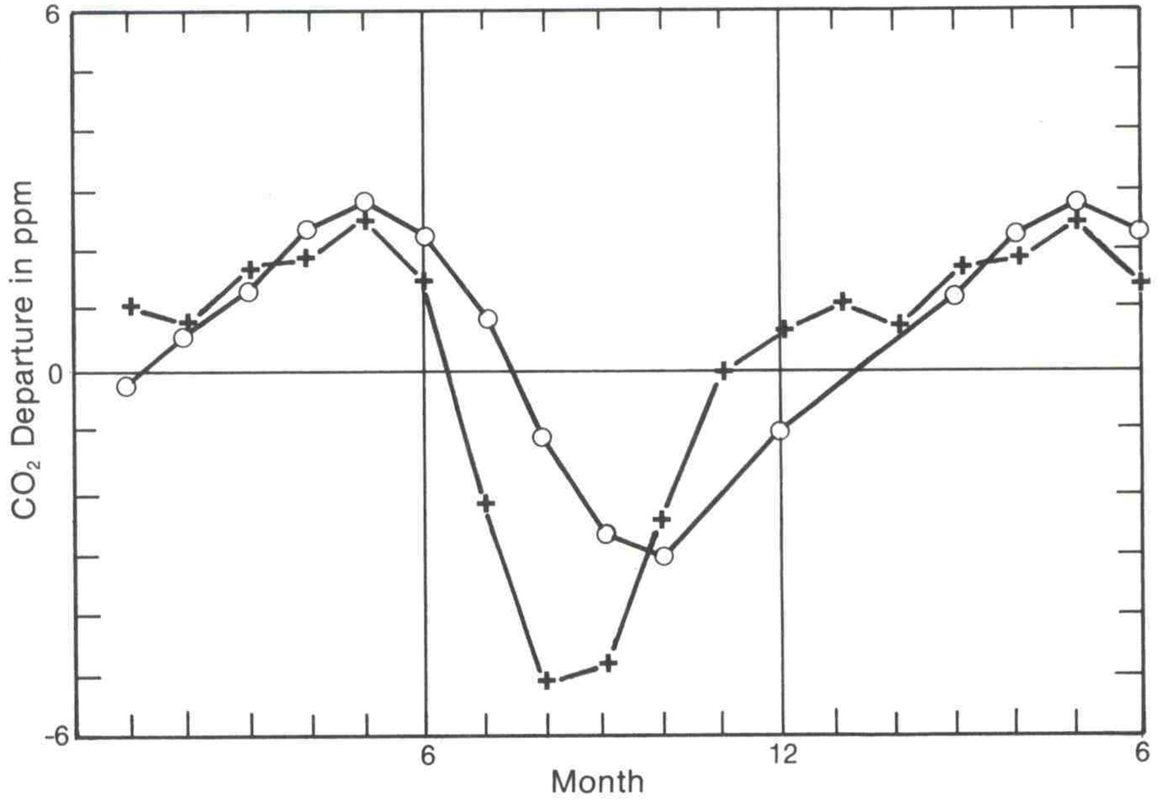


Figure 8. Atmospheric CO_2 as a function of the month of the year determined as a departure of the monthly mean concentration from the long-term trend for Mauna Loa. Data are shown for MLO by dots, and for the west coast of the United States by crosses. Months 1 to 6 (January through June) are plotted twice to reveal the seasonal patterns more fully.

Figure 9. Trend in atmospheric CO_2 concentrations at MLO. The dots indicate the monthly average concentration. Data in 1955, 1956, and 1957 are proxy data based on observations for the west coast of the United States. The oscillatory curve is a spline fit of the sum of the long-term trend and the average seasonal variation determined as in Fig. 7.

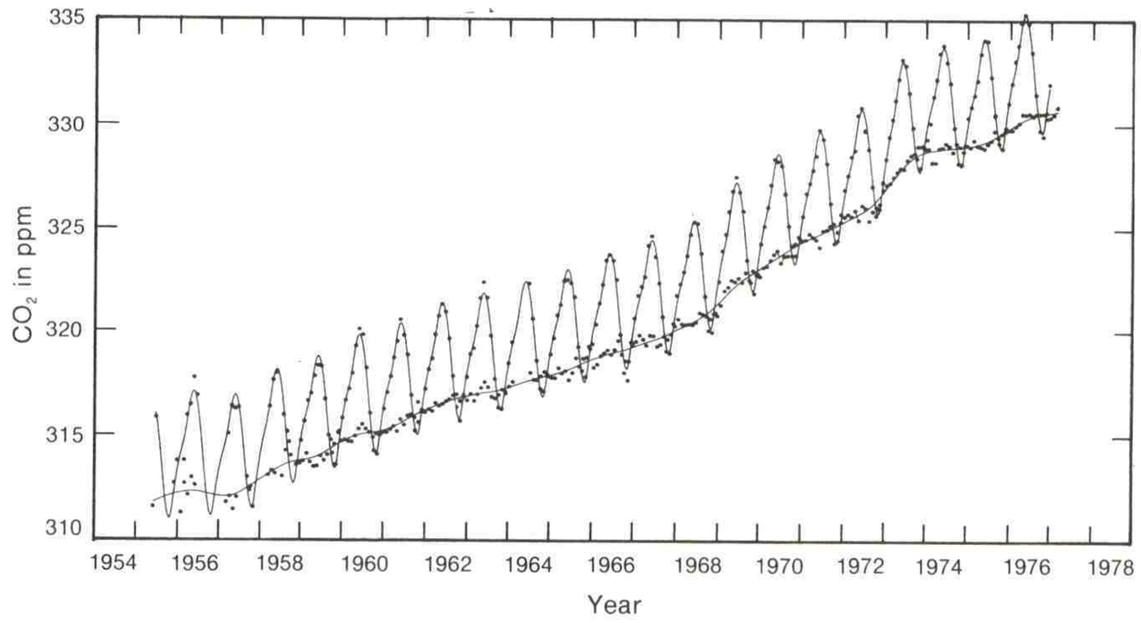


Table 7. Monthly average concentration of atmospheric carbon dioxide (ppm) at MLO expressed according to the 1974 manometric mole fraction scale

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1955						315.84*						313.77*
1956		313.79*	315.93*	316.42*	317.71*	316.87*						
1957			315.04*	316.36*	316.23*	316.30*			312.37*	311.57*		
1958			316.33	317.59	317.93	317.71	315.92	315.15	314.02	312.83	313.64	314.71
1959	315.62	316.59	316.94	317.77	318.29	318.24	316.67	314.96	314.12	313.58	315.14	315.77
1960	316.62	317.16	317.90	319.21	320.02	319.74	318.15	316.00	314.23	314.07	315.04	316.19
1961	316.97	317.74	318.63	319.43	320.47	319.71	318.78	316.84	315.16	315.56	316.14	317.13
1962	318.06	318.59	319.74	320.63	321.21	320.83	319.55	317.75	316.27	315.62	316.84	317.70
1963	318.80	319.08	320.15	321.49	322.25	321.50	319.67	317.61	316.25	316.17	317.01	318.36
1964	319.37					322.19	320.49	318.48	317.13	317.02	317.84	318.78
1965	319.55	320.65	321.15	322.31	322.35	322.19	321.53	319.13	317.99	317.70	319.15	319.27
1966	320.22	321.23	322.13	323.30	323.57	323.29	322.36	319.71	317.89	317.54	319.36	320.51
1967	321.60	322.03	322.50	324.00	324.46	323.46	322.19	320.57	318.91	318.81	320.24	321.59
1968	322.15	322.73	323.50	324.52	325.11	325.06	323.62	321.55	319.89	319.80	320.73	322.25
1969	323.73	324.53	325.62	326.58	327.24	326.53	325.63	323.28	322.21	321.67	322.61	324.07
1970	324.91	325.81	326.85	328.07	327.97	327.77	326.44	324.92	323.49	323.50	324.34	325.39
1971	326.46	326.93	327.56	328.23	329.51	329.04	327.87	326.00	324.06	324.20	325.48	326.62
1972	327.30	328.20	328.50	330.22	330.58	329.48	328.56	326.77	325.39	325.72	326.97	328.09
1973	329.16	330.02	330.95	331.95	332.85	332.58	331.30	329.64	328.12	327.67	328.69	329.05
1974	329.84	331.13	331.93	333.16	333.53	332.73	331.77	329.63	327.87	327.84	328.77	330.12
1975	330.64	331.20	331.89	333.14	333.78	333.75	332.06	330.25	328.85	328.58	329.61	330.82
1976	331.75	332.81	333.55	334.62	335.01	334.58	333.22	331.24	329.48	329.19	330.35	331.72

*Proxy data.

Figure 10. Long-term trend in atmospheric CO_2 concentration at MLO. The plot is the same as Fig. 9 except that the seasonal variation has been subtracted out.

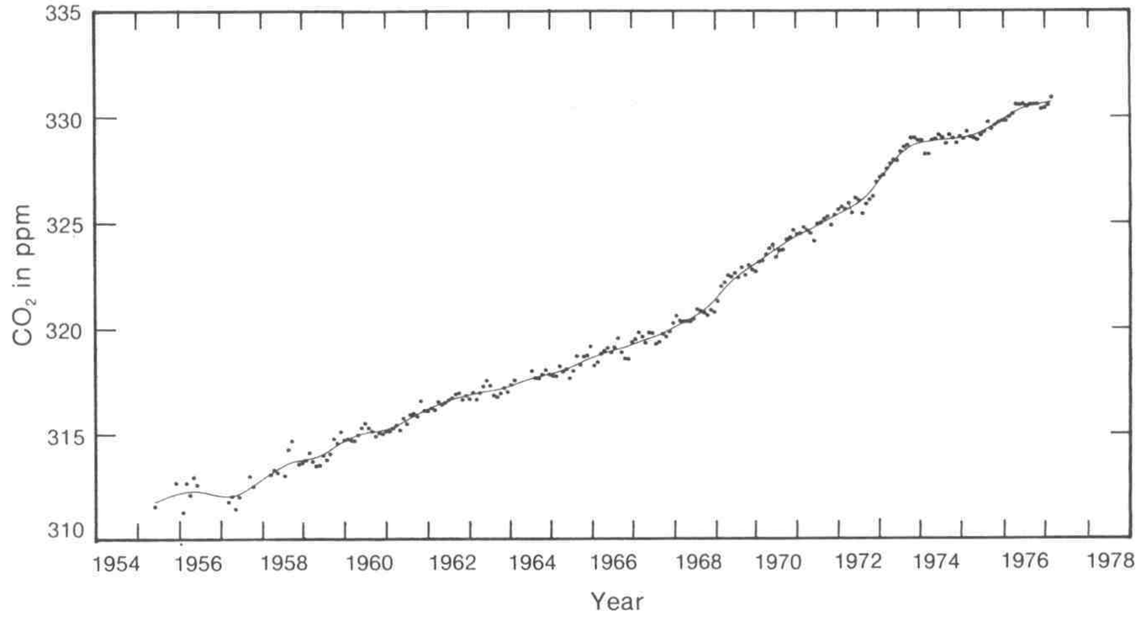


Table 8. Seasonally adjusted concentration of atmospheric carbon dioxide (ppm) at MLO for the 15th of each month expressed according to the 1974 manometric mole fraction scale*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1955						313.81	313.88	313.96	314.03	314.10	314.16	314.21
1956	314.25	314.28	314.31	314.33	314.34	314.33	314.31	314.28	314.24	314.21	314.17	314.13
1957	314.11	314.09	314.09	314.12	314.16	314.22	314.30	314.39	314.50	314.60	314.71	314.83
1958	314.94	315.05	315.15	315.26	315.36	315.46	315.55	315.63	315.69	315.74	315.77	315.79
1959	315.82	315.85	315.88	315.93	315.99	316.07	316.16	316.26	316.37	316.48	316.58	316.67
1960	316.76	316.83	316.90	316.96	317.01	317.05	317.08	317.11	317.13	317.15	317.18	317.22
1961	317.27	317.33	317.40	317.48	317.56	317.66	317.75	317.84	317.94	318.02	318.10	318.18
1962	318.25	318.32	318.39	318.45	318.51	318.57	318.63	318.68	318.73	318.76	318.80	318.84
1963	318.87	318.91	318.94	318.98	319.01	319.03	319.05	319.08	319.12	319.16	319.21	319.27
1964	319.33	319.39	319.44	319.50	319.56	319.61	319.66	319.70	319.74	319.78	319.82	319.86
1965	319.90	319.95	320.00	320.06	320.12	320.20	320.28	320.36	320.43	320.50	320.57	320.63
1966	320.69	320.75	320.80	320.85	320.90	320.94	320.98	321.03	321.08	321.13	321.19	321.25
1967	321.32	321.38	321.43	321.48	321.54	321.59	321.65	321.73	321.80	321.89	321.97	322.06
1968	322.14	322.22	322.30	322.39	322.47	322.57	322.68	322.80	322.93	323.08	323.24	323.42
1969	323.60	323.78	323.94	324.10	324.24	324.38	324.50	324.62	324.73	324.83	324.94	325.05
1970	325.16	325.28	325.38	325.49	325.60	325.71	325.82	325.93	326.03	326.13	326.22	326.30
1971	326.38	326.45	326.52	326.60	326.68	326.77	326.86	326.95	327.04	327.13	327.22	327.30
1972	327.39	327.47	327.56	327.65	327.76	327.89	328.03	328.20	328.39	328.59	328.81	329.02
1973	329.23	329.45	329.63	329.82	329.99	330.14	330.27	330.37	330.45	330.50	330.54	330.57
1974	330.59	330.62	330.64	330.66	330.68	330.69	330.70	330.72	330.73	330.75	330.78	330.81
1975	330.85	330.90	330.96	331.03	331.11	331.20	331.29	331.40	331.50	331.61	331.72	331.82
1976	331.93	332.02	332.10	332.17	332.23	332.27	332.31	332.34	332.37	332.40	332.44	332.47

*Entries before March 1958 are based on proxy data.

EPILOGUE

Since these proxy data for Mauna Loa were originally obtained from sampling sites presumed to be disturbed locally, it seems paradoxical that truly reliable data were not obtained by investigators who deliberately sought undisturbed locations to obtain baseline CO_2 data. As Bray (1959) noted, several nineteenth-century investigators, who claimed analytical analyses accurate to 1.0 ppm, made serious attempts to obtain data representative of locally undisturbed air. I conclude that these scientists, perhaps from an inadequate knowledge of meteorology and atmospheric motion, underestimated the difficulty in finding truly uncontaminated sites. When their analytical and sampling methods failed to give them the high reproducibility that they thought they had attained, they ascribed the scatter to the atmosphere itself and not to weaknesses in their methods.

In the first half of this century declining interest in atmospheric CO_2 was kept alive by only a few investigators. The most notable was Kurt Buch of Finland, who concluded after many years of study that the CO_2 concentration varied systematically with air mass. His claims (Keeling and Bacastow, 1977) that high arctic air had concentrations in the range of 150 to 230 ppm, north and middle Atlantic air, 310 to 345 ppm, and tropical air, 320 to 370 ppm, strongly influenced preparations for the IGY CO_2 program, especially the Scandinavian program, which he initially supervised. When from inadequate chemical and sampling techniques the Scandinavian pre-IGY program produced CO_2 concentrations in the same range as previous data, these new data were readily justified as resulting from different properties of the air masses passing over the sampling sites (Fonselius et al., 1956).

How long would the findings of the Scandinavian CO_2 network have been accepted if new manometric and infrared studies had not been begun? The Scandinavian data continued to appear in the back pages of *Tellus* until after the infrared analyzer results for Mauna Loa and other locations had been presented at the International Union of Geodesy and Geophysics meeting in Helsinki in 1960. But reform was on the way. Walter Bischof in 1959 had assumed responsibility for Swedish measurements. He soon became suspicious of their variability on the basis of discrepancies between ground-level and aircraft sampling (Bischof, 1960). Also, he had begun to use an infrared gas analyzer. With this abandonment of the traditional chemical method of analysis, the Swedish CO_2 data ceased to include unreasonably low CO_2 values. Then in 1960 Bischof turned to investigating suspiciously high values using aircraft to verify ground-level data. Probably within a year or two, considerably more accurate systematic data would have begun to appear from the Scandinavian program.

But it is far from certain that a Scandinavian site as reliable as MLO would have soon been established. The Scandinavian investigators lacked the funds to embark on an ambitious continuous sampling program at a remote station. Many years might have passed before data of the quality of the Mauna Loa record would have been forthcoming. Indeed, high costs almost caused MLO to close down in 1964 in spite of its obvious value as a CO_2 sampling site. Disruptions under that threat of closure account for a serious gap in the CO_2 record during the early part of 1964. Problems of cost also contributed to the decision to shut down the South Pole continuous-analyzer program at the end of 1963. If these two remarkable sites had not already been established and yielded high-quality data before 1964, it is likely that the stimulus to start work at such remote sites would not have occurred for at least several more years because of financial impediments. Thus it was a fortunate circumstance that Wexler and Revelle in 1956 saw the value of using the IGY organization to check out the possibility of near constancy in atmospheric CO_2 by inaugurating a precise sampling program. We all recognize now that such a program is essential if we are to document adequately the rise in atmospheric CO_2.

ACKNOWLEDGMENTS

Many people who could not be included in the historical discussion contributed to the planning of atmospheric carbon dioxide measurements at Mauna Loa. I am particularly indebted to Oliver Wulf, U.S. Weather Bureau scientist stationed at the California Institute of Technology in 1955 and 1956. Wulf first brought my manometric work to the attention of Dr. Wexler. I am also indebted to Paul Humphrey, Dr. Wexler's assistant, who coached me on making the best use of the short time I would have to talk with Wexler. Humphrey later devoted many hours to coordinating funding and logistics involved in setting up CO_2 research at Mauna Loa.

In addition, I am indebted to Kenyon George, engineer of the Applied Physics Corporation, Pasadena, California. George patiently replied to my detailed questions during 1956 about the performance characteristics of his firm's nondispersive infrared gas analyzer. He was not himself convinced that atmospheric CO_2 could be determined by infrared analysis to the accuracy I sought, but his frank answers and total lack of bias provided sound arguments in favor of trying out the infrared method during the IGY.

I also owe thanks to John Miller, present director of MLO, who suggested this article and allowed me time to complete it, and to Robert Bacastow, who devised the computer programs that executed many of the computations of this paper and who offered valuable criticisms. Financial support for the work described was by the Climate Dynamics Program of the U.S. National Science Foundation under grants ATM76-23053 and ATM77-25141.

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ATMOSPHERIC TRITIUM SAMPLING ON MAUNA LOA

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OUTLINE OF SCIENTIFIC EFFORT

The Tritium Laboratory of the University of Miami developed a technique for simultaneous sampling of tritiated water vapor (HTO) and tritium gas (HT) in 1968. The technique has been described fully elsewhere (Östlund and Mason, 1974) and will only be summarized here. A 1- to 2-liter/min air flow from a diaphragm pump is mixed with 1‰ of tritium-free hydrogen. The mixture is passed through a trap of 300 g of molecular sieve which absorbs all water species (H_2O, HTO, etc.) and then into a trap of 100 g of palladium-coated molecular sieve. This trap oxidizes the carrier hydrogen plus the ambient species (H_2, HT, etc.) and adsorbs the resulting water in situ. The traps are sent to Miami, where the samples are recovered by baking the traps under vacuum. The water samples are reduced to hydrogen gas and analyzed for tritium by low-level proportional gas counting. The mixing ratios of HT and HTO are calculated from the volume of air sampled, the amounts of water samples recovered, and the specific activity of the samples. The specific activity of the water vapor is also calculated, but that of the atmospheric hydrogen is not obtainable because of the dilution by carrier gas.

At the inception of the program it was recognized that data from remote sites would be helpful in establishing the global backgrounds of HT and HTO. Fairbanks, Alaska, was chosen as the first such site in 1970, in 1971, Mauna Loa, Hawaii, was added, and in 1975, Baring Head, New Zealand.

The data obtained from Mauna Loa have confirmed the value of remote sampling stations. Since 1971, only one incident of apparently local contamination has occurred. This event, between February and March 1972, was an increase in the local HT mixing ratio by a factor approaching 2. It has never been explained. In late 1973 Mauna Loa data permitted the estimation of the HT seepage to the atmosphere from a series of three large underground thermonuclear explosions in the Arctic. A 15% HT mixing ratio increase appeared and persisted for several months following the detonations (Mason and Östlund, 1974). The long time series of data have enabled us to detect trends in the global HT budget (Östlund and Mason, 1974).

A new sampler has been installed with the capability of separating samples from the characteristic upslope and downslope wind regimes. It is actuated by a controller provided by the Health and Safety Laboratory of the U.S. Energy Research and Development Agency (ERDA).

FIELD OPERATIONS

The first tritium sampler at Mauna Loa Observatory (MLO) was a prototype, assembled on site by the first author with the capable assistance of Howard Ellis of MLO. It was located in a trailer adjacent to the main building. The visit was memorable to Östlund both for the experience of visiting Mauna Loa for the first time and also for the experience of seeing the areas around Hilo and finding the unique white wild strawberries that grow in the national park near Kilauea, just as tasty as the red ones in the author's old homeland, subarctic Sweden.

The sampler was relocated in the main building in 1972 and inspected there by the second author in the fall of that year. This was also a first visit and was memorable to Mason for the observing of lidar operations at night. The drive up at night, in the company of Ron Fegley and Howard Ellis, was most impressive.

The new sampler was sent to MLO in late 1975 and placed into manual mode operation by Howard Ellis. In April 1976 the second author met Herbert Volchok and Fred Wilson, both of the Health and Safety Laboratory, ERDA, for the installation of the upslope-downslope controller. Working in the wind and rain and helping to push the rented station wagon up the last slope to the observatory form Mason's chief memories of that visit.

Our association with MLO has been both fruitful and enjoyable. The unfailing efforts of the directors and staff, with particular recognition to Howard Ellis, are the mainstay of our operations at MLO.

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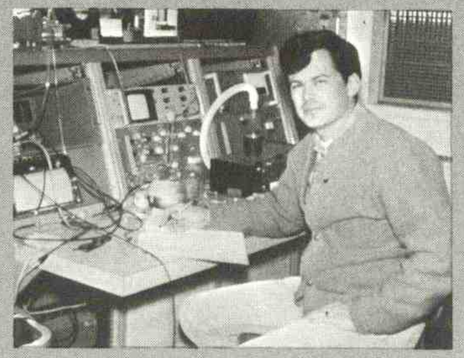
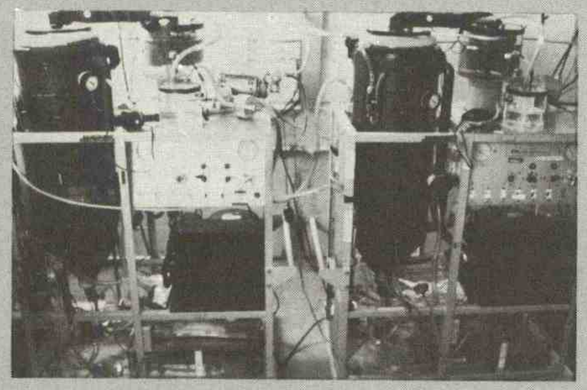
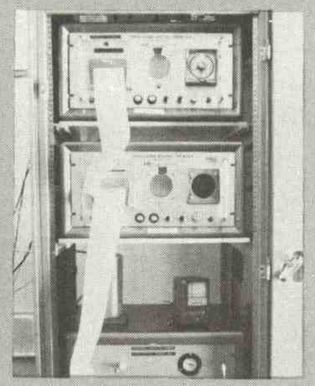
Aerosol measurements



Barry Bodhaine with flame photometer measuring concentration of aerosol particles at MLO, March 1972. An NRC Resident Research Associate at the time, Barry later became a staff member.

Measuring condensation nuclei with Gardner counters at Kilauea volcano during an eruption in 1969 (Bernard Mendonca and Janice Sias).



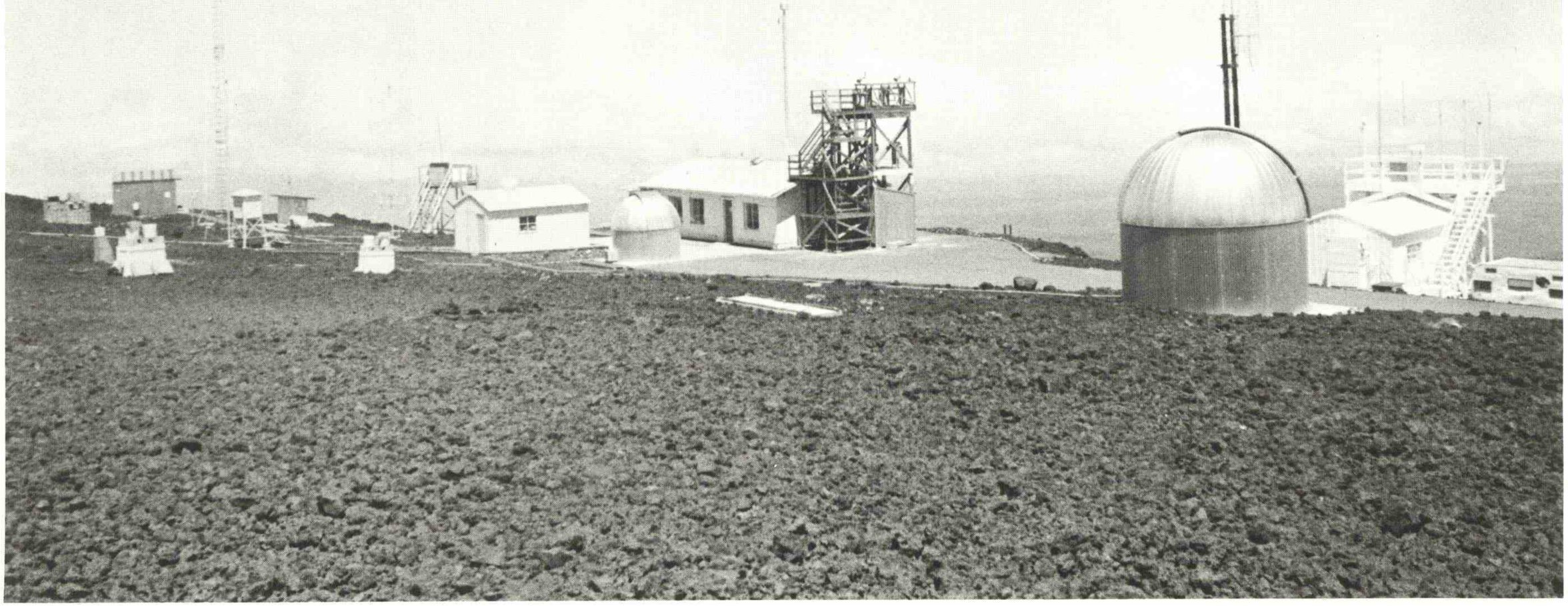


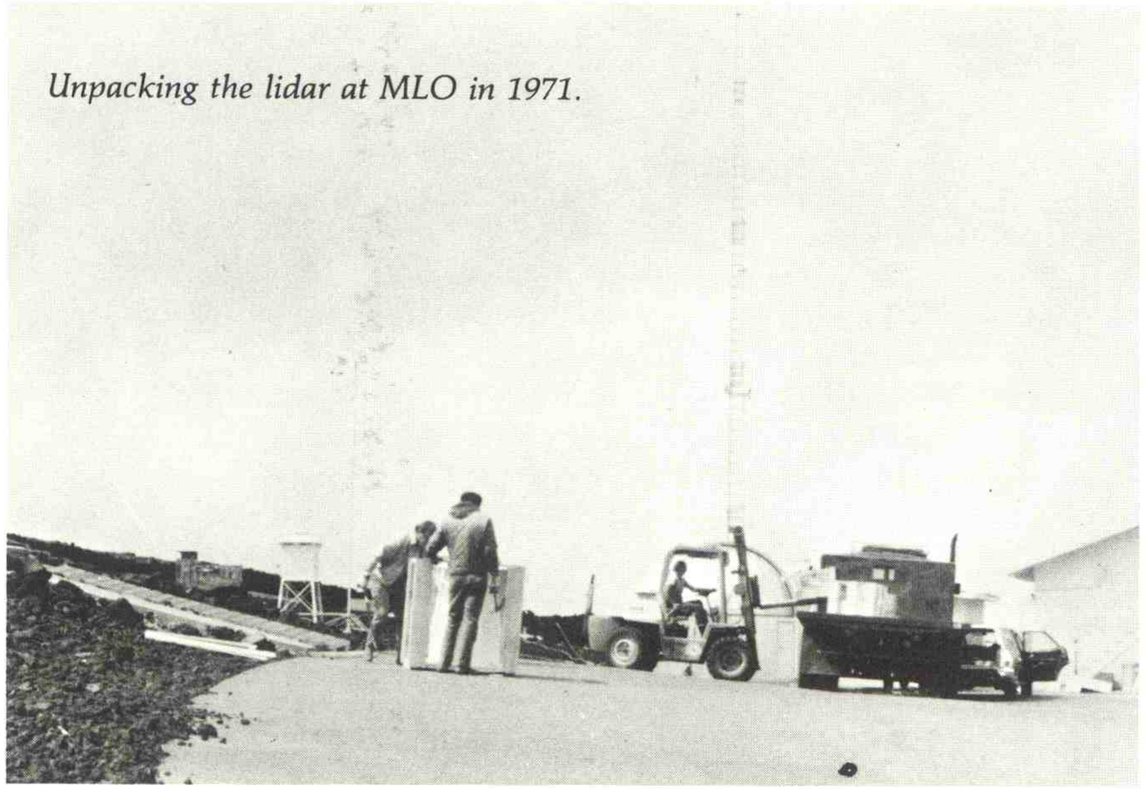
The "NCAR" acoustic ice nucleus counters.

Recording equipment for the ice nucleus counters, and the G.E. counter.

The buildings and trailers housing ice nucleus experiments in 1967. The trailers have since been removed. The building now contains a kitchen and living quarters for staff and visitors.

Mauna Loa Observatory in March 1978. Structures, left to right: Camera building, CO_2 sampling intake on 80-ft tower, instrument shelter, "clean rest rooms", precipitation sampler, AEC sampling platform, "Butler building" for storage, Dobson dome, main building, new solar radiation platform, lidar dome, "AEC building".





Unpacking the lidar at MLO in 1971.

LIDAR MEASUREMENTS AT MAUNA LOA OBSERVATORY

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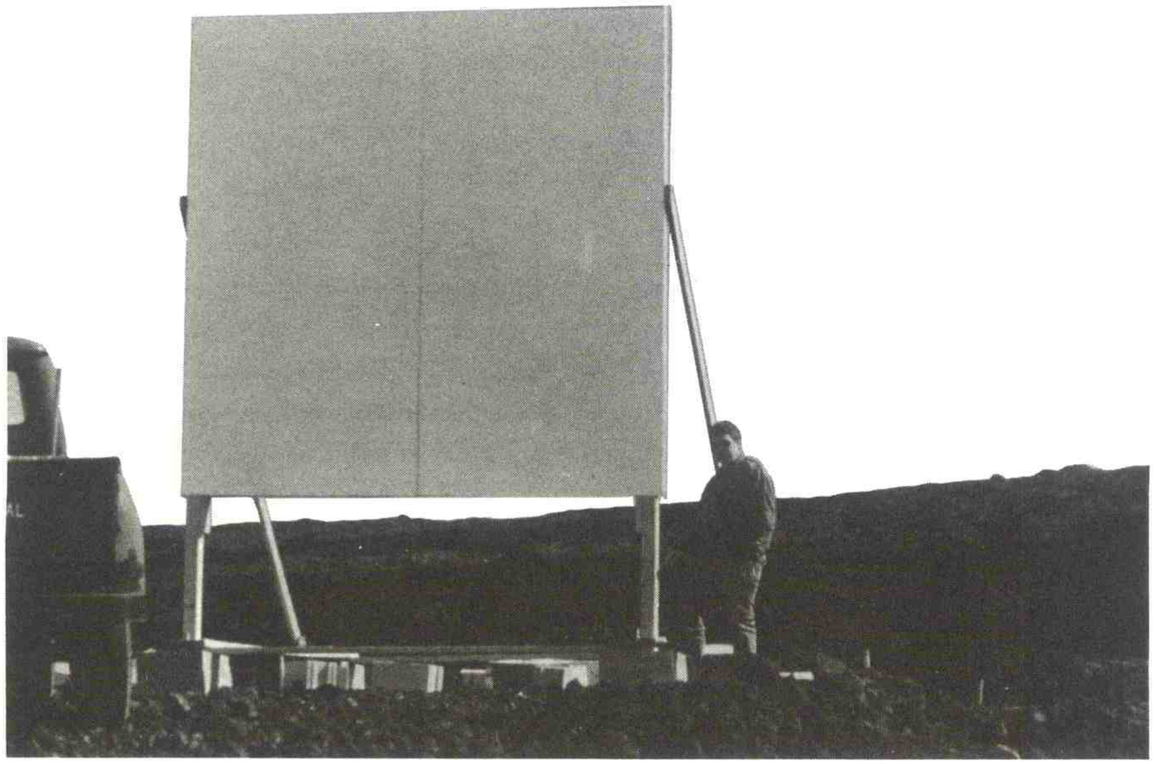
The Mauna Loa lidar was the first in the world to be used in the field for routine continuous observations. Its main purpose is to provide detailed information on stratospheric events in the northern tropics (Fegley and Ellis, 1975 a,b). An accurate time-history of optical backscatter in the lower stratosphere above Hawaii now exists for 1973–1978. From this parameter, simple optical models can be used to calculate other important parameters such as aerosol mass loading, number densities, and stratospheric extinction coefficient. Eventually, stratospheric aerosol size distribution information may also be obtainable using two-color lidar. These data from Mauna Loa Observatory (MLO), a prototype station, will eventually be supplemented with those from other stations in the GMCC network to provide valuable information for climate studies (Oliver, 1976). A secondary use of the lidar is to provide profiles of backscatter in the lower atmosphere to improve our understanding of aerosol and cloud dynamics in the tropical atmosphere.



Richard Proulx beside the target used for calibration and alignment of the lidar.

DESCRIPTION OF THE MLO LIDAR SYSTEM

The transmitter for the system is a ruby laser with nominal maximum pulse energy of 3 joules at 694.3-nm wavelength. Pulses are formed by Pockels-cell Q-switching; nominal pulse length is 30 ns. Beam divergence is less than 7 mrad; maximum pulse repetition rate is 4 per minute. An interference filter centered on the ruby wavelength, a converging lens, and a solid-state photodiode are located behind the rear laser reflector; the radiation sampled by the lidar system provides a measure of relative pulse energy as well as synchronizing pulses for the data display and processing components. The diode output is fed to an integrator and sample-and-hold circuit; the output, which is proportional to pulse energy, is measured by a digital voltmeter. The BCD information produced by the DVM is also picked up by the automatic data processing (ADP) system at read time and used in evaluation of the data.

Because of the tremendous dynamic range of lidar signals (100 dB or more), the system is equipped with two receivers. The long-range collector is a 40.6-cm diameter (16-in) catadioptric Cassegrain instrument. The collected light is collimated by an achromat lens of 50-mm diameter and 160-mm focal length. The collimated beam passes through an interference filter with 1-nm bandwidth before impinging on the cathode of a 14-stage photomultiplier tube with S–20 response. Output of the photodetector is coupled by 50-ohm coaxial cable to a low-pass filter with a 4-MHz cutoff frequency. The output from the filter is fed through a very short length of cable to the input port of the transient recorder. (This system was specially designed by one of the authors, Earl W. Barrett, hereafter referred to as E.W.B.)

To prevent overload of the PM tube by the near-field return, alternate dynodes of the tube were supplied with a blanking pulse which began at laser flash lamp firing time and ended at a time that could be preset by the operator. A time corresponding to a range of 7.5 km was approximately correct to avoid PM tube overload and also excessive signal clipping at the input of the digitizer.

The second receiver, intended for short-range and daytime use out to 7.5 km, uses a 10.2-cm-diameter (4-in) telescope of the same type, a 25-mm-diameter, 60-mm focal length collimating lens, and a 1-nm bandwidth interference filter. The detector is a 10 stage PM with S–20 response. No blanking pulse is applied to this tube; some overload does occur when full laser power is used. The output of this PM is fed to the digitizer through a low-pass filter of the same type as in the long-range receiver, but has a cutoff frequency of 9 MHz so that finer details of the return are preserved. Both PM housings are equipped with slots for neutral-density filters, so that the returns from the calibration and alignment target can be attenuated, or so the larger receiver can be used in the daytime. Control circuitry is provided to steer the synchronizing trigger pulses from the laser system and the power-measuring diode to appropriate points on the digital voltmeter and digitizer.

In the interest of simplicity, and to avoid laser output power losses in prisms, no beam-steering mechanisms are used. The laser and the two receiving systems are attached rigidly to a heavy I-beam which is moved in azimuth and elevation by gearing. The entire steerable system rests on a heavy steel pedestal, which is bolted to the concrete floor of the observatory-type dome.

The transient recorder, or digitizer, stores 2024 digitized sequential samples of the output of either receiver. Maximum sampling rate is 10^8 samples per second (one per 10 ns, or one per 150 cm of range), and the resolution is 8 bits (one part in 256). Sampling is initiated by the sync pulse from the monitor photodiode at lasing time. After sampling, the digitized data are displayed repetitively at low rate on any convenient oscilloscope. The operator can thereby assure himself that the data from a particular shot are of acceptable quality and that the laser has not malfunctioned. If all is well, the operator switches to the dump, or data transfer, mode. Contents of memory are transmitted sequentially (8 bits in parallel) over a 77-m cable to the minicomputer. The two-way multiplexed data-transmission system between the digitizer and the computer was designed by Dennis Wellman of APCL. In order that the number of digitized shots sent to the computer for averaging (to improve signal-to-noise ratio) shall agree with the preset value supplied by the operator to the computer, a digital LED display at the operator's position in the dome is updated each time a shot is received by the computer. The relative laser energy as displayed on the digital voltmeter is also transmitted to the computer via this data exchange link.

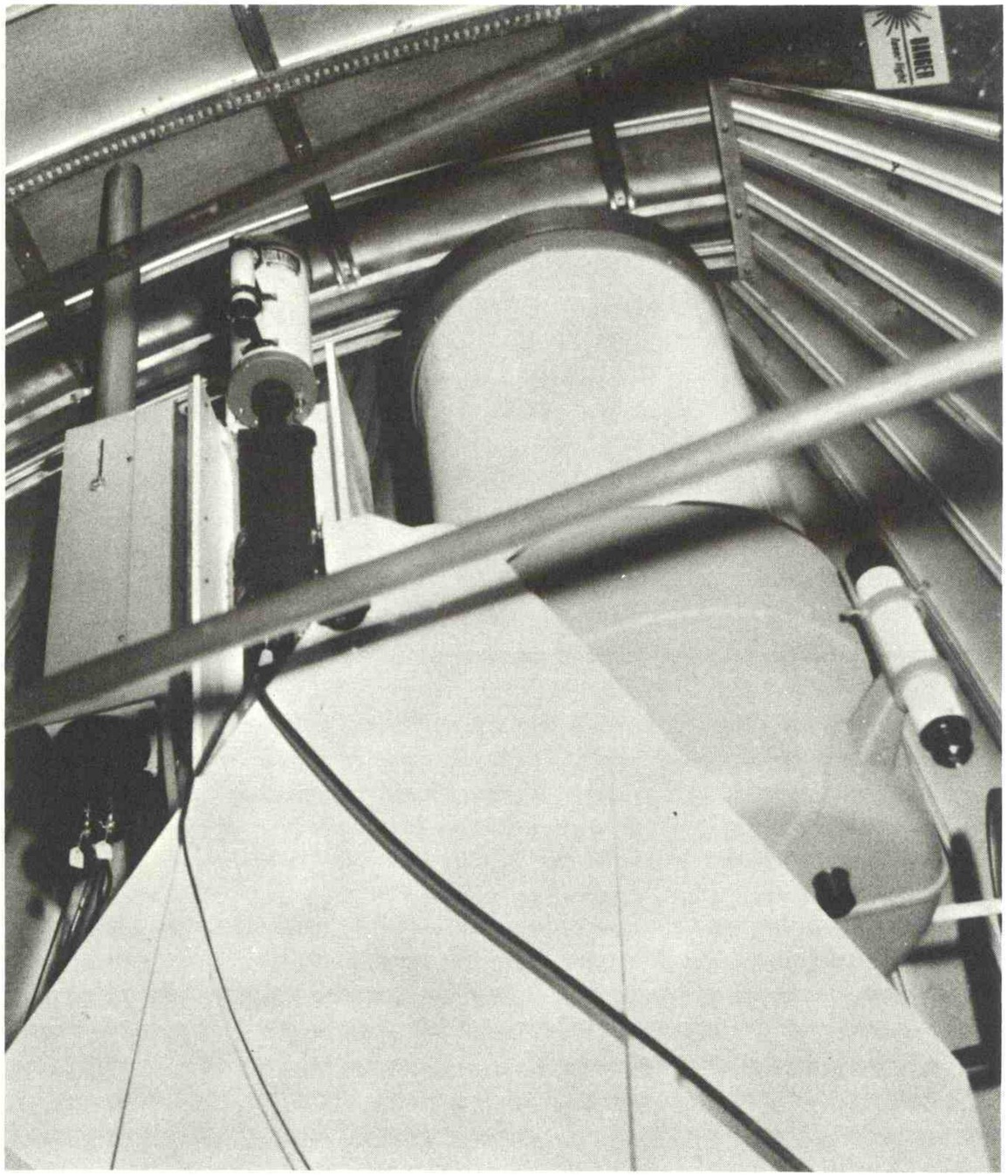


Figure 1. Laser transmitter and receiving optics mounted on steerable I-beam support in observatory dome.

The data processing is controlled by a BASIC main program, with calls to assembly language subroutines that control data and flag transfers between the console and the computer. The main program can be altered to suit different circumstances. In the original setup the operator supplied the computer with the sampling rate (i.e., maximum range) and the number of shots to be averaged. After receipt of the data from the last shot, the computer printed out on the teletype the time mean relative backscatter (average of all shots) corrected for range and Rayleigh scattering extinction and also averaged in range over 10 sample intervals. The theoretical Rayleigh backscatter coefficient for each of these 100 significant levels in a tropical standard atmosphere was also printed out for use in interpreting the results. Program changes have been made in the 3 years since the system was placed in operation; some of these changes will be discussed in a following section.

To provide a target with stable scattering properties for absolute calibration of the system, and to aid in boresighting the system (making the axes of the laser beam and the receiver telescopes parallel), a billboard 3 m (10 ft) on a side was erected at a point on the mountain some 300 m (1000 ft) south of the dome. The billboard can be lowered when not in use. The surface is fiber glass sheeting painted with flat white paint (85% diffuse reflectance). Three black spots, spaced the same distances apart as the axes of the laser and telescopes, are provided for assistance in the boresighting operation. Unfortunately, the board was damaged by wind and repaired with glue and therefore no longer presents a homogeneous surface. It therefore cannot be used for absolute calibrations, but is still useful for alignment.

The physical arrangement of the system in the dome as of June 3, 1974, is shown in the figures. Fig. 1 shows the transmitting and receiving optical hardware in position for making a vertical sounding. The laser with its plastic

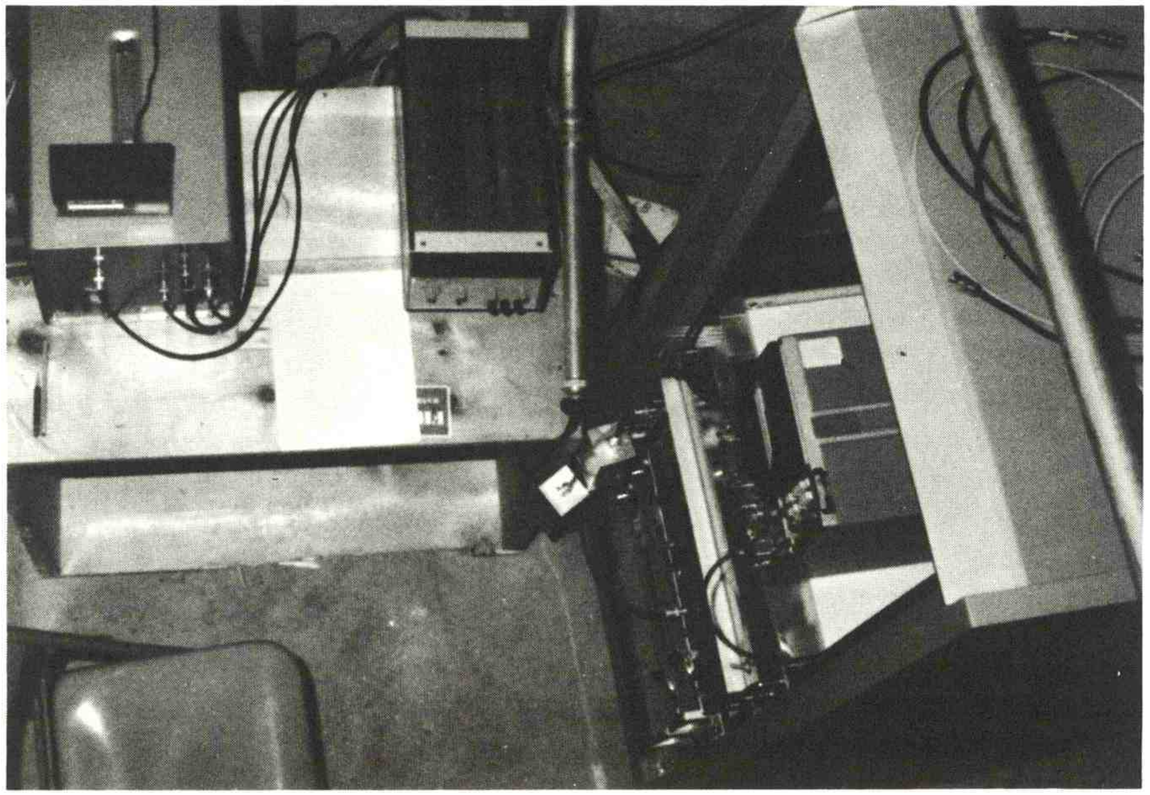


Figure 2. Lidar operating position viewed from lidar pedestal.

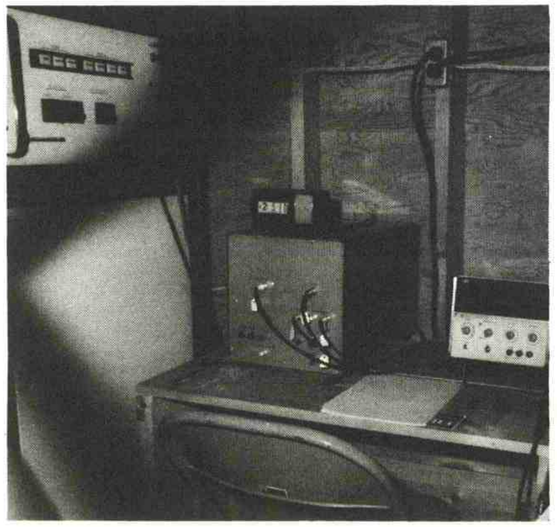


Figure 3. Center of operating position viewed from eye level.

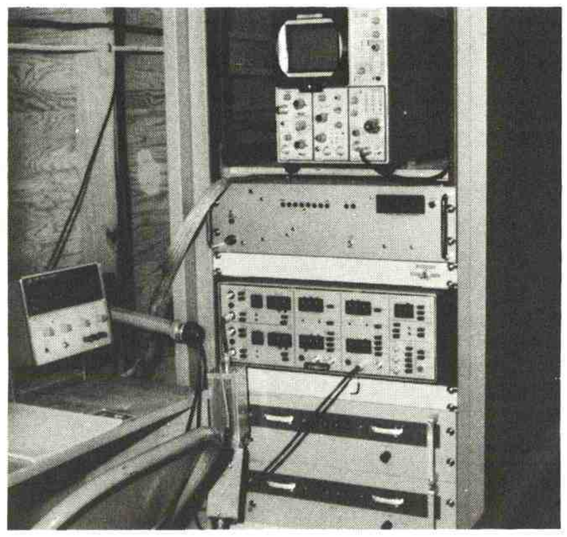


Figure 4. Right side of operating position viewed from eye level.

stray-light baffle is at the left, bolted to one flat face of the I-beam. The short-range receivers, scope, and PM tube housing are in the center, attached to the inner surface of the beam. The long-range receiver is at the right, attached to the other flat face of the beam. The PM tube housing is concealed by the heavy steel trunnion; it is located at the lower right. The handwheel at the far right is the elevation control.

Fig. 2 shows the operating position as seen from above. From left to right, the various components are laser power supply and control circuits; the system master control box and sync pulse distributor; the digital voltmeter for the power monitor; and the rack containing the PM power supplies and blanking-pulse generator, the digitizer, the data transmit-receive link to the computer, and the monitor oscilloscope. Cabling to the PM tubes passes through the rigid conduit at the right.

Figs. 3 and 4 show the operating position from eye level. The laser power supply, master control box, and digital voltmeter appear in Fig. 3; the remaining hardware is displayed in Fig. 4. The miniboxes connected to the digitizer contain the special low-pass filters. The two PM power supplies are at the bottom of the rack with the digitizer just above them. The blanking-pulse generator occupies the very narrow panel above the digitizer; the next panel above is the data transmitter-receiver with LED displays of bit status and shot count. At the top is the monitor oscilloscope (a laboratory scope served as temporary substitute for the regular unit which was being repaired).

DESIGN AND INSTALLATION OF THE MLO LIDAR SYSTEM

The desirability of having a high-powered lidar system at MLO was the subject of several discussions between E.W.B. and Helmur Weickmann, Director of the Atmospheric Physics and Chemistry Laboratory (APCL), as early as 1968. The influence of the dust from the eruptions of Agung volcano in 1963 on the solar radiation received at Mauna Loa (Ellis and Pueschel, 1971) and the concern over pollutants from aircraft operating in the stratosphere were indications of the value of long-term monitoring of stratospheric aerosol levels. While solar radiation measurements can be used to estimate

total particulate loadings, lidar has the additional capability of ranging to permit the study of the vertical distribution of the aerosols.

Funding for a lidar system was included in the APCL budget for fiscal 1971. At that time the observatory was a part of APCL under the direction of Rudolf Pueschel.

The lidar system was designed to be as versatile as possible, so that it could be used not only for stratospheric aerosol monitoring but also for low-level aerosol and cirrus cloud studies. Preliminary design work took place in the summer and fall of 1970, and component procurement began in December of that year. By the early summer of 1971 the major elements of the system had been obtained, and the mechanical design work (by David Eyre, APCL mechanical engineer) was well advanced.

At about that time a major administrative reorganization took place, in which MLO was transferred from the jurisdiction of APCL to that of the Air Resources Laboratory (ARL).

The lidar system began to take shape on the mountain in October 1971, when David Eyre, with an engineer from a private contractor and a crew of NOAA workmen, erected the observatory-type dome near the east end of the parking area and set up the heavy pedestal that supports the laser and receiving optics. At the same time E.W.B., assisted by Bruce Uhlenhopp, electronic engineer, and Charles Johnson, electronic technician, of APCL, completed the design and construction of the signal-handling and control circuitry. In February 1972 E.W.B. and Richard Proulx, meteorological technician of APCL, proceeded to MLO to put the system together and check it out.

The installation and initial testing of the lidar system was characterized by problems like those that accompany the development of any complex scientific system: failure in the laser power supply, overloading on the receiver-photo-multiplier tube, radio frequency interference problems, and a high receiver noise level due to fluorescent afterglow from the laser being scattered off the dome into the receiving optics. The automatic data-processing system also offered difficulties which meant a year's delay before it became operational. Hardware and software problems arose with the minicomputer. Yet despite delays and frustrations all the necessary components of the system were designed, installed, and debugged. It took four years, from the preliminary design work of summer 1970 to the first computerized soundings taken on May 30, 1974. The entire system was turned over to Ronald Fegley on June 3, 1974.

OPERATIONAL EXPERIENCE

In August 1972, Ronald Fegley became Director of MLO. Because of his prior experience with atmospheric aerosols and lidar systems, he was interested in starting a long-term atmospheric monitoring program to detect atmospheric phenomena that would escape short-term observational programs.

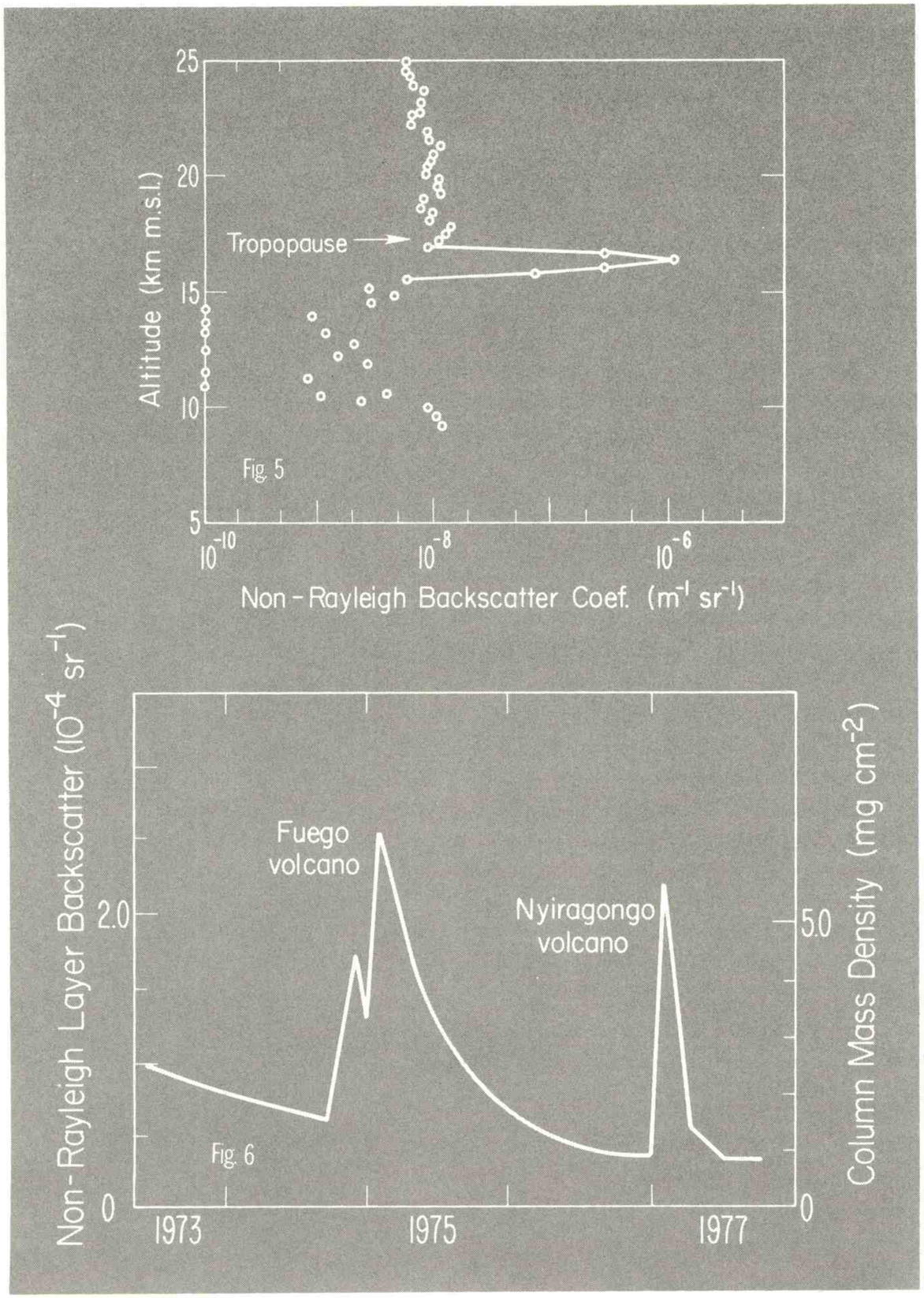
Stratospheric soundings began during the fall of 1972 and were recorded photographically. These photos were laboriously hand-reduced and a processing technique was developed by Howard Ellis. The manual technique was designed to allow a "clean air" calibration to be made at some upper tropospheric level.

In March 1973 problems had been resolved to the point that the authors were confident of their results. Therefore that date is given as the beginning of the Mauna Loa stratospheric data record.

After the first computer was installed, refinement of the analysis program continued over the years. Routines were developed to allow real-time graphical display of the scattering ratio profile on a cathode-ray tube display. Automatic calibration of the lidar returns at the clean air level and at maximum range was implemented. Data were averaged and put onto paper tape for semi-permanent storage. Corrections were made to the program to allow analysis at various zenith angles.

Procedures were finally well developed when the intense dust cloud from Fuego volcano in Guatemala appeared in late 1974. This event confirmed interest in stratospheric monitoring and led to discussions concerning expansion of the lidar network to other GMCC observatories.

In fall 1976 a second computer dedicated to lidar operation was installed in the dome and so total operation was possible at one site. The lidar has operated reliably, considering the complexity of the electro-optical system. The persistent problems have been due to the poor room-temperature regulation in the dome. Future GMCC lidars will be housed in a temperature-regulated room



and will fire through a glass skylight. Future development will also emphasize further automation to decrease the difficulties of operation in the cold at high elevations.

SUMMARY OF RESULTS

The first regular lidar data were taken in March 1973. The returns were recorded on photographic film, and reduced manually. Data were taken approximately once every 2 weeks. Profiles were generally the average of a few shots.

This technique continued until about May 1974, when an electronic transient digitizer was incorporated to simplify the analysis. Data were then taken approximately once every week with additional series made in the case of significant geophysical events such as volcanic eruptions. From August 1976 to the present, data have been taken approximately once every 2 weeks.

A stratospheric profile was included in each of the above data sets. Profiles of lower regions in the atmosphere were also included in many of the data sets. For example, Fig. 5 shows a profile taken on January 26, 1977. A smooth layer covering the entire sky was observed visually, and the lidar showed it to be at 16.3 km msl. The maximum backscatter was two orders of magnitude greater than that of adjacent layers. This layer reappeared sporadically several times, but dissipated rather rapidly compared with the 1974 volcanic event (Fegley and Ellis, 1975a). Within error, air trajectory analysis placed the volcanic source near Nyiragongo volcano in the country of Zaire, Africa. By the conventional definition of tropopause height, the layer was slightly below the tropopause, which may explain the short lifetime of this veil.

Fig. 6 summarizes the Mauna Loa stratospheric data. From the short data record, it is hard to say whether there is a steady background level at about 0.3×10^{-4}/sr or a slowly declining value since 1973. Other observers have reported a stratospheric injection early in 1973, a month or two before the onset of our measurements (Hofmann et al., 1976).

Figure 5. Profile of lidar backscatter for January 26, 1977, at Mauna Loa. Note intense veil at 16.3 km msl.

Figure 6. Aerosol backscatter integrated through 16- to 24-km layer above MLO. (Data are preliminary.) Wavelength is 0.6943 μm. Volcanic assignments are tentative. Aerosol column density is calculated using simple optical model.

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A POSSIBLE EFFECT OF LOCAL VOLCANIC ACTIVITY AT MAUNA LOA OBSERVATORY

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INTRODUCTION

The Geophysical Monitoring for Climatic Change (GMCC) program of the National Oceanic and Atmospheric Administration (NOAA) is currently monitoring background atmospheric properties at four baseline sites: Barrow, Alaska; Mauna Loa, Hawaii; American Samoa; and South Pole. All stations are now operational and are collecting continuous data for many gases, particulates, and solar radiation (NOAA, 1975). Mauna Loa Observatory (MLO), located at an altitude of 3.4 km on the island of Hawaii, has been in operation since 1956.

Aerosol monitoring is an important part of GMCC because of the potential effects of aerosols on climate. Aerosols may interact directly with solar or infrared radiation and could produce a general warming or cooling depending on the physical properties of the aerosol and its location in the atmosphere. Furthermore, aerosols may have an indirect effect by acting as cloud or ice nuclei which may affect the albedo, weather, or climate of the earth. It is conceivable that mankind may have the capability of producing enough aerosols to compete with those occurring naturally, although this is open to question at present.

Currently, the GMCC aerosol program is monitoring Aitken nuclei and total light scattering. Activities planned include the monitoring of cloud condensation nuclei (CCN), ice nuclei (IN), and the chemical properties of aerosols, although it is not yet clear what methods are most suitable for background locations.

During July 1975 an experiment was performed in cooperation with Keith Bigg in an attempt to obtain a better understanding of the character of surface aerosols at MLO. His techniques (Bigg, 1977) are especially applicable at MLO because it is likely that Mauna Loa, owing to its high elevation, is often exposed to a background upper tropospheric aerosol composed primarily of sulfates. The chance occurrence of an eruption of Mauna Loa (5 km from the site) during this experiment provided a unique opportunity for a comparison of the instruments measuring background, island, and locally generated volcanic aerosol.

The local meteorology of Mauna Loa has been discussed by Mendonca and Iwaoka (1969) and Mendonca (1969) and has been summarized (NOAA, 1974a, 1974b, 1975). The sources of aerosols on the island of Hawaii have been studied by Bodhaine and Pueschel (1972), Pueschel and Mendonca (1972), and Pueschel et al. (1973). Also, Bodhaine and Mendonca (1974) have compared normal background aerosol monitoring conditions with a brief period of volcanic contamination at Mauna Loa.

INSTRUMENTATION

Aerosol monitoring equipment used for this study included a Pollak CN counter, a G.E. automatic CN counter, and a four-wavelength integrating

nephelometer. The basic design and operation of a four-wavelength nephelometer have been described in detail by Ahlquist and Charlson (1969) and Charlson (1972), whereas the Mauna Loa instrument was described by Bodhaine and Mendonca (1974).

Briefly, the Pollak counter is an expansion instrument operated in the overpressure mode at a supersaturation of about 300%. It is calibrated in terms of the attenuation of a light beam passing through the cloud produced by the expansion and is sensitive to less than 10 nuclei/cm^3. The G.E. nucleus counter is an expansion instrument operating in the underpressure mode, also at a supersaturation of about 300%. Detection of the cloud is accomplished at low forward scattering angles. The instrument performs five expansions per second and is sensitive, in its present modified form, to less than 10 nuclei/cm^3.

The Mauna Loa nephelometer measures the total integrated light scattering due to aerosols (b_{sp}) simultaneously at wavelengths 450, 550, 700, and 850 nm and is capable of measuring b_{sp} of the order of 10^{-7} m^{-1}, which is about 1% of the molecular scattering of air.

To gain a better understanding of the aerosol data it is necessary to assess other atmospheric variables such as relative humidity, wind direction, and speed. As a further aid in determining the origin of air masses at Mauna Loa, it is useful to examine the surface ozone record, produced by an instrument based on the electrochemical cell method (NOAA, 1974a). In general, the highest ozone values are associated with air of upper tropospheric or, possibly, stratospheric origin.

The equipment supplied by Bigg consisted of an impactor and an electrostatic precipitator which captured particles directly upon electron microscope screens. These screens were then subjected to further chemical treatment and investigated by means of electron microscopy as discussed more fully by Bigg (1977).

DISCUSSION

It is likely that global trends in the atmospheric aerosol may show up as changes in concentration or size distribution. However, it is possible that changes in the chemistry of the aerosol may occur, which could also have important implications for both direct and indirect effects on climate but which would not show up as changes in either concentration or size. For this reason it is important to perform regular intensive experiments, such as this one with Bigg, in conjunction with background monitoring.

In general, instruments that measure Aitken nuclei respond to aerosols in the size range 0.001 μm $< r <$ 0.1 m, and the nephelometer responds in the size range 0.1 μm $< r <$ 1.0 μm, so that it is not unusual to find little or no correlation between the two types of instruments if the aerosol size distribution is shifted towards one end of the size spectrum. However, under stable background conditions the two types of instruments generally show high correlation. With the addition of Bigg's technique it is possible to span the size distributions of both instruments to provide a better understanding of the size range in which they overlap, in addition to obtaining information on the chemistry of the aerosol.

Fig. 1 gives a composite presentation of wind direction and speed at 3-hour intervals, relative humidity, surface ozone, Aitken nuclei measured by both Pollak and G.E. counters, and 550-nm light scattering for July 1975 at MLO. While, literally, a "mountain" of information is contained in this illustration, it is useful to point out a number of features before delving into a detailed analysis of relationships among the various parameters.

The volcanic eruption occurred at the summit of Mauna Loa (altitude of 3.6 km) directly upslope (due south) of the observatory at approximately 2330 hours (LST) on July 5, 1975. At about 0800 hours the next morning, the power lines feeding the observatory were threatened by a lava flow, and the power was turned off. This was unfortunate, since data lost during this 24-hour outage would have been valuable indeed. Other than this one outage, all instruments performed properly throughout July except for the G.E. counter, which was inoperative during the last two weeks.

The classic diurnal upslope-downslope wind flow is apparent for much of July, showing a southerly component at night which brings dry upper tropospheric air to the site and a northerly component during the day which brings humid island or marine air from below the temperature inversion to the site. This diurnal effect is especially apparent in the humidity trace but also

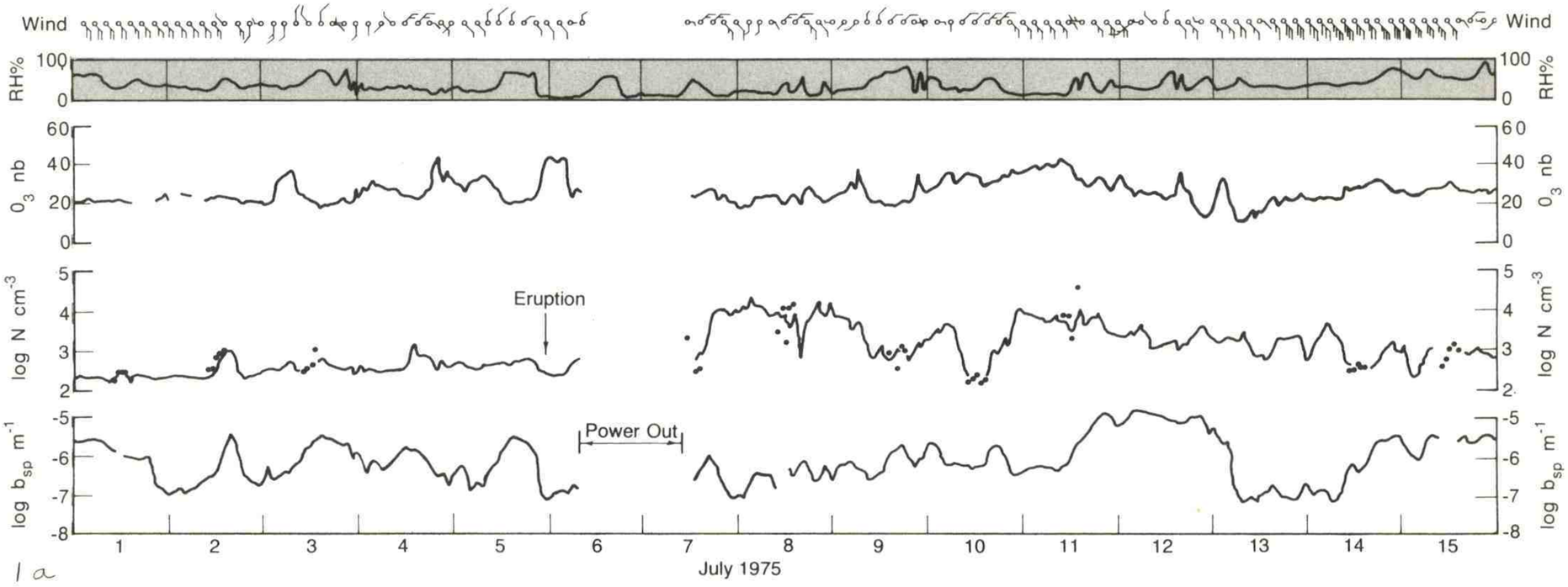
shows up to a certain degree in the records of all quantities monitored at Mauna Loa. Occasionally, this diurnal pattern is overpowered by strong southerly winds, usually from the southeast, and probably associated with large-scale high-pressure regions over the Pacific. Experience has shown that these strong southeasterlies are usually very dry (RH < 20%) and provide the best conditions for monitoring upper tropospheric air. Examples of these strong southeasterlies are seen on July 13–15, 24–26, and 30.

Previous to the eruption, all quantities showed fairly typical behavior with some evidence of the diurnal cycle. Ozone data show high nighttime values, whereas Aitken nuclei data show background levels of about 150/cm^3, and b_{sp} (550 nm) data approach a low of about $10^{-7}m^{-1}$. Also, during this period, good correspondence between Aitken nuclei and light scattering is seen. After the eruption, high levels of Aitken nuclei were observed for about a week, after which all quantities returned to approximately pre-eruption levels. For the week following the eruption, Aitken nuclei show a general decrease, and light scattering shows a general increase with no obvious relationship between shorter-term variations. Apparently, the island was contaminated with a small-sized volcanic aerosol which gradually aged to a larger-sized aerosol before being cleansed from the local atmosphere. It is interesting that Aitken nuclei show an inverted diurnal behavior subsequent to the eruption (i.e., the downslope wind gives higher values than the upslope wind, whereas light scattering shows no obvious short-term relationships, even though upslope effects are apparent on the ninth and on the tenth).

Typical diurnal oscillations in all quantities appear July 18–23, with a gradual return to background levels during the early morning hours of July 23 and 24. Although fairly typical background aerosol conditions occur July 24–26, the period July 28–30 is more typical of high ozone values associated with these strong southeasterlies.

It is interesting to compare the Bigg (1977) data with the data presented here. The concentrations of large particles given in Bigg's Figure 8 follow very closely the trends in light scattering data for the entire month, whereas there is

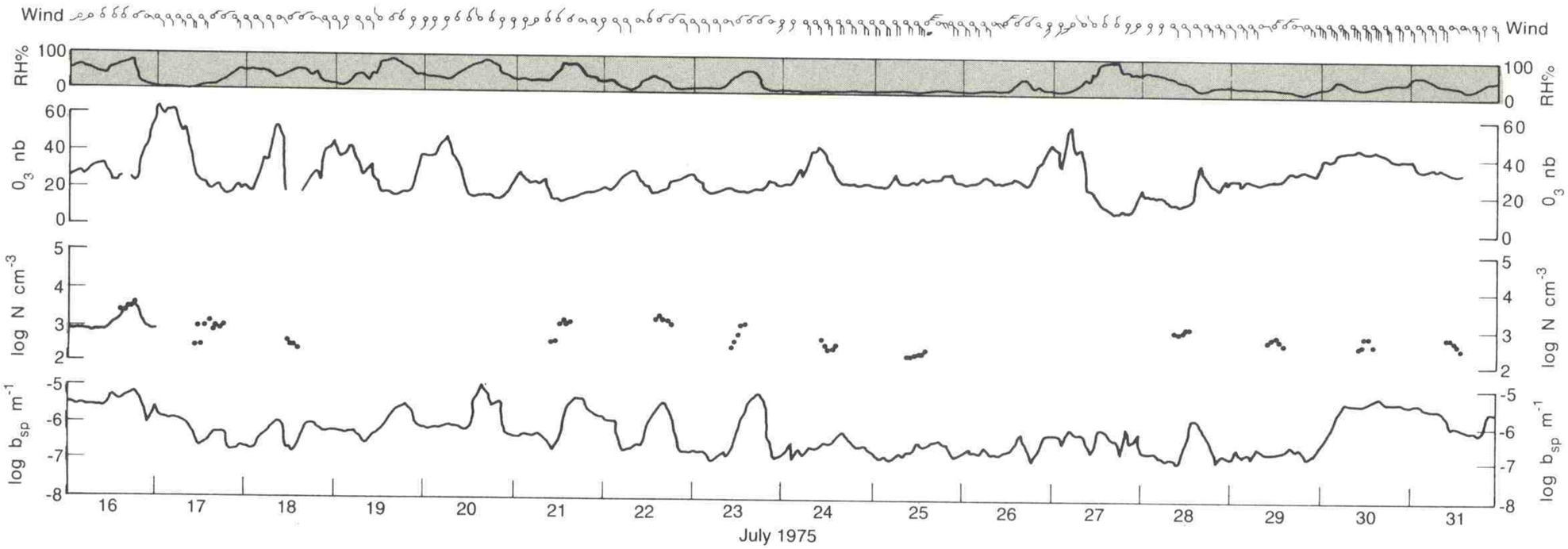
Figure 1. Hourly averages of wind direction and speed plotted at 3-hour intervals; hourly averages of relative humidity; hourly averages of surface ozone; hourly averages of condensation nuclei from a G.E. counter along with occasional observations from a Pollak counter; hourly averages of total light scattering at 550 nm.



no correspondence between those data and the Aitken nucleus data for July 8–15. This further supports the contention that the volcano contributed a smaller-sized aerosol, probably derived from gas-to-particle conversion processes, whereas the nephelometer was seeing a larger haze-type aerosol. During the last two weeks of July, conditions returned to the usual Mauna Loa background.

July 12 shows unusually high light scattering values in agreement with the high concentrations of large particles in Bigg's Figure 8. Richard Hansen, of the NCAR High Altitude Observatory (personal communication), observed an unusual "incredibly dramatic sky brightness pattern, mottled, milky white, distinct haze, etc.," above Mauna Loa on that day. Although the source is unknown, it was most likely from the island itself, and it is significant that the surface aerosol measurements were strongly correlated with the remote effects of the upper troposphere.

Since the four-wavelength nephelometer essentially measures light scattering as a function of wavelength, a three-segment approximation of the Angstrom exponent may be derived, and information on the aerosol size distribution may be inferred (see Butcher and Charlson, 1972, for a brief discussion). Calculations of the slope of the aerosol size distribution were performed on the nephelometer data for the periods shown in Bigg's Figure 7 and are given in Fig. 2 of this paper (along with Bigg's size distribution curves). It is found that the upslope flow (solid curve a) shows a tendency towards larger particles with slope $\beta \cong 3.3$ and slightly concave upward. However, the downslope flow (solid curve b) shows a tendency towards smaller particles with a steeper size distribution at larger particle sizes and slightly concave downward. Although the nephelometer cannot resolve a bimodal size distribution such as that appearing in Bigg's Figure 7, there is a definite indication of a change of slope over its range. Note, however, that the vertical scale is arbitrary and that actual concentration must be provided by a supplementary method. Furthermore, Heintzenberg (1976) investigated the Mauna Loa aerosol in September 1975 with a Royco-225 particle counter. By applying a numerical inversion technique to three channels of Royco data and four channels of nephelometer data he found size distributions quite similar to those given by Bigg with a minimum for downslope flow occurring at about $r = 0.4\ \mu m$.



CONCLUSIONS

It is suggested that Bigg's techniques are clearly applicable to the GMCC aerosol monitoring program and in fact provide useful information not otherwise easily obtained. Furthermore, his size distribution data rather conclusively support a bimodal size distribution with a minimum in the vicinity of $r = 0.3$ m.

In light of Bigg's results concerning the relative appearance of sulfuric acid and ammonium sulfate in the background aerosol at MLO, further investigations of the influence of Mauna Loa volcano are currently underway.

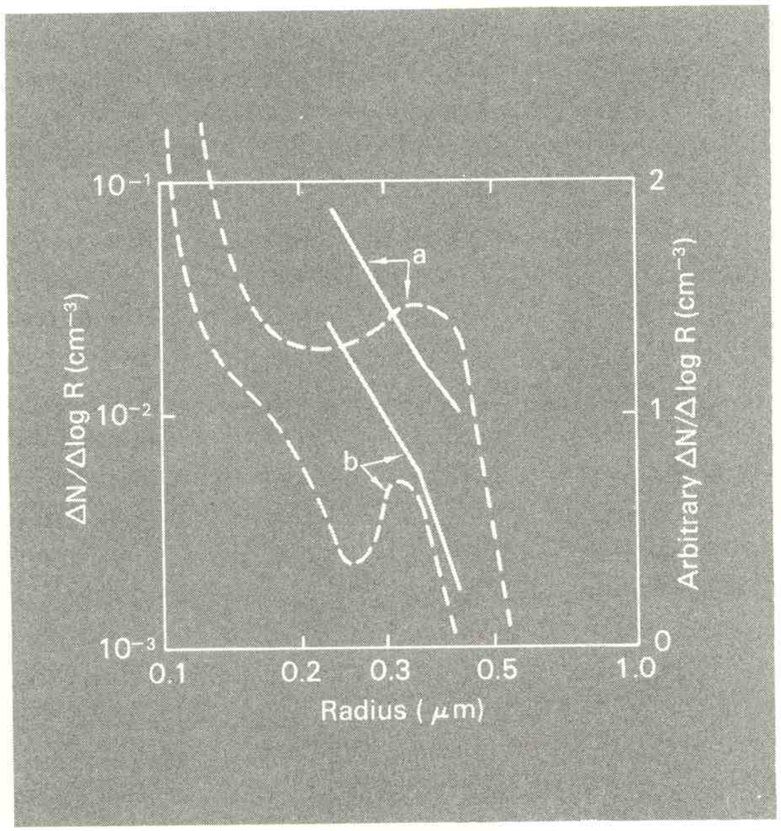


Figure 2. Estimate of the size distribution of the Mauna Loa aerosol.
(a) Upslope winds, July 21–22.
(b) Downslope winds, July 21–23. Solid lines are three-segment approximations derived from nephelometer data with arbitrary vertical scale. Dashed lines are from Bigg (1977).

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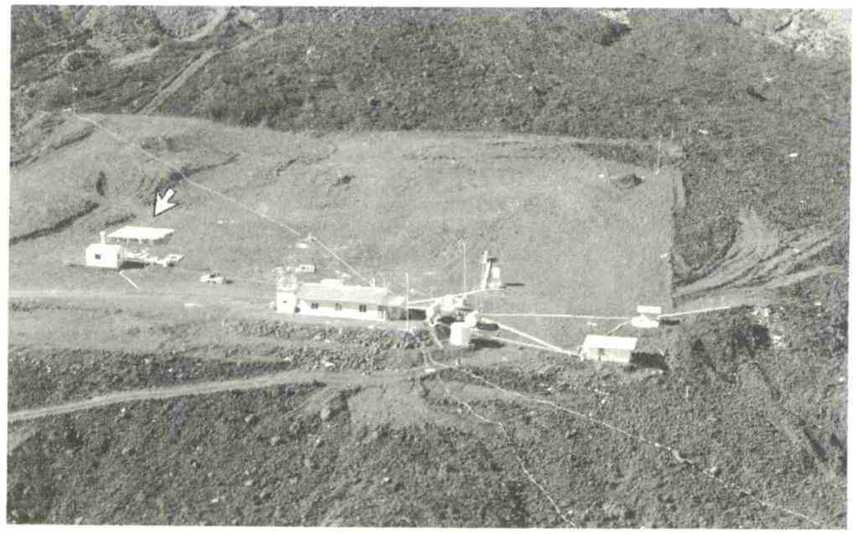
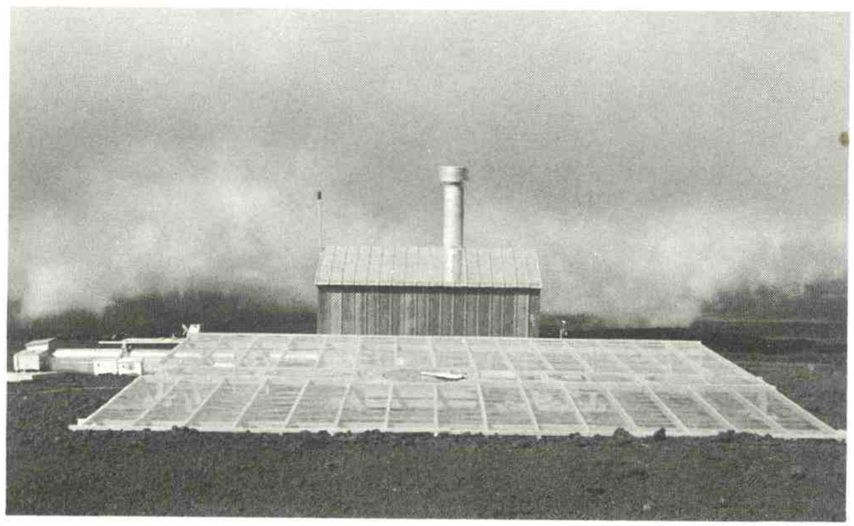
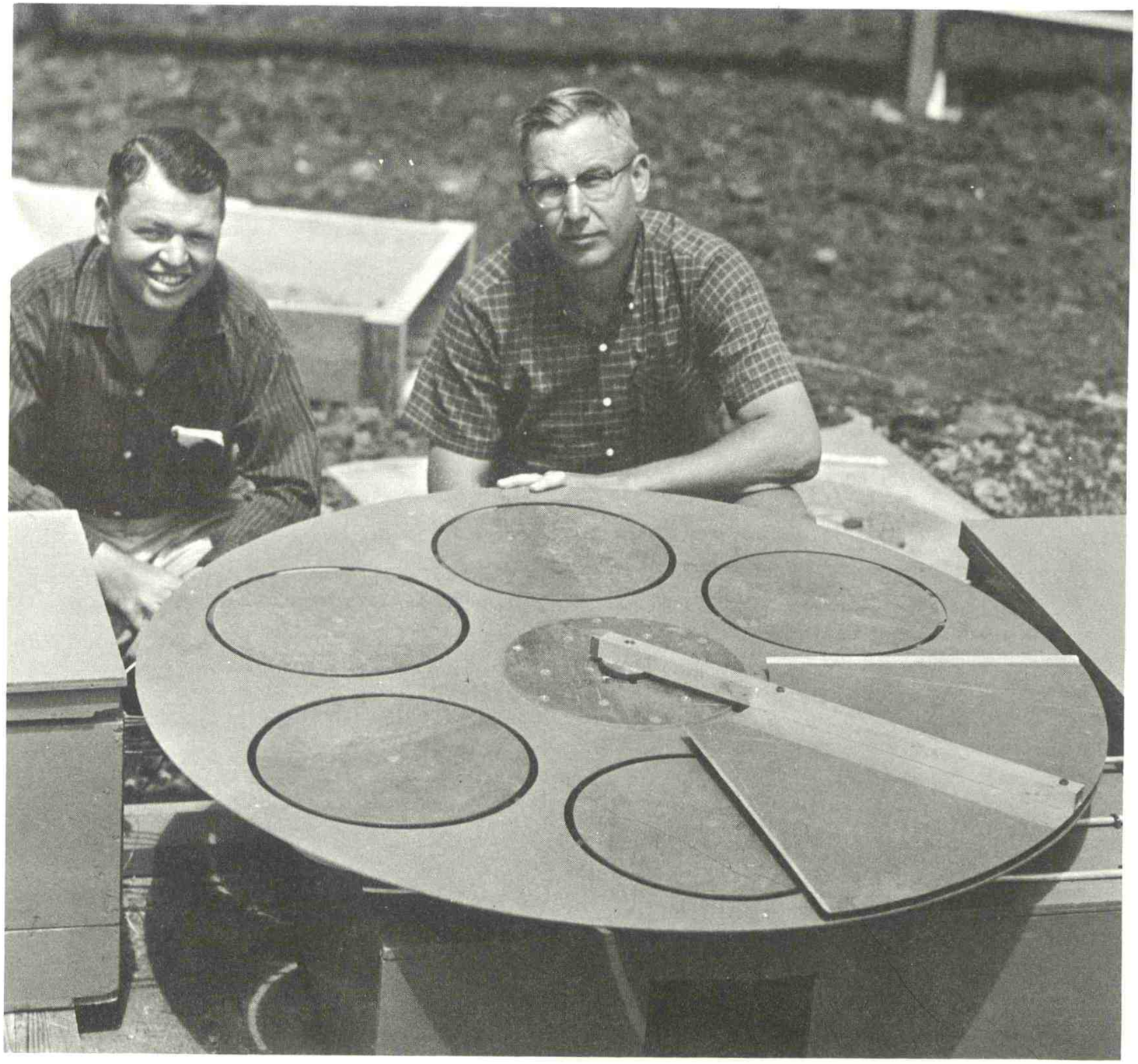
Equipment for measuring atmospheric electricity was installed on MLO's 4-acre site in 1960. The ground screen is at the far left: The screen is now gone, and the building has been moved. The building at the lower right housed the generator.





The current-measuring instrument is in the center of the ground screen. Atmospheric electricity instruments are housed in the building. The chimney is the intake for air, which is sampled to determine electrical properties of the atmosphere.

In 1959, Bill Cobb and Byron Phillips were part of the atmospheric electricity program at MLO. The instrument shown measured electric current from the ionosphere to the ground.



ICE NUCLEI AT MAUNA LOA

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BACKGROUND TO THE MEASUREMENTS AT MAUNA LOA OBSERVATORY

Bergeron's (1935) proposal that the formation of ice crystals is essential to the initiation of precipitation in many clouds led to interest in the concentration of ice crystals in clouds and in the particles, or ice nuclei, on which they formed. Pioneer work by Findeisen and Schulz (1944) shows that such particles are relatively rare and are present in quite variable concentrations. When Schaefer (1946) demonstrated that spectacular changes occurred in clouds seeded with dry ice, the prospect of beneficial weather modification created considerably more interest in the nuclei. Clearly, the ability to predict occasions when concentrations of natural ice nuclei would be too low for efficient production of precipitation would be helpful in selecting occasions suitable for cloud seeding, and a knowledge of the sources of the ice nuclei and meteorological conditions should be sufficient to allow such a prediction if the sources were well defined and not too numerous.

In principle, there could scarcely be a simpler measurement than that of finding the concentration of ice nuclei. All that is necessary is to cool a sample of humid air to the temperature of interest and to count the ice crystals that fall from the resulting cloud. The only stipulations should be that cooling rates, concentrations, and sizes of cloud drops are comparable with those in natural clouds. Unfortunately, measurements are rarely as simple as they seem in principle. With a container of manageable size, a slow expansion to match normal rates of cooling of the air in clouds causes most of the available water to be deposited on the walls instead of on the cloud drops. There it promptly freezes, shedding into the air ice crystals that are indistinguishable from, but completely independent of, those formed on nuclei. In addition the ice crystals are difficult to detect.

Many of the early measurements probably include spurious ice crystals in the count, and therefore are completely worthless. It is impossible, of course, to know now whether precautions to avoid counting spurious crystals were adequate. In the absence of nearby special sources, such as silver iodide generators, blast furnaces, and so on, any concentrations exceeding 10/liter at −20°C or warmer must be suspect. The methods used to overcome the defects of a simple system have varied widely, but all have had to compromise between practicality and the provision of cloudlike conditions.

The "spurious ice crystal" problems were overcome in the early 1950s by coating the container walls with glycerine or glycol. These substances do not seem to hamper the measurements if used carefully in normal circumstances; in warm humid situations, however, they rapidly become diluted, allowing ice crystal production from the walls, whereas in very dry situations they become too concentrated and reduce cloud lifetime. Detection of ice crystals in early experiments was accomplished usually by observing their scintillations in a beam of light, but many natural particles scintillate, giving false counts. Supercooled solutions of sugar or other soluble materials turned out to be very useful for crystal counting, since they grow ice crystals only when an ice crystal falls into the solution, provided that the supercooling is kept to a minimum. Two of the most popular early methods of counting ice nuclei have used either static "mixing" chambers, where the air is introduced into a cold container coated with glycerine and having a supercooled sugar solution at the bottom, or "rapid expansion" chambers. In the latter method the air is cooled to the temperature of the container walls without more than transient condensation; it is then cooled to some lower temperature by a sudden expansion. Although the results of measurements using these two methods may agree at one temperature, they usually disagree considerably at others, owing probably to

the effects of different temperature-humidity histories or of cloud drop properties or lifetimes. Neither method really provides a good approximation to cloud conditions, though the maximum supersaturation and cloud drop properties in a mixing chamber are probably a better representation of those in natural clouds than occurs in an expansion chamber.

More recent counting methods include the filter technique and several continuous-flow cloud chambers, of which the "acoustic counter" is the most important. In the filter method all the particles in a sample of air are collected on a filter; the filter is then cooled in a thermal diffusion chamber to the temperature of interest, and the humidity is raised; after a suitable interval the ice crystals that form are counted. The temperature-humidity history of the air sample could be made to match that in a cloud exactly if it were not for vapour depletion by hygroscopic particles and the filter itself; however, interaction between cloud drops and the nuclei is difficult, perhaps impossible, to model.

In the acoustic counter, air is drawn into a cold chamber and sucked out through a special orifice in which particles larger than a certain size make audible clicks that can be counted. The early models of the acoustic counter were designed more for plume tracking from silver iodide burners than for counting natural ice nuclei, and a few spurious counts did not matter. However, the attractions of a real-time printout soon led to the use of these counters for counting natural nuclei under conditions where the inherent difficulties of ensuring appropriate humidification and ice-free operation rendered many of the results useless. After many refinements the acoustic counter is apparently capable of giving reproducible results when it is used with care. However, since, in common with all other methods in use, there is a possibility of consistent bias due to failure to model natural clouds exactly, its results cannot be considered absolute.

INITIATION OF PROGRAMS OF COUNTING ICE NUCLEI AT MAUNA LOA OBSERVATORY

At the time Mauna Loa Observatory (MLO) commenced operations, Bowen's (1953) "meteor dust" hypothesis had created a major controversy. This theory stated that meteor dust reaching the earth's atmosphere on certain calendar dates reached the lower troposphere 30 days later, where it seeded clouds and produced rain. Critics had claimed that this was entirely improbable, but Bowen's answer was that measurements of ice nuclei would demonstrate the correctness of his hypothesis. Indeed, there was a certain measure of success in early measurements which were concentrated on the month of January; Bowen claimed (though others disputed) well-defined anomalies in rainfall about January 12, 22, and 31. About a dozen rapid-expansion counters were made in Australia and shipped to various sites, including MLO. Later the U.S. Weather Bureau constructed many similar instruments, and these were used both at Hilo and at MLO.

The early results showed that, when the observatory was isolated from low-level air, concentrations of ice nuclei were always less than 0.1/liter even at −24 °C. (The early work appears not to have been published in detail, although I have a sample of such early data.) In other sites at this temperature, nuclei were present to the extent of 10/liter or more. This result, of course, argued strongly against the meteor dust hypothesis, unless the unusual conditions at the observatory had caused some instrumental malfunction.

I made my first visit to MLO in April 1959 and was able to compare results from the operation of the U.S. Weather Bureau instrument used as an expansion chamber with those obtained when it was used as a mixing chamber with additional moisture supplied. The results were totally different: as a mixing chamber the instrument gáve concentrations of nuclei comparable with those from other sites.

In 1960 the U.S. Weather Bureau commenced continent-wide sampling of nuclei with expansion chambers, and that at Mauna Loa again showed unusually low counts, except during periods of upslope flow (Price and Pales, 1964). To verify my 1959 impressions, I spent a longer time at the observatory in 1961 (Bigg, 1964) and again found concentrations to be much the same in upslope and downslope flows. The difficulties that I experienced in dry conditions were an increase in concentration of the glycerine on the walls, leading to reduced cloud lifetime and droplet size. There was also an increase in sugar concentration of the surface layer of the sugar solution, leading to failure to detect ice crystals that fell into it. When diluted glycerine and sugar were used,

the results were similar to those obtained elsewhere.

In 1964, Droessler and Heffernan (1965) attempted to settle the question of whether humidity was the main variable by using the recently developed "millipore filter" technique for counting the nuclei. Since the filters were not processed on the site, the answer should have been independent of ambient conditions. They attempted to allow for reductions in the count by hygroscopic particles (more numerous in the upslope air) by simultaneously sampling filters at two volumes at three sites: the observatory, Hilo at sea level, and a midlevel site (Kulani prison). Their conclusion was that there was no significant difference in ice nucleus content of the air above and below the temperature inversion. This result might have settled the question if the filter method had not had some obvious defects and had not failed to model natural clouds in allowing for capture of nuclei by water drops. Another problem was that of "background nuclei," i.e., those that come with the filters.

The advent of an "acoustic counter" for ice nuclei (see Langer et al., 1967) provided an opportunity to reexamine concentrations of ice nuclei on a continuous and automatic basis. The first reported measurements with the counter at MLO were made from January to March 1967 (Nagamoto et al., 1967); these showed much the same sort of variation with upslope and downslope winds that had been found earlier by Kline (1963) with expansion chambers. I had seen several of the early commercial counters in action and was unimpressed: they clearly failed to work in low humidities and were prone to frost troubles and changes in counting rate which were due to changes in internal air flow patterns. Langer (1971) conceded these points but claimed that modifications, which he has subsequently introduced, would avert these difficulties. At the Workshop on Ice Nuclei held at Ft. Collins, Colorado, in 1971, two modified commercial counters were tested which were plainly unreliable, so that I still felt doubtful on these points. On the other hand, Langer himself operated a more sophisticated counter which appeared to be very good.

In 1968 a most important experiment was organized at MLO, at Blue Glacier in Washington, and at other sites, to compare two independent techniques. The first used the acoustic counter, the results being analysed by Hobbs et al. (1971a) and Hobbs et al. (1971b). The second used a novel instrument described by Isono et al. (1971) in which ice crystals falling from a cold chamber were collected on a moving paper roll and allowed to evaporate. Ice nuclei on the paper were subsequently revealed by humidifying the filter paper at a temperature of −15 °C and pouring a supercooled solution over it to reveal the ice crystals. Any environmental effects at the observing site should therefore have been avoided, while frost from the walls of the cold chamber should contain no ice nuclei and therefore fail to be counted.

Detailed measurements from the acoustic counter at Mauna Loa were not published, but the Japanese technique showed precisely what Droessler and Heffernan's (1965) filters had shown earlier: no significant diurnal variation. Fortunately, the 3-hourly measurements of the acoustic counter at Blue Glacier were reported in detail in a University of Washington publication and could be compared with the 6-hourly measurements of the Isono et al. (1971) instrument. The fluctuations were found to be exactly out of phase. From this I concluded, because of my doubts about the acoustic counter's performance, that it was responding to an ambient condition negatively correlated with ice nucleus concentrations.

Possibly as a result of this disagreement — though it was never discussed in the literature — two acoustic counters were operated simultaneously at the observatory through 1971–1972 with some improvements in construction and procedure. The possibility that frost on the walls or erratic flow patterns within the counters could contribute to variations in apparent ice nucleus concentrations was reduced by considering only those occasions when the reading of the two counters agreed. The results of a long series of observations have been reported and discussed by several authors (Mendonca and Langer, 1973; Mendonca and Pueschel, 1973; Fullerton et al., 1975). It was unequivocally shown once again that air coming from below the trade wind inversion generally had a higher ice nucleus content than the air above the inversion.

At the same time, further filters were exposed, and some of these were sent to me for analysis. The mean concentrations of ice nuclei are given below (in numbers per cubic metre active at −15 °C):

Date	*Morning*	*Afternoon*
2/23–3/4/72	2.7 (16 filters)	2.2 (11 filters)
5/11–5/19/72	4.7 (19 filters)	3.7 (20 filters)

The situation therefore is that the acoustic counter, the reliability of which seems to have been adequately demonstrated, gives an entirely contrary conclusion to the filter method, which itself has been found to agree reasonably well with other techniques in other localities.

How is this conflict to be resolved? At present the only simple solution seems to be to invoke the demonstrated difference between nuclei activated from the vapour phase (known as "deposition nuclei") and those which require contact with a water drop to become activated (known as "contact nuclei"). As I have used it, the filter method detects only the former, whereas the acoustic counter could detect both. If we assume that nuclei from below the trade wind inversion were exclusively "contact" nuclei, the results from the two methods would no longer be in disagreement.

There is a difficulty in this simple solution: neither the mixing chamber measurements that I had made using diluted glycerine and sugar nor the expansion chamber measurements made by Droessler and Heffernan (1965) yielded unusually low concentrations of nuclei in air that appeared to have originated from above the trade wind inversion. Langer (1971) suggested that because tests with clean air were not made, the chambers we used may have been contaminated, producing their own nuclei. Since this proposal would remove what appears to be an otherwise insuperable difficulty, I am now more ready to accept it than I would have been in 1971.

CONCLUSION

Further experiments should be carried out at MLO to verify that the differences are indeed due to the response of different techniques to different types of nuclei. Quite clearly they should be carried out by using methods capable of detecting both deposition and contact nuclei. I would recommend the use of Ohtake's (1971) "cloud settling chamber" for this purpose. The principle with this instrument is to generate a cloud in a region above the temperature inversion of a static cold chamber and allow the cloud drops to fall through the precooled air sample. With care it is possible to avoid more than transient supersaturations on admitting the air sample, to ensure frost-free operation and proper detection of ice crystals. The tedious and time-consuming nature of the operation of the instrument would preclude its use except on an intermittent basis at times selected according to the origins of the air. The fact that it gives a better representation than most other techniques of the processes in a cloud and is inherently simple outweighs its disadvantages.

If the results from the Ohtake (1971) chamber should agree with the findings of the acoustic counter, there could be little doubt that failure to detect contact nuclei when filter methods were used was the reason for the conflicting results. All the work that has gone into the measurements would not then have been wasted, for a valuable distinction between the nature of sea level and high-altitude nuclei would have been demonstrated.

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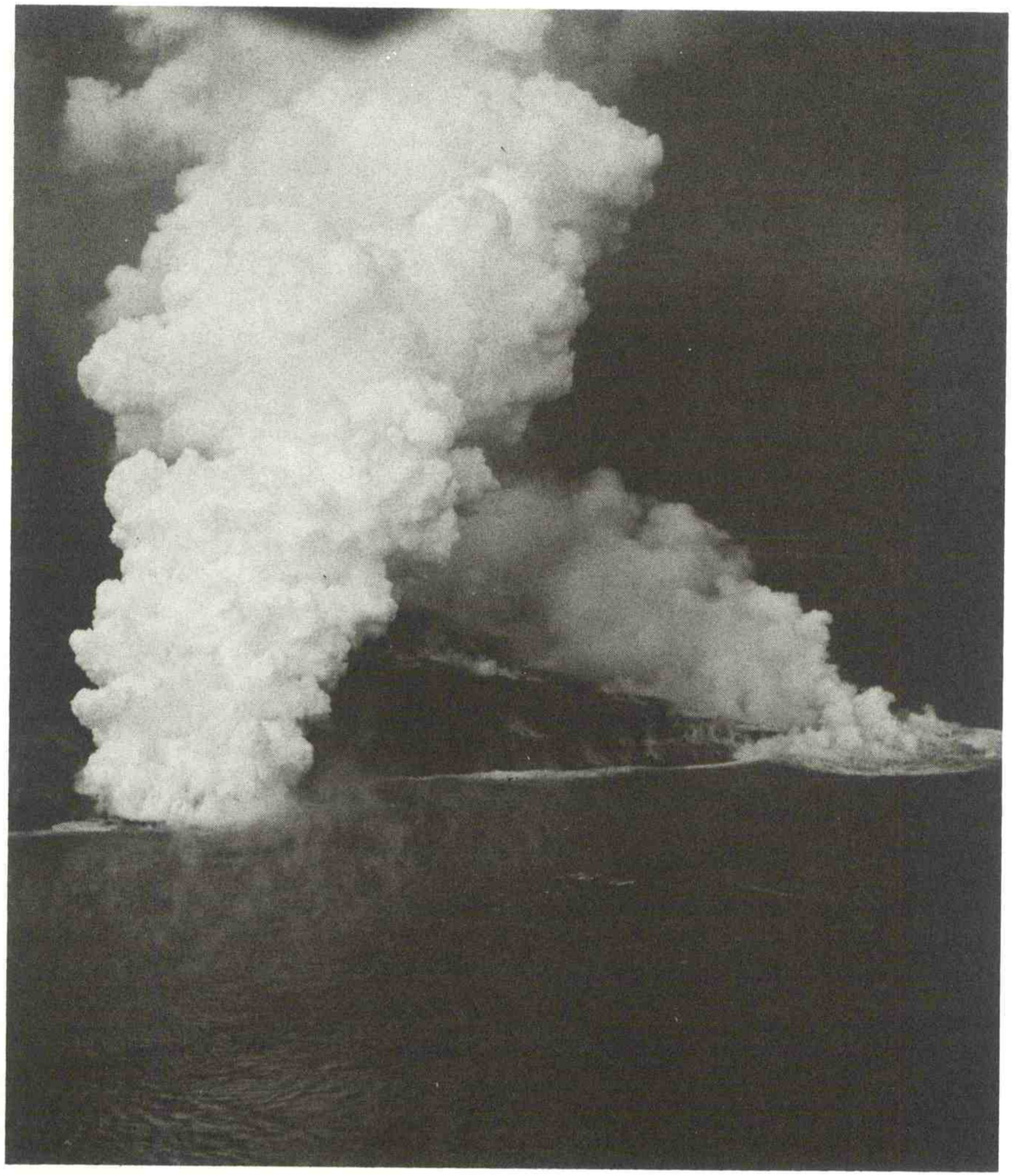

"Lava entered the ocean with a spectacular burst of rolling clouds of white steam [and] over the next few days . . . engulfed nearly the entire village of Kapoho."

VOLCANOES AND ICE NUCLEUS MONITORING AT MAUNA LOA OBSERVATORY[1]

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INTRODUCTION

Measurements of atmospheric ice-forming nuclei (hereafter referred to as IN) have been carried out at Mauna Loa Observatory (MLO), Hawaii, almost from the time it was established in 1956. The location, altitude, and physical site of the observatory, combined with a relatively well defined diurnal circulation, make MLO a particularly attractive and potentially valuable site for IN measurements.

It is somewhat disappointing, therefore, that IN measurements at MLO have been rather sporadic, that most programs were carried on for only a few days to a few weeks, and that the longest period of continuous IN measurements lasted less than 1 year and ended 5 years ago.

Ideally, a regular program of observations should have been established and maintained years ago, along the lines of the outstanding carbon dioxide

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and solar radiation monitoring projects long identified with MLO. A number of reasons may be suggested for the lack of a long-term IN monitoring program:

1. A fundamental skepticism exists concerning the importance of IN as variable constituents of the atmosphere. After years of worldwide study the basic nature, structure, composition, and origin of such nuclei remain largely unknown. Under these circumstances it is difficult to assess precisely what role these elusive particles may play in atmospheric processes.

2. Although a number of methods and devices have been developed to detect and measure IN, no single device has become established as the recognized (standard) instrument. Workshops conducted to compare instruments and technical approaches to the problem, including the activation process employed, have not resolved the differences. This is probably to be expected, in view of the fundamental uncertainties mentioned above.

3. Several investigators have made IN measurements at MLO, but none has carried out a carefully monitored continuous program of sufficient duration to establish even seasonal trends at the site. As investigators come and go, and instrument types and methods change, the basic continuity that such a program requires has never become established.

4. Certain questions of long-standing interest remain unresolved. From our perspective one of the most fascinating is the possible relationship between local volcanic activity and the IN concentration measured at MLO. This problem has been the subject of several research papers and a recent brief review which concluded that "the correlation between ice nuclei and volcanic activity on Hawaii remains largely inconclusive" (Langer et al., 1974).

VOLCANIC ACTIVITY AND ICE NUCLEI

We believe that confusion has arisen in the past because of the assumption that IN are present, or at least potential, in fresh volcanic effluent. This assumption derives from the report of Isono et al. (1959) that volcanic eruptions in Japan (principally, Mount Asama in November 1958) are a source of IN. If the assumption is valid for Hawaii, then local eruptions should produce IN, which under favorable wind conditions should increase the measured IN concentration at MLO.

The assumption has been suspect, however, since Price and Pales (1963) reported a decrease in IN concentration during local eruptions. Moreover, when Pueschel and Langer (1973) sampled IN concentration near potential sources in Hawaii, they found the lowest concentration in the effluents of Mauna Ulu, an active vent of the Kilauea volcano. When an NCAR counter and membrane filters, both at -20°C, were used, measurements directly in the fume showed IN concentrations of about 0.5 IN/liter. Thus it appears that local volcanic activity is not a direct source of IN. How, then, may the observations of Hobbs et al. (1971b) be explained? In them, clear evidence of pronounced peaks in IN concentration, as measured at MLO, followed volcanic eruptions in 1969.

Perhaps the simplest way of explaining the variety of results reported by earlier investigators is to consider local volcanic activity as an indirect cause of IN activity through initiation of burning. Thus lava may set surrounding scrub vegetation and trees afire and in this way generate IN. Hobbs and Locatelli (1969) observed IN from a natural forest fire. Pueschel and Langer (1973) identified the burning of leaves during sugarcane harvesting as the most prolific source of IN on Hawaii, a finding verified by Fullerton et al. (1975) during a 9-month IN monitoring program at MLO. Laboratory studies by Langer et al. (1974) indicate that smoke from burning ohia-lehua branches is an active IN source at -20°C.

Our thesis is that some of the peaks in IN concentration observed at MLO during local volcanic eruptions arise from vegetation burned as a secondary effect of lava flows. Not all increases in IN concentration, however, are so related to volcanic activity. We know that sugarcane fires are the dominant local IN source and that major "IN storms" of distant origin occasionally arrive at MLO.

Data on the type and amount of material burned during eruptions are difficult to obtain for past events. We may, however, estimate the potential for burning on the basis of these considerations:

1. Eruptions within the summit caldera of Kilauea volcano, especially those in Halemaumau, should be accompanied by little or no burning, simply because frequent volcanic activity prevents vegetation from becoming established.

2. Eruptions confined to a given location may initially set the peripheral vegetation afire, but such burning would not long continue unless lava flowed from the source region into forested areas.

3. Rift eruptions into areas long free of lava inundation should set afire the existing vegetation and continue to burn new areas as the lava moves.

4. Rainfall before an eruption may decrease the material burned; rainfall after an eruption may extinguish fires that might otherwise continue.

If burning vegetation does produce IN or release IN to the atmosphere, existing wind patterns will determine the trajectory and transit time to MLO. Rainfall during transit may reduce the IN concentration by "washout and rainout" of aerosol particles. Kilāuea volcano is located at an elevation of 1.2 km on the southeast flank of Mauna Loa, whereas MLO lies on the northern slope of the mountain at an elevation of 3.4 km. Thus the volcano is not favorably situated with respect to upslope winds advecting nuclei directly to MLO.

Price and Pales (1963) argue that volcanic effluent probably reaches MLO by either or both of two primary trajectories. The first, illustrated by the Kilauea Iki eruption in 1959, is "southwestward along the slope and over the lower portions of the ridge of Mauna Loa by the prevailing trade wind . . . northward along the western (leeward) side of the island, and thence into the Mauna Loa–Mauna Kea saddle through its western entrance. Smoke of volcanic origin first reached MLO from the south-southwest on November 21, seven days after the eruption began."

The other, more direct trajectory was observed in the Kapoho rift eruption (1960) where effluent moved "directly westward into the Mauna Loa–Mauna Kea saddle, whence it ascended to the observatory within the daytime upslope wind, appearing there first less than thirty hours after the onset of volcanic activity." In these two cases, effluent arrived at MLO during upslope winds within 1 to 7 days after initiation of volcanic activity.

Other trajectories exist, however, depending on the presence and strength of the trade wind inversion. If the inversion is absent or weak, a vigorously expelled effluent may rise vertically and later be brought down to MLO by the downslope wind flow. This trajectory apparently was followed in the Aloe–Alae craters eruption (1969) when IN concentrations increased abruptly with the first downslope flow following both phases 3 and 4 of the eruption (Hobbs et al., 1971a), and volcanic smog was noted at MLO between 12 and 24 hours following the outbreak of volcanic activity.

Thus, depending on local wind conditions, rainfall, and the strength of the trade wind inversion, volcanic effluent may be detected at MLO within a few hours to a few days following an eruption. It is possible, of course, that strong northerly winds and/or heavy rainfall would completely prevent transit of volatile material to MLO. In the absence of high winds and rainfall, once volcanic smoke reaches MLO, the trade wind inversion and local circulation will tend to retain the effluent over the island for several days unless synoptic conditions develop to purge the atmosphere of contaminants.

In the past ten years there have been four periods of local volcanic activity during IN monitoring at MLO. Each of these periods will be examined for evidence of increases in IN concentration that may be associated with burning vegetation set afire by lava. Such cases usually appear as modulations of the normal IN variation due to other local sources (mainly sugarcane burning) and to "IN storms" of remote (off-island) origin.

ERUPTIONS AND BURNING VEGETATION

Before considering the eruptive episodes in detail we will outline our expectations of how each may have affected the IN concentrations measured at MLO. Two types of eruptions must be considered: those in the summit area of Kilauea volcano, and those occurring along the volcano's rift zones. Three samples of each type of eruption are available.

Summit eruptions

During the Kilauea Iki eruption in 1959 and the eruption of Halemaumau in 1971, only limited areas of forest, on the periphery of lava fountaining, were set afire. We would expect, under the most favorable wind conditions, only a slight enhancement in the IN background for a few days after the initial eruption.

The eruption of 1967–1968 took place entirely within the summit caldera, and there is no record of any vegetation burning. We would expect, therefore, no IN activity as a result of this eruption.

Rift zone eruptions

The Kapoho eruption in 1960 broke out in a sugarcane field, and considerable vegetation burned during the eruption. We would expect rather major increases in IN count, especially in the early stages of the eruption. Similarly, the third and fourth phases of the Mauna Ulu eruption (June 1969), in flowing to the sea, crossed and set afire major forested areas. Certainly, these two phases should be evident as major increases in IN concentration at MLO. Indeed, they are the clearest examples of isolated burning, caused by volcanic activity, in the events described in this report. The Mauna Ulu series of eruptions in February–May 1972 is more complicated, but forest was burned, and IN concentration should have been enhanced during this period.

KILAUEA IKI ERUPTION (1959)

The eruption began at 2008 on November 14, 1959, on the southeast wall of Kilauea Iki crater, which lies on the eastern edge of the Kilauea caldera. Fissures quickly lengthened both eastward and westward, and there soon was a line nearly 0.8 km long of lava fountains about 15 m high. Most of the fountaining lasted for only a few hours, and by the next morning only two small fountains remained active.

Activity began to increase on November 17, and by the afternoon of November 18 a single fountain reached a height of 230 m; on November 19 it occasionally reached 300 m. On November 21 the height of the fountain varied between 50 and 380 m until early evening, when fountaining suddenly ceased at 2000. For the next four days there was no activity.

Just after midnight on the night of November 25–26, the lava fountain suddenly resumed activity, beginning a series of brief eruptive episodes ranging in length from 2 to 32 hours, separated by brief quiescent periods. On November 28 the lava fountain reached a height of at least 460 m, possibly even 520 m—a height unprecedented in the records of Hawaiian volcanoes. Cycles of eruption and withdrawal were repeated at least 14 times until the eruption ended on December 19, 1959.

Price and Pales (1963) show a plot of IN counts at MLO from October 15, 1959, to March 15, 1960. Measurements were made with an expansion chamber twice daily, at 0800 and 1400. In the case of the Kilauea Iki eruption, Price and Pales found "the median count with effluent actually present was only slightly greater than the background median . . .," the values being, respectively, 4.0 and 3.4 IN/10 liters at -24°C. However, the median count in the period before the eruption was 3.3 IN/10 liters, whereas after the eruption it was 4.2 IN/10 liters.

The results of Price and Pales appear to be precisely what might be expected from a summit eruption in which the lava flow was confined within the walls of the crater, and very little vegetation was burned. Only a slight enhancement of the IN count would be expected, and that is what was observed. We view the data presentation of Price and Pales as indicating a general increase in IN activity at MLO between about November 25 and December 28, 1959, although the absolute count remained only slightly above background levels.

Variations in IN concentration during January and February 1960 appear to be different from those measured during the Kilauea Iki eruption. While the overall background count is lower, several peaks appear, especially in measurements made during downslope wind conditions.

KAPOHO ERUPTION (1960)

At 1930 on January 13, 1960, lava broke out in a sugarcane field a few hundred meters northwest of the village of Kapoho, on the east rift of Kilauea volcano. The erupting fissure opened gradually eastward until the line of lava fountains was almost 1 km long. By midnight the three westernmost fountains had ceased activity, but farther east was a row of 15 to 20 fountains, ranging in height from 10 to 100 m. Steam blasts accompanied the fountains sporadically throughout the eruption.

By the morning of January 14 the number of lava fountains was reduced to seven, and through most of the eruption there were only one to three active fountains. The main fountain occasionally reached heights of nearly 300 m, with ash clouds to 600 m.

Lava entered the ocean on the morning of January 15 with a spectacular burst of rolling clouds of white steam. Gradually, over the next few days, lava engulfed nearly the entire village of Kapoho. On January 28 an ash-laden steam cloud rose from the 1959 vent in Kilauea Iki crater.

By the time the Kapoho eruption ended on February 9, 1960, a total volume of about 115 × 10^6 m^3 of lava had poured out (three times that contained in the Kilauea Iki lava lake), and the shoreline had been pushed seaward nearly 0.8 km, adding approximately 2 km^2 of new land to the island.

In the 10-day period (January 6–15, 1960) just prior to the Kapoho eruption, the Hilo Airport Weather Station received a total of about 60.7 cm of rain. Daily accumulations ranged from 1.9 to 18.0 cm. Rainfall was especially heavy during January 13–15, when 38 cm were recorded in the 3-day period. Volcanic haze was first observed in Hilo on January 18.

The weather then changed markedly, with no measurable rainfall in Hilo between January 19 and February 10. Rainfall again became prevalent from February 11 through 17, when 39 cm fell in daily amounts ranging from 1.8 to 14.8 cm. This rainfall seems to have effectively washed out the volcanic effluent present at MLO.

These heavy rainfall periods resulted from synoptic changes accompanied by advection of nucleus-laden air to Hawaii. We would therefore interpret the high IN counts recorded by Price and Pales (1963) just before the onset (January 10–15) and just after cessation (February 16–22) of the Kapoho eruption as "IN storms" of remote origin, similar to those discussed by Hobbs et al. (1971a).

During the drought period (January 19–February 10), several IN peaks appeared in the measurements taken at MLO. The increases in IN concentration that were recorded about January 21 and 30 and February 2 and 5–7 clearly exceeded any IN peak recorded during the Kilauea eruption. Although most peaks occurred in the morning (0800) measurements, under apparently clear air downslope wind conditions, they may still indicate IN generated by vegetation burned during the eruption. Similar IN peaks during the 1969 rift eruption also appeared during downslope flow at MLO (Hobbs et al., 1971b).

It should be noted that the nightly downslope flow at MLO normally changes to a daytime upslope wind at just about 0800. Measurements made during this transitional period may not be truly representative of either upslope flow (conditions below MLO) or downslope flow (air descending from higher elevations).

HALEMAUMAU ERUPTION (1967–1968)

At about 0230 on November 5, 1967, lava fountains broke out along a line extending nearly north-south across the floor of Halemaumau. Lava poured into the crater at a rate of more than 1.2 × 10^6 m^3/h. Fountains gradually increased in height from 15 to 60 m. By midnight the strength of the activity was decreasing, and an hour later, fountaining stopped.

The eruption resumed on the morning of November 9 and gradually increased in strength over the next several days, with occasional lava jets as high as 15 to 20 m. This phase of the eruption ended on November 19 at 1945.

This alternation of periods of fountaining and lava lake activity with periods of drainback and inactivity continued for 3 months, through a total of 28 active periods. Phase 29, which began on February 27, 1968, signalled the beginning of continuous lava lake activity, which lasted until the end of the eruption on July 8, 1968.

From late January to March 1968, simultaneous IN measurements were carried out at four widely separated locations around the rim of the North Pacific Ocean. Observations were taken at MLO and in Alaska, Washington State, and Japan. Two instruments were used in Hawaii. Throughout the measurement period (January 27 to March 31), IN active at −21°C were monitored with the NCAR continuous IN counter (Langer et al., 1967). From about February 1 to March 1, observations also were taken with an IN collector (at −15°C), and samples were examined by electron microscope (Isono et al., 1971). Bigg (1973) has noted some ambiguity in the published results from the two instruments during measurements made in Washington State as a part of this program. He asserts that a detailed comparison of the two data sets shows fluctuations in IN concentration that were exactly out of phase.

Detailed variations in IN activity cannot be extracted from published records of the Hawaii measurements. Unfortunately, Hobbs et al. (1971a) presented the −21°C IN counts at MLO in the form of 1-week running means, and Isono et al. (1971) showed the −15°C data as 28-hour running means.

Having been involved with the NCAR counter measurements at MLO during this period, we have some doubt about the quality of the results. Through most of the period we were essentially learning how to operate the

instrument. Later measurements, in the summer of 1969 and in 1971–1972, were taken with much greater care and appreciation of potential sources of error.

Both the -21°C and the -15°C data are consistent in showing that the lowest IN activity measured at the four observation sites occurred at MLO. The winter of 1967–1968 was unusual in Hawaii. Trade winds were almost totally absent from early December to early March. Trade wind conditions returned about the second week in March and continued through the month. Widespread, heavy rainfall occurred in the last week of March. The major increase in IN concentration in late March is attributed to an "IN storm," similar to those that occasionally appeared in Alaska and Washington State during the simultaneous monitoring program. We do not associate this with local IN sources.

In the absence of detailed information on the variation in IN count at MLO, we can only conclude that the concentration was very low (less than 0.1 IN/liter) until the last few days of March. It is probable that only minor fluctuations about the background level occurred during the measurement period.

ALOI-ALAE CRATER ERUPTION (1969)

On May 24, 1969, lava fountains broke out at three locations along the east rift zone from just southeast of Aloi crater to Kane Nui o Homo. Lava poured into Alae crater and covered part of the Chain of Craters Road. Activity ceased on May 25 but recommenced on May 27 and continued until May 29.

IN measurements began at MLO on June 1 using two NCAR counters, one operating at -21°C and the other at -15°C. Pronounced IN peaks were recorded during downslope wind flow on June 1 and 2, and minor IN peaks during downslope flow the succeeding two mornings. Afternoon values, during upslope flow, were low but clearly higher than the background IN concentration. We suggest that the enhanced IN activity on June 1–4 may be related to the second phase of the eruption (May 27–29) through localized burning of the forest around the eruption site.

With the exception of two small IN peaks on June 7 and 9, again during downslope wind conditions, the IN count remained virtually zero from noon on June 4 to noon on June 12. Island-wide rainfall occurred on June 11–12, 1 cm of rain falling in the volcano area on June 12 up to 0900.

The third phase of the eruption began at 1330 on June 12 and lasted for 21.5 hours. Lava fountains up to 150 m again shot from the fissure between Aloi and Alae craters, and a voluminous and rapid lava flow poured southward down and over the cliffs of the Hilina fault system to form a broad pool on flat land about 0.6 km from the coastline. Volcano observatory personnel reported that considerable forest burned during this lava flow.

Late on the afternoon of June 12 the IN concentration at MLO began to increase. During the downslope wind flow on June 12–13 the IN count peaked at approximately the same concentration as that measured on June 1–2. MLO personnel reported "heavy volcanic smog" at the observatory early on the morning of June 13. The IN count returned to background levels about noon on June 13 and remained practically zero until June 26. Hobbs et al. (1971b) argue convincingly that the June 12–13 IN peak was related to the third phase of the eruption.

The fourth phase of the eruption began at 2145 on June 25 and ceased about 9 hours later. Fountains 125 m high in the same east rift area again sent voluminous lava flows down the Hilina fault scarps. A narrow tongue of lava entered the ocean just east of Apua Point.

Volcanic smog was first noted at MLO on the morning of June 26, but the IN count remained low until downslope winds began about 2100. The IN concentration then increased rapidly to values similar to those recorded on the nights of June 1–2 and 12–13, with a clear peak during downslope flow on June 26–27. By noon on June 27 the IN concentration returned to background levels and remained low until the afternoon of June 29. Undoubtedly, the June 26–27 IN peak was related to the fourth phase of the eruption.

Synoptic conditions then changed dramatically, beginning on June 28–29. Cirrus clouds were common, and the winds at MLO were constantly from the southeast at speeds exceeding 10 m/s. Island-wide rainfall occurred from June 29 to July 11, with several days of moderate rainfall in the volcano area. These conditions suggest that the "IN storm," measured at MLO between June

30 and July 10, was not of island origin but rather was due to advection of IN into the air above Hawaii by upper level synoptic disturbances (Hobbs et al., 1971b).

HALEMAUMAU ERUPTION (1971)

On August 14, 1971, there was a 10-hour eruption (0900–1900) in Halemaumau, with fountaining up to 75 m. Forest on the edge of the crater was set afire, and some 26 ha were burned before the fire was brought under control on August 15 at about 2000.

Fortunately, the day before the eruption, IN monitoring began at MLO using two modified NCAR ice nucleus counters, operating in parallel. Detailed IN plots from the two instruments for the period August 13–23, 1971, are given by Langer et al. (1974). These plots indicate enhanced IN activity at MLO following the eruption, in particular, pronounced peaks in the daytime upslope flow. Additional details on the monitoring program and island-wide rainfall are given by Fullerton et al. (1975).

Another eruption began about 1920 on September 24, 1971. The initial outbreak occurred on the floor of Kilauea caldera, with lava flows cascading down into Halemaumau and fountains rising to about 50 m. Sporadic and irregular activity continued until the evening of September 29. Fullerton et al. (1975) show plots of IN activity from August 13 to September 28. IN concentrations, very low on September 22–23, increased progressively from September 24 to September 27. IN peaks appeared daily in the upslope flow.

The interpretation of IN events in August and September 1971 is difficult. IN peaks in mid-September may be related to sugarcane fires, which were common because of dry weather island-wide. Furthermore, at the same time these two brief eruptions took place in the summit area, activity continued on the east rift, the Mauna Ulu vents emitting copious fume. During the September 24–29 Halemaumau eruption, fountaining also occurred at Mauna Ulu, and as late as mid-October, sporadic sounds of fountaining and splashing lava could be heard from the area. After this time, however, seismic evidence indicated that the 1971 phase of the Mauna Ulu eruption had ended.

There was no volcanic activity on the island from mid-October 1971 through early February 1972. This lull in volcanic activity corresponded closely in time to the annual hiatus in sugarcane field burning. Under these conditions, very low IN concentrations would be expected at MLO, and this is what was observed (Fullerton et al., 1975).

MAUNA ULU ERUPTION (1972)

Mauna Ulu began fountaining again on the afternoon of February 6, 1972. Considerable quantities of new lava were deposited from Alae crater on February 12–16. Activity continued, but at much less magnitude, until February 25, when lava overflowed the Mauna Ulu summit crater. From February 25 to March 4–5, lava flowed out to form a tongue about 400 m wide and about 4 km long. Fountaining averaged about 40 m, with bursts to 75 m. Low-level activity continued over the next two weeks.

On March 18, new vents opened west and southeast of Mauna Ulu and were vigorously active until March 23–24. At the same time, the eruptions in Mauna Ulu crater remained strong. Throughout April and early May the eruption continued at a fairly steady rate, lava flowing from one or more vents essentially without interruption.

Fullerton et al. (1975) show plots of IN concentration at MLO from February 14 to May 15, 1972. Numerous high IN peaks appear. Those on February 26–28 and March 22–27 may well reflect vegetation set afire by migrating lava flow. High IN concentrations on several days in April and May may similarly be related to volcanic activity. Unfortunately, the chronology of the eruption is not sufficiently detailed to positively correlate IN peaks with vegetation ignited by lava. Many of the days exhibiting low IN concentrations occurred during periods of heavy and widespread rainfall, for example, on the afternoon of February 18 and 23 and on March 4–5.

Ice Nucleus (IN) Monitoring and Volcanic (VOL) Activity on the Island of Hawaii

IN Monitoring Period	IN Instrument	References	Volcanic Activity	IN Activity expected/observed
15 Oct 59 to 15 Mar 60	10-liter expansion chamber (modified Bigg-Warner), –24 °C daily counts at at 0800 and 1400	IN: Price and Pales (1963) VOL: Macdonald and Abbott (1970)	Kilauea Iki (summit) 14 Nov 59 to 19 Dec 59 Kapoho (E rift) 13 Jan 60 to 19 Feb 60 Lava entered sea on 15 Jan at 1930 hrs	Slight EB*/Slight EB* EB* and isolated IN peaks/ Isolated IN peaks ("IN storm")
25 Jan 68 to 31 Mar 68	NCAR counter at –21 °C; continuous IN collector at –15 °C (Isono)	IN: Hobbs et al. (1971a) Isono et al. (1971) VOL: Macdonald and Abbott (1970)	Halemaumau (summit) 5 Nov 67 continued through 28 phases 27 Feb 68: Phase 29 begins: continuous lava lake to 8 July	None/Cannot extract detailed IN activity from published data; very low IN count at MLO ("IN storm")
4 June 69 to 10 July 69	Two NCAR counters continuous; one at –21 °C, the other at –15 °C	IN: Hobbs et al. (1971 a,b) VOL: Macdonald and Abbott (1970) Wright et al. (1975)	Aloi-Alae (E rift) Phase 1: 24–25 May 2: 27–29 May 3: 12–13 June 4: 25–26 June Lava entered sea on 26 June at 0835	Major IN peaks from phases 2, 3 and 4/ Expected peaks observed ("IN storm")
14 Aug 71 to 14 May 72	Two NCAR counters in parallel at – 21 °C but with different supersaturations	IN: Mendonca and Pueschel (1973) Langer et al. (1974) Fullerton et al. (1975) VOL: Hawaiian Volcano Observatory field notes	Halemaumau (summit) 14 Aug; 24–29 Sept Mauna Ulu (E rift) 1969 activity continues to mid-Oct 6 Feb 72 to mid-May and continuing	EB* and isolated IN peaks/Expected EB* observed along with occasional IN peaks; low IN activity in absence of volcanic activity

*enhancement of IN background count

CONCLUSIONS

A reasonable case appears to have been made relating volcanic activity on the island of Hawaii to increased IN concentration at MLO through vegetation set afire by lava flows. With the exception of the 1968 Halemaumau eruption, where adequate documentation of the IN measurements is not available, existing data indicate the following:

1. Kilauea summit eruptions, characterized by minimum burning, produce only slight enhancement of the IN concentration at MLO.
2. Rift zone eruptions through forested areas may, under optimum conditions, give major IN peaks.

IN concentrations at MLO are modulated by prevailing winds and clearly affected by widespread rainfall. Sugarcane field burning is probably the major source of IN on the island and thus the determinant of the IN background level. "IN storms" occasionally move into Hawaii to further complicate the problem.

The accompanying table summarizes volcanic activity and IN monitoring programs at MLO from 1959 to 1972, along with our interpretation of how lava-induced burning of forested areas may have affected the IN concentration.

We urge that a program of continuous IN measurements be established and maintained at MLO. If this is done, future measurements may confirm that forest burning is the connection between eruptions and enhanced IN concentrations. The type and amount of material burned should be determined. Trajectory and transit times should be assessed and information on the strength of the trade wind inversion obtained. A detailed chronology of eruptic activity should be maintained. With these data it should be possible to establish clearly the link between eruptions and the ice nucleus concentrations measured at MLO.

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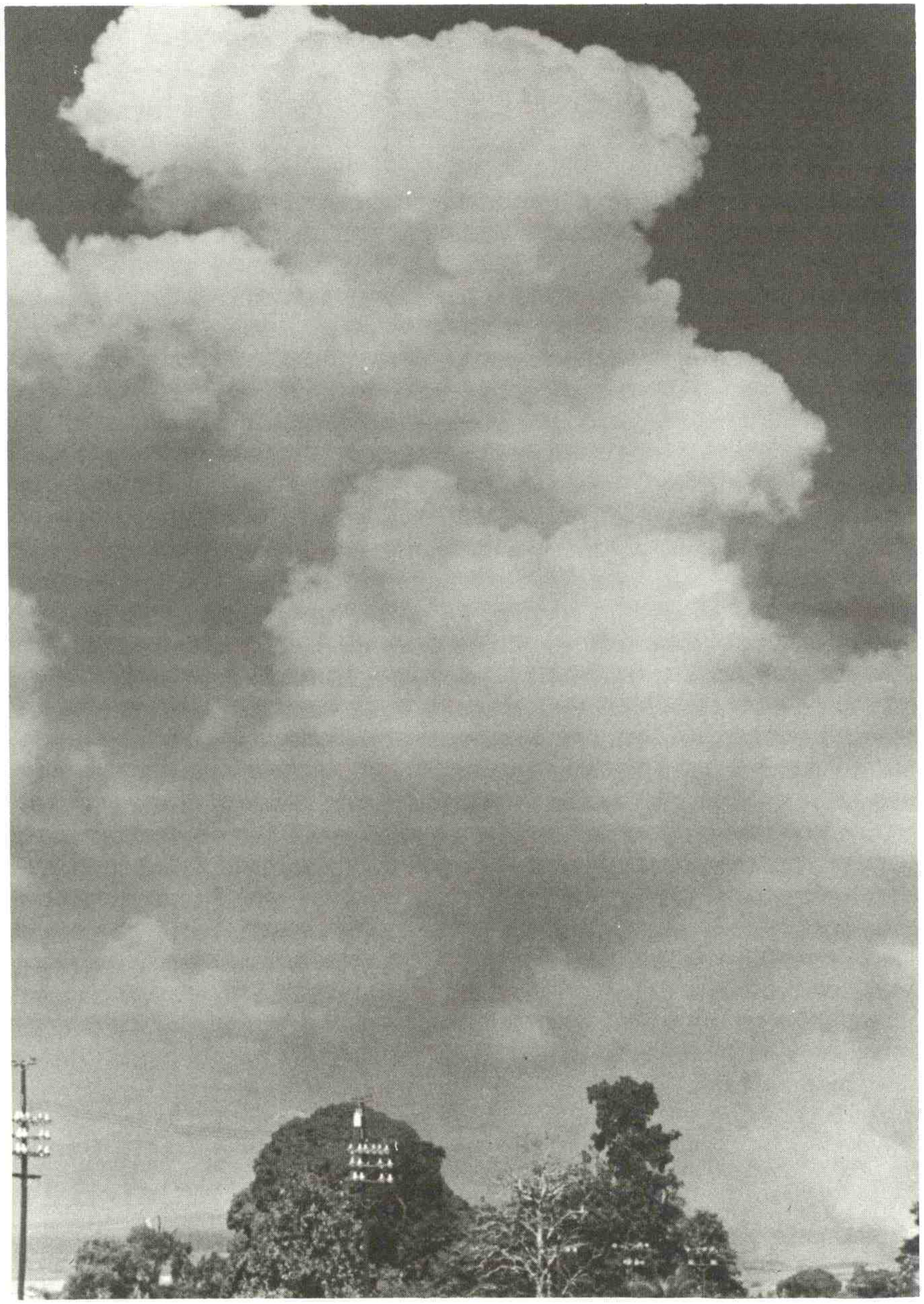

ICE NUCLEATION PROPERTIES OF SOILS FROM HAWAII AND THE CONTINENT

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INTRODUCTION

Our interest in the nucleation properties of soils arose from a study carried out at the Mauna Loa Observatory, Hawaii, to determine the extent to which local sources form ice nuclei. A major source of nuclei was found to be the smoke or, more specifically, the ash particles from cane field fires (Pueschel and Langer, 1973) — the sugarcane leaves are set on fire just before harvest. A subsequent observation that lava dust nucleates effectively (Langer et al., 1974) led us to question whether the soil from the sugarcane plantations has enhanced nucleation properties because it contains lava and trace elements from fertilizer and agricultural sprays. An alternative explanation is that the plant growth process leads to the synthesis of a nucleating material, and therefore all the activity originates with plant ashes. In this paper we discuss soil nucleation activity and the possibility that dust generated by vehicles and cultivation is an erratic source of nuclei. Soil samples from the continental United States were also examined to provide a basis for comparison with Hawaiian soils, since to our knowledge no such work had previously been carried out.

On the island's eastern coast, the smoke plume from burning sugar cane (lower right) rises into cumulus clouds.

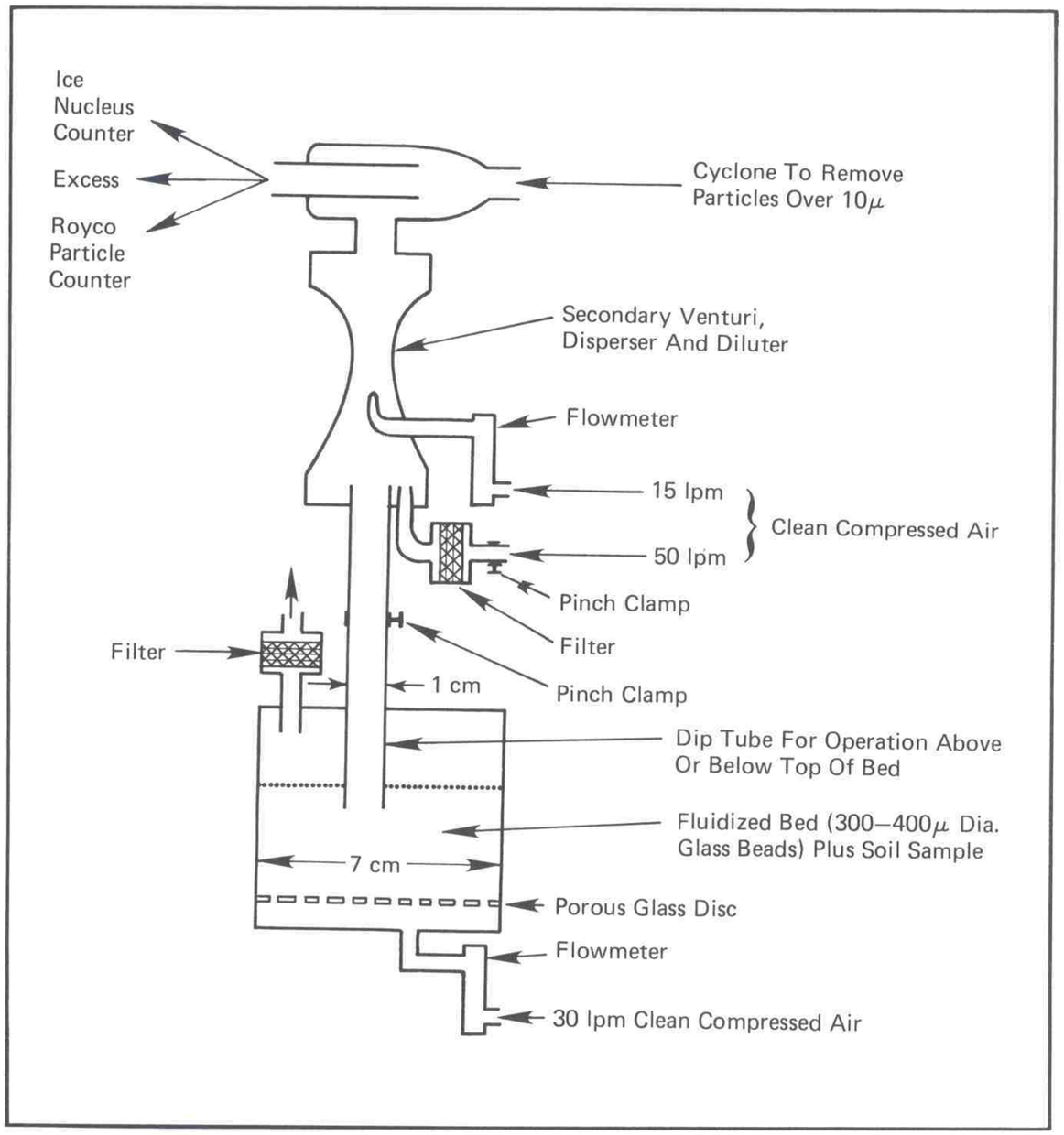

Figure 1. Fluidized bed disperser to generate soil aerosols.

EXPERIMENTAL PROCEDURE

The soil samples are collected right at the surface, dried at 100°C, and sieved through a 44-μm screen. The fluidized bed disperser shown in Fig. 1 is used to produce an aerosol from about 0.1 g of soil sample; the dust is gradually released from the bed of glass beads, and particles larger than 10 μm in diameter are separated out by a cyclone. The size distribution and the concentration of the resulting aerosol are determined with a light-scattering counter. Another stream of the aerosol is diverted to two NCAR ice nucleus counters (Langer, 1973), one operating at -16°C and the other at -20°C. The data are thus obtained in terms of the fraction of the particles nucleating out of the total aerosol. We assume that the particles of less than 0.5-μm diameter, which are not counted by the light-scattering device, are not involved in the nucleating process. That assumption certainly merits verification; however, the necessary resources were not available for our study.

In the case of the Hawaiian soils, some additional work was done to narrow down the particle size range in which most of the nucleus activity exists. By adjusting the airflows in the aerosol generator we reduced the fraction of particles leaving the system by a factor of 10 in the 3- to 9-μm range. As can be seen from Table 1, there is essentially no activity in the 0.5- to 3-μm-size range. By making use of this fact and recalculating the nucleus activity on the basis of the particles in the 3- to 9-μm range for the Hawaiian soil, we obtained the results shown in parentheses in Table 1. Those results show a high activity for the large particles; they also indicate that cane ashes are no more active than soil.

In Hawaii cane fires do represent an important source of ice nuclei in comparison with windblown soil particles because the soil is usually too moist to release much dust. After a fire the residual ashes of the dry leaves become airborne when the harvesting machines pick up the stalks. The smoke itself, mostly oily organic material, does not nucleate until the burned leaves are mechanically disturbed and ash particles are airborne. In contrast to the situation in Hawaii, windblown soil could be an important source of ice nuclei in the continental United States, especially during dust storms in the southwest.

Table 1. Soil Ice Nucleus Activity

Source of soil**	% of particles active as ice nuclei			
	0.5- to 9-μm range		0.5- to 3-μm range	
	At -16 °C	At -20 °C	At -16 °C	At -20 °C
Miles City, Montana, 15 different locations, includes cultivated fields.	0.01–0.06	0.08–0.9	—	—
NE. Colorado, 2 locations, prairie soil.	0.01–0.07	0.04–0.2	—	—
Texas, 4 locations, includes windblown dust.	0.01–0.1	0.09–0.7	—	—
Nebraska, 4 locations, cultivated fields and prairie soil.	0.01–0.02	0.02–0.03	—	—
Hawaii:				
Papaya field, barren lava sand until 1974.	0.01 (.5)*	0.06 (3)*	not detectable above background	
Sugarcane field, freshly planted, in use 15 years.	.008 (.4)*	0.07 (4)*	"	"
Sugarcane field, mature plants, in use 20 years.	.008 (.5)*	0.05 (3)*	"	"
Sugarcane field, recently harvested, in use 20 years.	.01 (.6)*	0.08 (5)*	"	"
Ashes from cane leaves, right after fire.	.009 (.4)*	0.04 (2)*	"	"

**The Montana soil samples were obtained through the courtesy of Dr. A. B. Super, Bureau of Reclamation; Texas and Nebraska soil samples from Dr. D. Gillette, NCAR; Hawaii soil samples from Dr. J. Miller, Mauna Loa Observatory, NOAA.

*Recalculated on the assumption that all of the activity is in the 3- to 9-μm size range.

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AEROSOL CONCENTRATIONS AND FALLOUT AT MAUNA LOA

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The Health and Safety Laboratory (HASL) participated in two environmental programs at the Mauna Loa Observatory (MLO): (1) collections of monthly fallout deposition, and (2) continuous high-volume aerosol sampling.

FALLOUT DEPOSITION COLLECTION

Fallout deposition collection at Mauna Loa was started in February 1959 as part of an expanding research program concerning the global distribution of debris from nuclear weapons tests (Hardy and Klein, 1959; Harley, 1976). At that time this and 21 other new sites were chosen and set up at U.S. Weather Bureau stations, through the cooperation of Dr. Lester Machta.

The sampling device that permitted this rapid expansion of our fallout studies is a plastic funnel-ion exchange column combination. The substances of interest (originally fission product cations) are retained in the column while the bulk of the precipitation passes through. Dry fallout is also captured and retained in the top of the column. Only the actual column needs to be returned for analysis. Hence the system is practically accident-free and can be operated by relatively untrained personnel. The record at Mauna Loa is virtually unmatched in our entire 150-station network. Through more than 17 years of continuous monthly sampling (206 samples), only two samples failed to arrive at HASL.

The isotope of major interest in the HASL fallout studies has been Sr^{90} because of its potential toxicity. Generally following calcium's geochemical pathways (e.g., United Nations, 1972; Bennett 1976a) after being deposited on the earth's surface (primarily in precipitation), Sr^{90} enters the food chain by being taken up in vegetation and ultimately appears in measurable quantities in many foods, cow's milk being perhaps of most concern (Bennett, 1976b). From time to time a shorter-lived isotope, Sr^{89}, was also measured.

All of the fallout deposition data are published quarterly (Hardy, 1977) and are reproduced here as Table 1. The data are also used in computing the annual fallout and deposit on the earth's surface (Feely, 1976) as part of HASL's unique responsibility for maintaining a complete inventory of Sr^{90} from nuclear explosions.

In April 1976, additional collectors were installed at MLO to obtain separate samples of wet and dry deposition. The wet and dry samples are being studied specifically with the goal of obtaining "global baselines" for major cations, anions, and other trace substances in precipitation.

AEROSOL SAMPLING

The HASL Surface Air Sampling Program is a direct outgrowth of a program initiated by the U.S. Naval Research Laboratory (NRL) in 1957 and continued through 1962 (Lockhart et al., 1964). The NRL program at Mauna Loa was established in 1960. Direction was transferred to HASL in 1963. The objective of the program is to study temporal and spatial distributions of specific natural and man-made radionuclides as well as other trace substances in surface air.

The present network of 21 stations extends from about lat. 76°N. to lat. 90°S. Air is drawn through filter paper continuously at the rate of about 1 m^3/min and, for the most part, analyses are carried out on monthly composites. We have routinely analyzed the filters for 7 radionuclides and stable lead; however, as many as 13 different isotopes have been measured for special purposes. Additional stable trace metal analyses are being added to the

program. Since portions of many of the samples dating from 1968 have been saved, these and other analyses may be carried out at selective sites retrospectively.

All of the surface air data from this program are also published quarterly (Feely et al., 1977), and the quality of the analytical results is summarized once each year (Toonkel et al., 1977). Tables 2 and 3 are included as examples of the available data. Table 2 lists the monthly Sr^{90} results for the entire period of the program. Table 3 summarizes the concentrations of the natural, cosmic ray-produced nuclide, Be^{7}. These analyses were started in 1970. Again, the record for successful delivery of samples from the site to the laboratory has been very close to perfect.

We acknowledge with great respect the on-site personnel at MLO, who have so successfully maintained our sampling programs year in and year out: We are well aware of the functional difficulties in performing complex technical manipulations at this altitude and therefore take this opportunity to commend all of the people associated with the Geophysical Monitoring for Climatic Change program (and its predecessor programs at MLO) for this extraordinary cooperation.

Table 1. Monthly Sr^{90} Fallout at MLO, Hawaii
Lat. 19°32'N, Long. 155°35'W, Elevation 3,401 m (Column)
(Millicuries per square kilometer)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1959	—	0.49	—	0.01	0.02	0.00	0.03	—	—	0.01	*	0.04	0.60
1960	0.06	0.07	0.07	0.05	0.06C	0.13C	*	*	0.00C	0.00C	*	*	0.44
1961	0.01C	0.05C	0.05C	0.06C	—	—	0.00C	0.01C	*	0.02	0.02	0.03	0.25
1962	0.16	0.02	0.41	0.41	0.57	0.07	0.00	0.02	0.05	0.00	2.31	0.02	4.04
1963	0.32	0.15	0.84	0.31	1.42	0.76	0.39	0.18	0.17	0.03	0.02	0.23	4.82
1964	0.12	0.10	0.31	0.23	0.23	0.01	0.20	0.06	0.03	0.05	0.06	0.09	1.49
1965	0.16	0.06	0.09	0.18	0.27	0.08	0.07	*	0.07	0.04	0.02	0.03	1.07
1966	*	0.25	0.04	0.04	*	0.01	0.02	*	0.01	0.06	0.02	0.04	0.49
1967	0.03	0.01	0.06	0.05	0.04	0.01	0.03	0.01	0.01	*	*	*	0.25
1968	0.01	*	0.05	0.11	0.02	0.05	0.02	0.04	0.04	0.01	0.02	*	0.37
1969	0.02	0.02	0.04	0.02	0.02	*	*	*	0.02	0.01	*	0.01	0.16
1970	*	0.01	*	0.11	0.04	*	0.01	0.01	*	*	*	0.02	0.20
1971	0.02	0.01	0.01	0.14	0.05	0.04	0.02	*	0.01	*	*	*	0.30
1972	0.10	0.02	0.02	0.02	0.02	0.01	0.03	*	*	*	*	0.04	0.26
1973	*	*	*	*	*	*	*	*	*	*	*	*	0.00
1974	*	0.04	0.05C	0.05C	0.05	0.02	*	*	*	*	—	—	0.21
1975	0.03	0.04	*	*	*	*	*	0.01	*	*	*	*	0.08
1976	*	*	*	—	—	—	—	—	—	—	—	—	0.00

—: Data not available
*: Zero or trace
C: Proportioned from originally consolidated data

Table 2. Surface Air Sr^{90} Concentration at MLO, Hawaii (Femtocuries/cubic meter)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1957	—	—	—	—	—	—	—	—	—	4.14	5.86	6.31
1958	8.11	9.45	27.90	22.10	22.50	27.90	23.00	—	—	—	—	—
1960	4.19	—	6.25	—	5.59	—	—	—	1.84	—	1.73	—
1961	1.73	1.73	4.44	4.44	4.95	4.95	2.70	2.70	1.45	1.45	7.61	7.61
1962	22.00	22.00	39.30	39.30	36.70	36.70	19.50	19.50	9.19	9.19	17.60	17.60
1963	51.30	78.80	49.90	89.70	70.90	87.30	81.60	39.00	17.30	22.00	20.80	19.50
1964	42.60	96.20	49.90	68.50	84.80	42.90	36.10	15.40	12.60	8.96	8.26	9.10
1965	20.30	40.80	27.60	22.80	16.50	18.40	13.90	7.87	4.64	6.34	4.19	6.95
1966	8.07	8.40	16.50	14.00	14.10	9.86	6.84	2.58	1.94	1.10	1.97	3.60
1967	5.38	5.59	3.24	5.63	2.75	1.80	1.40	—	0.79	0.68	3.82A	0.98
1968	2.57	1.38	3.70	6.80	5.18	5.80	3.08	2.66	2.03	1.07	0.66	1.80
1969	2.28	1.79	2.73	4.54	5.76	4.88	4.34	2.46	1.80	2.17	1.14	1.08
1970	1.58	4.08	7.74	8.25	8.16	5.71	4.86	2.27	2.62	0.87	1.05	0.00
1971	2.67	2.44	4.15	2.70	7.18	10.40	5.11	2.29	1.45	1.01	0.89	1.22
1972	2.05	2.09	1.60	2.12	2.32	1.96	1.66	0.66	0.58	0.47	0.41	0.57
1973	0.52	1.18	0.68	1.52	1.21	0.80	0.50	0.21	0.16	0.14	0.16	0.42
1974	0.67	2.47	4.28	3.47	3.89	3.18	1.76	0.99	0.66	0.71	0.87	1.24
1975	1.30	2.06	1.52	2.49	2.81	1.45	1.07	0.43	0.30	0.12	0.20	0.23
1976	0.43	0.47	0.40	—	—	—	—	—	—	—	—	—

—No data
Errors are less than 20% except:
A–error between 20% and 100%
B–error greater than 100%

Table 3. Surface Air Be^{7} Concentration at MLO, Hawaii (Femtocuries/cubic meter)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1970	—	—	—	—	246.00	253.00	247.00	197.00	298.00	181.00	141.00	166.00
1971	236.00	250.00	242.00	—	164.00	229.00	205.00	260.00	209.00	215.00	178.00	221.00
1972	241.00	206.00	168.00	304.00	215.00	168.00	176.00	149.00	167.00	172.00	136.00	255.00
1973	189.00	197.00	194.00	255.00	196.00	216.00	176.00	165.00	173.00	151.00	118.00	132.00
1974	136.00	191.00	247.00	213.00	201.00	194.00	224.00	247.00	161.00	186.00	218.00	213.00
1975	199.00	184.00	231.00	225.00	307.00	249.00	231.00	259.00	276.00	188.00	226.00	246.00
1976	262.00	227.00	191.00	—	—	—	—	—	—	—	—	—

—No data
Errors are less than 20% except:
A–error between 20% and 100%
B–error greater than 100%

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ISOTOPIC COMPOSITION OF LEAD AEROSOLS AT MAUNA LOA OBSERVATORY

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INTRODUCTION

Industrial societies have begun to appreciate, especially during the last few decades, the importance of understanding the effects of their activities on the atmosphere. Degradation of air quality in urban areas is one of the most obvious results of modern civilization; there have been other, more subtle changes on a global scale. Nuclear weapons testing in the atmosphere, especially during the early 1960s, produced radioactive debris that spread throughout the troposphere and lower stratosphere. Combustion of fossil fuels has produced a readily measurable and continuing increase in the CO_2 content of the global atmosphere (Pales and Keeling, 1965; Keeling et al., 1976).

Although the effect of humans on hemispheric scale aerosol patterns is less clear, measurements of electrical conductivity of marine air from surface ships indicate that the aerosol burden of the air over the North Atlantic probably has substantially increased over the last half century (Cobb and Wells, 1970). The potential global climatic implications of significant changes in atmospheric gases and aerosols are still intensively debated, but there is no question about altered urban climates and measurable health effects on a local scale during air pollution episodes. Considerable research is now in progress on a number of potential interactions of man with large-scale climatic trends.

It is important to establish the extent and consequences of changes in the characteristics of the atmosphere far removed from local pollution sources, particularly with respect to aerosols. Aerosol concentrations in the upper troposphere and some remote areas of the lower troposphere are very small in comparison with most continental areas, and especially with urban areas. The term background aerosols has often been used for aerosols in remote areas of the lower troposphere and much of the upper troposphere, but the relative importance of the sources and many of the chemical and physical properties of these aerosols are still largely undefined (Junge, 1968). Background aerosols are probably a mixture derived from both natural and anthropogenic sources in continental areas and by natural processes at the sea surface. Since the relative importance of the various sources is not established, we cannot accurately assess the potential alteration by humans of the balance of the background aerosol burden.

Aerosols in urban regions are chemically substantially different from aerosols in remote areas of continents, the most obvious differences being the high concentrations of sulfur and heavy metal in urban aerosols. These chemical differences can potentially be exploited to help define the anthropogenic portion of background aerosols. Heavy metal concentrations of aerosols from remote areas have been determined by a number of investigators. During 1970–1971, aerosols collected at Mauna Loa Observatory (MLO) were analyzed to determine which heavy metals would be the most promising as indicators of that portion of the aerosols derived from distant (greater than 1,000 km) urban sources (Simpson, 1972a). On the basis of the analytical techniques used in that study, observed concentrations of metals in samples from MLO and other sites on the island of Hawaii, and relative strengths of natural and anthropogenic sources of several metals (Fe, Mn, Zn, Cu, Ni, Pb), it was concluded that lead was the best indicator of man's contribution to aerosols in remote regions. Duce et al. (1975) have discussed the enrichment relative to average crustal ratios of a number of trace elements in aerosols from remote areas. This enrichment may be due primarily to natural processes which supply volatile trace elements to the atmosphere or to pollution sources. Thus defining processes that are most important to the aerosol budget of lead in remote areas could provide better understanding of the atmospheric transport of a large number of trace elements.

A number of other studies of atmospheric lead concentrations in remote areas have been made. Chow et al. (1969) used isotope dilution mass spectrometry to analyze air filter samples collected from shipboard in the Pacific. They estimated lead concentrations in central Pacific aerosols to be on the order of 1 ng/m^3 of air (1 ng $= 10^{-9}$ g), with significant uncertainty introduced by shipboard contamination problems. The results of several studies of background aerosol lead concentrations were summarized by Chow et al. (1972), and isotope dilution mass spectrometry data for remote mountain sampling

sites in California were reported, indicating an annual average baseline for the continental United States of ~8 ng/m³. Published Indian Ocean values range from 1 to 4 ng/m³ (Egorov et al., 1970); values for arctic areas have been reported to be 0.2 (Egorov et al., 1970) to 0.5 ng/m³ (Murozumi et al., 1969). Hoffman et al. (1972), using atomic absorption spectrometry, reported an average of 3 ng/m³ on the windward side of Oahu, while Simpson (1972a), also using atomic absorption spectrometry, suggested that the concentration of lead in aerosols collected above the trade wind inversion on the island of Hawaii averaged about 1-2 ng/m³. Volchok (1973) has summarized lead concentration data for the five most remote of the twenty surface-air monitoring stations maintained by the Health and Safety Laboratory of ERDA primarily for study of radioactive debris from nuclear weapons tests. These stations, two in the Northern Hemisphere and three in the Southern Hemisphere, all have median values below 10 ng/m³ of aerosol lead, the lowest values at all the sites being in the range of 0.2 to 2 ng/m³ found by other investigators. All of the published values for the concentrations of aerosol lead in the central Pacific are quite low, averaging about 3 orders of magnitude less than the values found in urban continental air.

Unfortunately, there are no measurements of aerosol lead in remote areas that predate the large-scale use of lead alkyl additives to gasoline, so there is no direct evidence that aerosol lead burdens in remote regions have increased appreciably because of leaded gasoline combustion. However, on the basis of mass balance calculations a number of investigators believe that most of the present total standing crop of aerosol lead is probably anthropogenic (Patterson, 1965). Estimates of the natural level of aerosol lead in remote areas vary greatly but in general are substantially lower than the 1 to 2 ng/m³ currently found (Patterson, 1965). The most dramatic evidence suggesting that current levels of background aerosol lead are far above natural levels is the increase of lead content found in polar snows from Greenland and Antarctica (Murozumi et al., 1969). These measurements, made by isotope dilution mass spectrometry on large samples with good stratigraphic control, indicate that current Greenland snow contains lead in amounts hundreds of times larger than snows of a few thousand years ago.

STABLE ISOTOPE COMPOSITION AS A TRACER FOR THE SOURCE OF AEROSOL LEAD

In studies of human contribution of metals to the overall composition of aerosols, lead has several advantages relative to other atmospheric heavy metals introduced in large amounts from urban areas. One is the relatively high proportion of total aerosol lead that can be directly attributed to a single source: automobile exhaust. In addition, there are large variations in the isotopic composition of anthropogenic aerosol lead. There are four nonradioactive (stable) isotopes of lead: ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb. All of these isotopes were present in the initial material that accreted to form the solar system, and the amounts of the latter three isotopes have increased with time because they are the stable daughter products of the radioactive decay of ^{238}U, ^{235}U, and ^{232}Th (Patterson et al., 1955). The isotopic composition of lead averaged over the bulk of the crust of the earth has evolved in a reasonably coherent fashion to a composition similar to that represented by pelagic sediments in the world ocean today (Chow, 1958; Chow and Patterson, 1962), although there is significant regional variation. Lead ores, on the other hand, have considerable variation in stable isotopic composition depending upon a number of complicated processes including the geologic period in which the concentration of the lead into ore bodies occurred (Brown, 1962). The isotopic composition of the lead used for gasoline additives is variable because different ore leads are used by different tetraethyl lead producers, and so it is difficult to predict the isotopic composition of anthropogenic aerosol lead of any given region. However, a few investigators, as discussed below, have been able to determine a great deal about urban regional variations in isotopic composition of aerosol lead and to use these variations to deduce the source of the lead in environmental samples. These studies of isotopic composition have generally focused on areas of relatively high aerosol lead content and have not been used to explore the isotopic composition of aerosols from remote regions.

Chow and Johnstone (1965) demonstrated that aerosol leads from Los Angeles, snow lead from a rural area in California, and lead from gasolines marketed in the Los Angeles area all had almost identical isotopic compositions, which could be readily distinguished from average crustal lead as represented by lead found in Pacific sediments. The dominance of automobile exhaust lead in the isotopic composition of environmental lead samples near major roads has been clearly shown in several subsequent studies (Chow, 1970; Ault et al., 1970). Chow (1971) later demonstrated that aerosols and soils from a number of cities had lead isotopic compositions identical with the gasoline marketed in those cities. There can be little question that aerosol lead in urban areas is derived almost entirely from local automobile exhausts. One of the most interesting findings of the latter study was the large spread in isotopic composition among the urban lead aerosols from region to region: aerosol leads from Southeast Asia were very primitive (low in radiogenic lead), approaching the composition of some of the most ancient lead ore deposits, while aerosol leads from the United States and Europe were much more radiogenic. The isotopic composition of urban environmental leads was extremely large, approaching the total range found for economically important lead ores (Brown, 1962; Chow, 1971) except for the most anomalous lead ores which have received very large radiogenic lead contributions. The observed range of variation for urban environmental leads is extremely large in comparison with the precision of the measurements and with the degree of agreement between the gasoline leads and aerosol leads within each urban area. Thus aerosol leads from different urban regions have characteristic isotopic compositions which potentially could be exploited to help determine the fate of lead aerosols traveling far from the relatively discrete urban source areas.

When lead is supplied to environmental samples from two sources of comparable magnitude, it is frequently possible to delineate the magnitude of each source with sufficient sampling and to determine the relative importance of the contribution of each to an individual sample. Rabinowitz and Wetherill (1972) used isotopic measurements to define the extent of local lead contamination from a smelter and milling operation in Missouri, in the presence of a large diffuse source of aerosol lead from automobiles. This was possible because the local lead ore in Missouri had an anomalously high radiogenic isotopic composition and could be readily distinguished from nearly all gasoline-derived leads. A similar study in California (Rabinowitz and Wetherill, 1972), this time near a smelter emitting leads with a very nonradiogenic "signature," gave comparable results. It was shown that horses from near the smelter site that had died of lead poisoning had derived approximately equal amounts of lead from the smelter and from local automobile exhaust. Chow and Earl (1972) measured the lead isotopic composition of coals and found it to be substantially different from that of most gasoline leads, thus indicating the possibility of distinguishing aerosol lead derived by coal burning from automobile exhaust lead. In general, lead smelters and coal combustion appear to be relatively small sources of aerosol lead in comparison with automobile exhaust except near point sources, and do not significantly affect the global scale budget of aerosol lead. Studies of lead smelter and coal lead isotopic compositions do indicate, however, the potential for distinguishing two sources of aerosol lead if the isotopic compositions are significantly different.

LEAD ISOTOPE MEASUREMENTS ON AEROSOL SAMPLES FROM MLO

A study of aerosol chemistry on the island of Hawaii was made during 1970–71, much of the work being based on samples collected at MLO (Simpson, 1972a). In general, it was shown that aerosols could be collected at MLO that were not contaminated by lead from towns along the coast of the island of Hawaii and that lead concentrations above the trade wind inversion were in the range found by Chow et al. (1969) for central Pacific samples collected on shipboard. The chemistry of sodium, potassium, calcium, and magnesium in aerosols collected above the trade wind inversion at MLO was shown to be substantially different from fresh marine aerosols and also from "fractionated" marine aerosols that could periodically be collected at the observatory site (Simpson, 1972b). The aerosol cation chemistry at MLO resembles greatly that of precipitation from continental areas (Junge, 1963), suggesting

Table 1. The Isotopic Composition of Aerosol Lead from Hawaii

Sample Number	Sample Code*	Collection Period (1970)	Ratios**			
			$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	ng/m³
1	P 4	11/9–11/16	18.90	1.210	0.4926	1.1
2	P 9	12/2–12/16	18.52	1.189	0.4978	1.0
3	P 10	12/2–12/16	18.10	1.164	0.4809	1.1
4	P 13	12/23–12/30	18.65	1.195	0.4896	5.5
5	P 14	12/23–12/30	18.60	1.193	0.4896	7.3
6	H 13	12/2–12/9	18.08	1.163	0.4800	1.6
7	H 14	12/9–12/16	17.65	1.138	0.4731	4.9
8	H 16	12/23–12/30	17.77	1.144	0.4755	22.5
9	C 1	11/19–11/20	18.29	1.176	0.4832	104.0

*P—Samples collected in remote area of MLO site, ~5 m above ground.
H—Samples collected from HASL surface air network filter ~1 m above ground near center of MLO site.
C—Sample collected near the Cloud Physics Observatory at the edge of Hilo.
**The precision of the measurement of the isotopic ratio of ^{206}Pb to ^{207}Pb was generally better than ±0.2%.

that aerosols collected above the trade wind inversion are comparable to "background" aerosols found in the upper troposphere over continents and represent material injected into the atmosphere far from the local Hawaiian environment (Simpson, 1972b). These aerosols could thus represent predominantly continental material derived from a mixture of distant source regions, despite their collection in an area surrounded by ocean for thousands of kilometers. Such a source is consistent with that suggested much earlier by Junge (1957) on the basis of the ammonia and sulfate composition of aerosols above the trade wind inversion in Hawaii.

Some of the aerosol samples from Hawaii that were analyzed for Na, K, Ca, Mg, Fe, Mn, Zn, Cu, Ni, and Pb by atomic absorption spectrometry were also analyzed for lead isotopic composition (Table 1). Of the 30 samples from MLO for which lead aerosol concentrations were reported (Simpson, 1972a) all but 6 had concentrations of ~3 ng/m³ or less, 1–2 ng/m³ being typical. Most of the samples with higher values (maximum of ~23 ng/m³) were from periods in which local contamination of the atmosphere at the observatory site by automobile exhaust lead was dominant. During a few well-documented periods, large numbers of visitor automobiles had come to the observatory site while aerosol collection was underway. These sampling periods had lead concentrations 5 to 10 times greater than those found at other periods. As an extreme example, during the last week of December 1970 approximately 500 automobiles visited MLO because of the coincidence of school vacation and a substantial quantity of snow down to the elevation of the observatory. We determined the isotopic composition of samples from such periods plus several from periods showing lead concentrations more typical of the whole collection period of 9 months, when the chance of site contamination was extremely unlikely. Thus the data in Table 1 should be reasonably representative of the total range of lead isotopic composition of aerosols at MLO during late 1970, including the few periods of significant local contamination as well as those in which background aerosol lead is dominant. The samples have a large range (Fig. 1) in isotopic composition, the least radiogenic values being found for the few periods of highest lead concentration in which local contamination was dominant. It appears that local lead contamination has an isotopic composition quite different from that of background aerosol lead usually present at MLO. The distribution of values is linear, falling along a trend close to that found by Chow (1971) for lead ores and urban aerosol leads.

Each aerosol sample that we analyzed generally represents 1 to 2 weeks of collection with a high volume pump (1–2 m³/min). Samples indicated with the code letter H in Table 1 were from the Health and Safety Laboratory (HASL) surface air monitoring site at MLO, which was located ~1 m above the ground near the middle of the MLO site during the period of our sample collection. We analyzed quarter sections of each of the circular (20-cm diameter) polystyrene filters used in the HASL network, each used for 1 week of continuous sampling. The total volume of air sampled by each of the HASL filters was $7–8 \times 10^3$ m³. Samples indicated with the code letter P in Table 1 were collected from a more

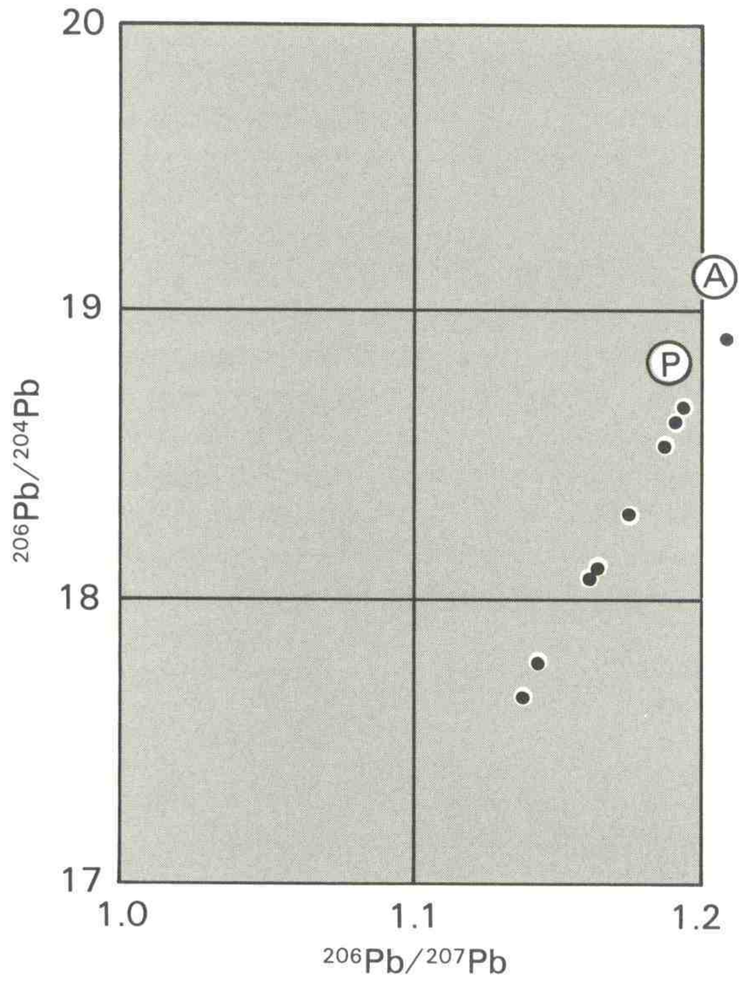
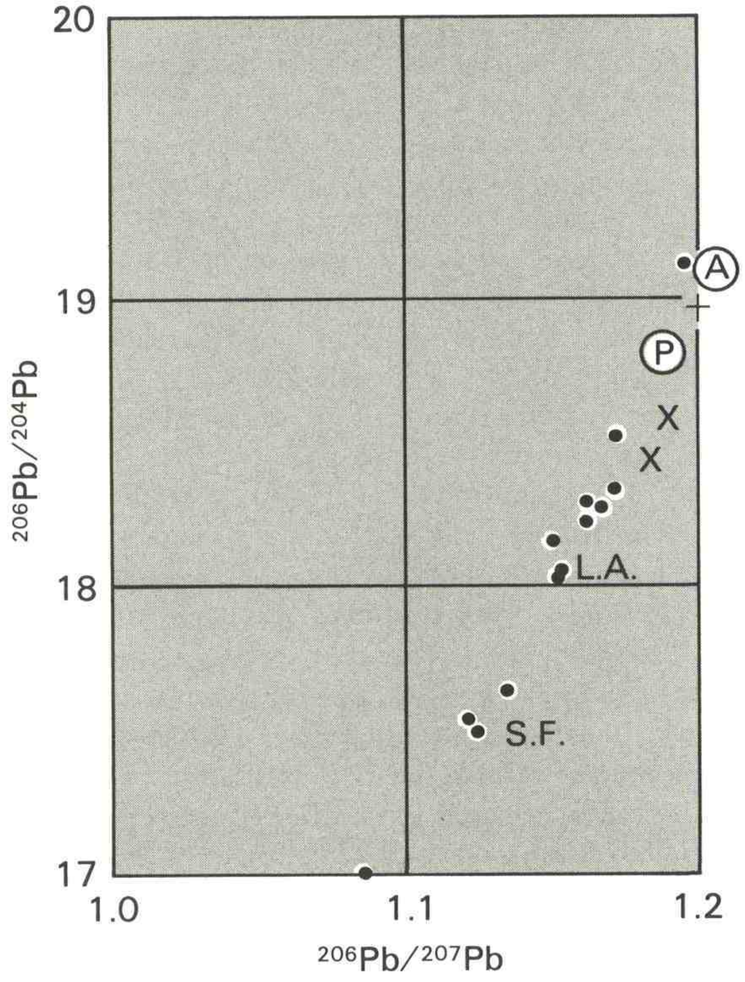


Figure 1. Aerosol lead determined in this study (Table 1) for the island of Hawaii during 1970. All of the data points except one are for samples from MLO. Average values for Pacific (P) and Atlantic (A) ocean pelagic sediments are also included (Chow, 1958; Chow and Patterson, 1962).

remote corner of the observatory site, relative to the observatory parking lot, using 20 × 25 cm polystyrene filters from the same stock supply as that of the HASL filters. Aerosol samples indicated with an odd number following the code letter P were composites of 1–2 weeks of "day" filtering (0600–2100). Even-number samples were 1- to 2-week composites of "night" filtering (2100–0600). All of these letter samples were collected ~5 m above the ground surface, and each represents a bulk composite of ~10–25 × 10^3 m^3 of air. One of the samples (C1) in Table 1 was collected over ~24 hours near the edge of Hilo, the largest town on the island of Hawaii.

Filter samples were ashed at 425°C in a covered beaker for ~6 hours, and the residue was dissolved in 5 ml of HCl and 2 ml of HNO_3 (high purity) and diluted to a total volume of 25 ml. The analytical scheme followed to this point is essentially that of Hoffman et al. (1972) and was originally intended here to be used only for flame atomic absorption analysis of a number of elements on the same sample. All of the sample preparation to this stage was done in a laboratory in Hilo (Cloud Physics Observatory), and filter leading and handling was done at MLO. Blanks measured by atomic absorption spectrometry of unexposed filters (5 samples), as well as the back half of exposed filters (9 samples), averaged 15%–20% of the total sample values for aerosol concentrations of 1–2 ng/m^3 and appeared to result primarily from the filter material rather than from filter handling procedures or reagents. We were not able to obtain a very good estimate of the lead isotopic composition of the overall blank.

The chemical procedures described below were carried out in a "clean lab" at Lamont-Doherty Geological Observatory by using reagents purified to reduce the possibility of reagent Pb contamination. An aliquot containing ~1 μg of Pb was withdrawn (by pipette) from the sample bottle, placed in a 30- or 50-ml Teflon-brand resin-coated beaker, and evaporated to a single drop. The drop was then diluted to 150 ml with triple distilled water, all of which was poured into a 250-ml Teflon-coated beaker (final pH ~3). One milliliter of a purified copper (0.5 mg/ml) solution was added to the sample, and a Teflon-covered magnetic stirring rod put into the beaker. Two 50-ml platinum wire electrodes were suspended in the sample, forming an electrolytic cell across which a 1.85-V potential was impressed, with continuous stirring.



Under these conditions, PbO_2 plates out on the anode, and Cu (and other metals) on the cathode. The electroplating was generally allowed to proceed overnight, although 6 to 8 hours were usually sufficient. The PbO_2 was then stripped from the platinum wire by immersing the wire in 1 ml of a 99:1 2% HNO_3:H_2O solution. This solution was evaporated to a large drop, and then two drops of a 0.375 molar H_3PO_4 solution and two drops of a concentrated silica gel solution were added, and the solution was reevaporated to a single drop. The lead isotope measurements were made on a 30-cm radius of curvature, 60° sector field, solid source mass spectrometer. A single-filament rhenium ribbon (30 mm wide) source was used. The sample drop was pipetted onto the filament and dried. The mass spectrometric analysis was performed by resistance heating at a filament temperature of 1250 ±100°C. Pb ion currents were on the order of 10^{-11} A and were measured with a vibrating reed electrometer connected to an expanded scale recorder. The precision of the isotopic ratio measurement was generally better than 0.2%.

Figure 2. Pollutant lead reported by Chow (1971) for urban aerosols and soils from a number of cities throughout the world. SF is San Francisco; LA is Los Angeles; P and A are pelagic sediments from the Pacific and Atlantic oceans (Chow, 1958; Chow and Patterson, 1962). The lead isotopic composition of coastal seawater off southern California, which is believed to be contaminated with sewage and other sources of pollutant lead, is indicated with x's (Patterson et al., 1976). Data for the average of two samples of Hudson River water (Catanzaro, unpublished data) are indicated with a +.

DISCUSSION

The range of observed data in Fig. 1 is large, indicating at least two sources of aerosol lead with significantly different isotopic compositions. In general, the samples from periods of local site contamination at MLO have less radiogenic lead and have an isotopic composition quite similar to that found for aerosols from Los Angeles (L.A.) and San Francisco (S.F.) by Chow (1971) (see Fig. 2). Since gasoline is supplied to Hawaii from California, this observation appears relatively easy to explain.

The presence of an end-member with more radiogenic lead isotopic composition is very interesting. In general, samples with less likelihood of local site contamination are found toward the upper end of the data in Fig. 1. The lead in these samples cannot be supplied as a contaminant of lead from the local Hawaiian lava dust because the concentration of lead in the lava is too low, by more than 2 orders of magnitude, to supply the lead collected in these aerosols. Aerosol mass calculated from the residual ash of exposed filters collected 5 m above the ground was $\sim 0.25\ \mu g/m^3$. In addition, the isotopic composition of lead from Hawaiian lavas is less radiogenic than that of nearly all the samples near the upper end of the curve. Samples discussed here were not collected during periods of local contamination of the MLO atmosphere by emissions from the active volcano Kilauea.

The isotopic composition of pelagic sediments from the North Pacific (P) and North Atlantic (A) oceans (Chow, 1958; Chow and Patterson, 1962) is indicated on Figs. 1 and 2. These data are probably the best indications available of the lead isotopic composition of aerosol lead prior to man's industrial contribution of lead. The trend of isotopic composition for aerosol lead at MLO has one end-member very similar to that of Pacific pelagic sediments. From published data (Chow, 1971) the weighted average isotopic composition of automobile exhaust lead appears to be considerably less radiogenic than that from Pacific pelagic sediments. Thus if the aerosol lead composition at MLO were dominated by automobile exhaust lead from distant urban sources, the expected isotopic composition would be considerably less radiogenic than that of pelagic sediment lead. There are indications, however, that the isotopic composition of pollutant lead may not differ as much from Pacific pelagic sediment lead as might be assumed on the basis of the urban aerosol data in Fig. 2 (Chow, 1971). Recent data (1972–1974) for lead from coastal seawater off Los Angeles and San Diego, California (Patterson et al., 1976), indicate isotopic compositions considerably more radiogenic than those for aerosol lead from Los Angeles (Chow, 1971). Representative isotopic compositions for coastal sea-water samples believed to be substantially contaminated with sewage lead and other pollutant lead are shown in Fig. 2 (Patterson et al., 1976). We have also recently analyzed the isotopic composition (Fig. 2) of lead from two samples of water from the Hudson River. The isotopic compositions of lead in water samples from both of these environments, which can be expected to be substantially affected by pollutant lead, are similar to the isotopic composition of Pacific and Atlantic pelagic sediment lead (Chow, 1958; Chow and Patterson, 1962). The relationship of the isotopic composition of lead from water samples collected near large urban areas during the last several years to the published aerosol lead isotopic compositions from urban areas during the late 1960s and early 1970s is not simple to interpret, but the observed differences do make conclusions about the source of aerosol lead in background aerosols in Hawaii considerably more difficult to reach.

Finally, it was recently brought to our attention by Clair Patterson that the isotopic composition of industrial lead in the United States underwent a substantial change during the period 1964–1974. The $^{206}Pb/^{207}Pb$ ratio increased from about 1.14 to about 1.20 as a consequence of more use of lead from southern Missouri (Chow et al., 1973; Chow et al., 1975). The data that we used here to characterize urban aerosol lead from California were collected during the mid- to late-1960s and thus probably are not a good indicator of the isotopic composition of urban aerosol lead in the United States during the period of late 1970, when our samples at MLO were collected. If automobile exhaust leads averaged over the Northern Hemisphere now have a $^{206}Pb/^{207}Pb$ ratio of approximately 1.20 (as appears not to have been the case 10 years ago), the isotopic composition of this pollutant lead does not differ appreciably from pelagic sediment lead, making it much more difficult to resolve the source of remote area aerosol lead on the basis of the lead isotopic composition.

The data we report for aerosol lead from MLO are consistent with the interpretation that a significant portion of background aerosol lead in remote areas today has an isotopic composition similar to that which probably existed before man's large contribution of aerosol lead. It is thus possible that background aerosol lead today in the central Pacific may be largely natural. This interpretation conflicts substantially with the large increase of lead in polar snows from recent years compared with snow from preindustrial periods (Murozumi et al., 1969) and with aerosol lead flux estimates (Patterson, 1965), both of which suggest that the anthropogenic source dominates background aerosols by more than an order of magnitude. The large change in the isotopic composition of industrial lead in the United States over the last decade does introduce a substantial complication. The similarity of the isotopic composition of industrial lead in the United States during the early 1970s to that in aerosol lead at MLO during late 1970 is also consistent with the dominance of pollutant lead in aerosols of remote areas in the Northern Hemisphere. The data from MLO are sufficiently interesting, however, to suggest that lead isotopic measurements of aerosols from remote areas could, if sufficient data were collected, provide key information for understanding the current global cycle of aerosol lead.

ACKNOWLEDGMENTS

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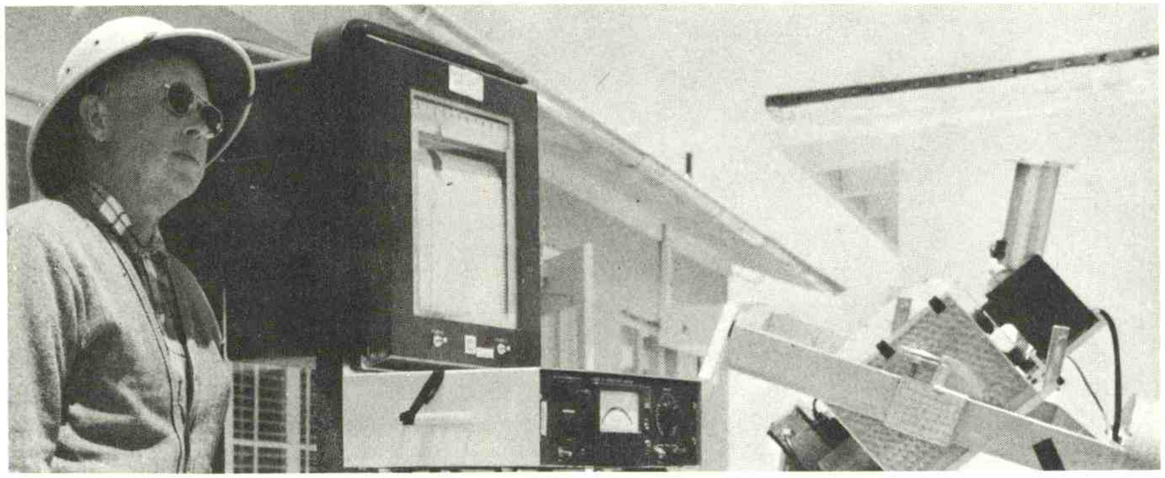
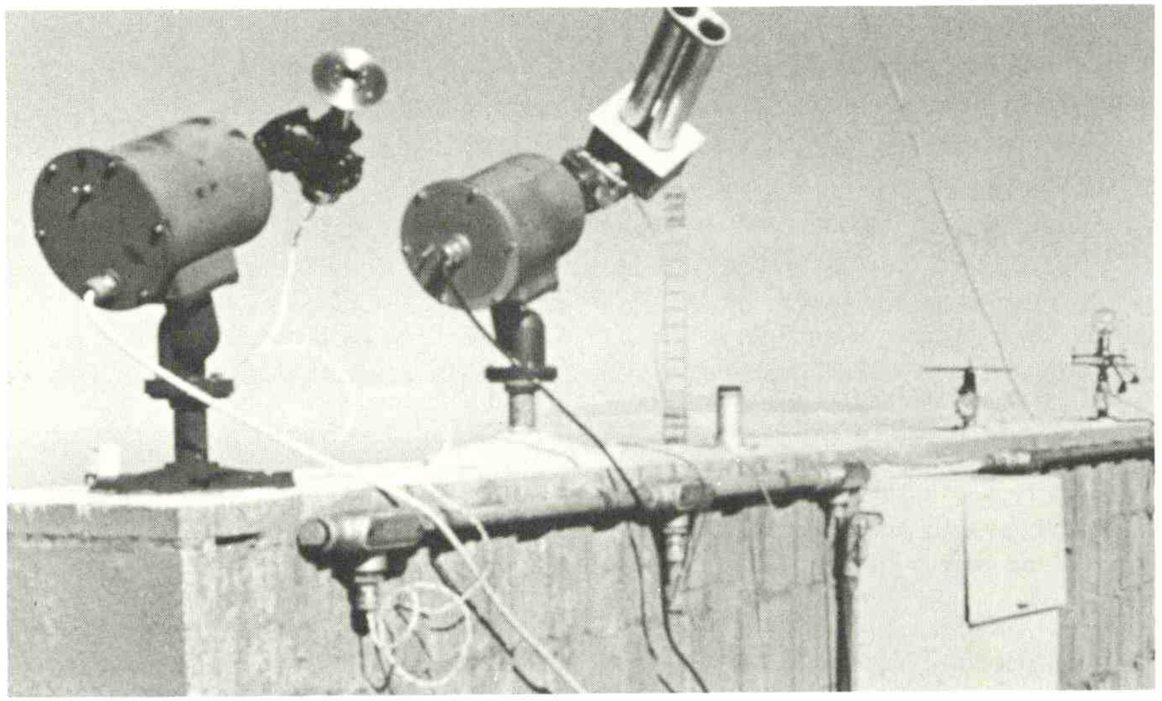
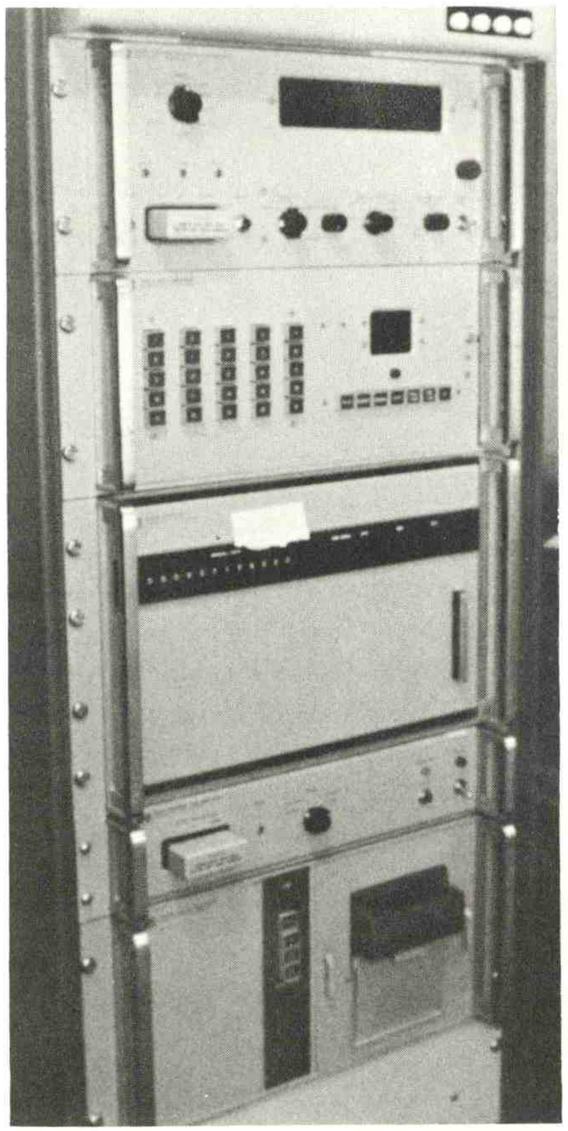


Ralph Stair making solar radiation measurements with a scanning photometer, August 29, 1966.



Solar radiation instruments at MLO, left to right: normal incidence pyrheliometer, infrared hygrometer, global pyranometer.



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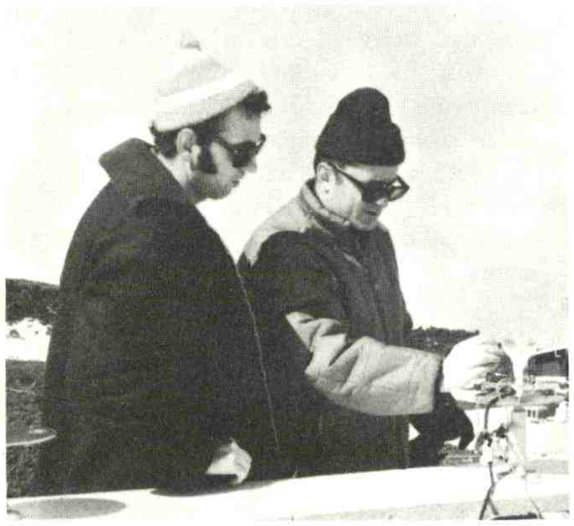
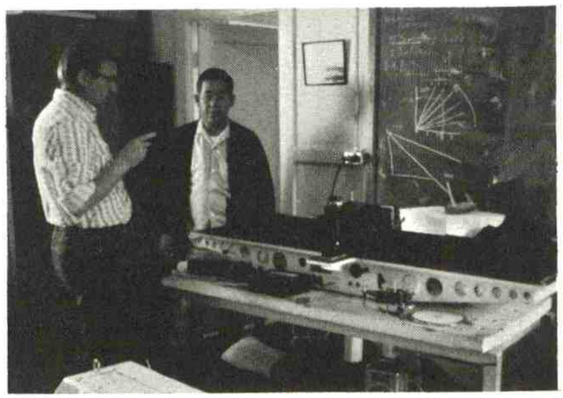
In the early '70s, Mauna Loa Observatory had one of the first automated solar radiation data recording systems.

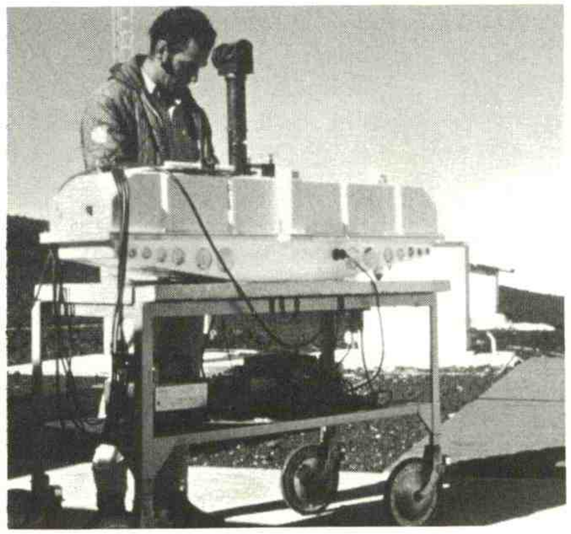
Bernard Mendonca and Rudy Pueschel check out solar radiation instruments, 1970.



Walter Komhyr and Al Shibata modifying a total-ozone Dobson spectrophotometer at MLO in February 1972.



Bernard Mendonca measuring ozone with a Dobson spectrophotometer, March 1972.



On June 28, 1966, Dick Hansen of HAO and Lothar Ruhnke of MLO (and others) installed a radiometer to monitor solar activity and cloud cover at the summit of Mauna Loa.

Solar measurements

ZENITH SKYLIGHT CHARACTERISTICS IN THE SUNRISE PERIOD AT MAUNA LOA

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INTRODUCTION

There is well known controversy about the effects of accumulations of smoke, dust, smog, and other types of particulate matter in the atmosphere. If we are putting aerosols into the atmosphere faster than the atmosphere is cleansing itself, it is not illogical to expect some long-term climatic effects to result from the buildup of the worldwide burden of aerosols. Unfortunately, it is not clear just yet whether the overall effect of such an increase of aerosols would be a cooling of the planet, as some scientists are predicting, or a warming of the planet. The most acceptable available analysis of the problem indicates that the trend could go either way, depending on the characteristics and location of the aerosols themselves.

However, whether there is a progressive buildup of atmospheric aerosols on a worldwide basis is also a question for which the answer is not completely known. The evidence on the point is conflicting. In some locations, such as over the North Atlantic and in the Caucasus, there is strong evidence of a relatively rapid buildup, whereas in the South Pacific area the available measurements indicate the aerosol content to be stable. The longest record of reliable measurements on which an assessment of aerosol loading of the atmosphere can be made is that taken at Mauna Loa Observatory (MLO), Hawaii. The measurements of direct solar radiation taken at the observatory over a 19-year period show a strong but temporary buildup of particulate matter following the eruption of Mt. Agung in 1963, but no trend, either upward or downward, is evident in the data available at the present time (Machta, 1972; Ellis, 1977, private communication). If there is a trend, its magnitude is less than the probable error of the measurements.

In view of the importance of the aerosol problem it is desirable to get as many independent measurements of aerosol loading as possible. A sensitive method of detecting the presence of aerosols and obtaining a rough estimate of their properties is through their light scattering effects. The scattering of sunlight by aerosol particles is different from that by the oxygen, nitrogen, and other gaseous constituents of the atmosphere. The total amount of energy scattered, its angular distribution, and its state of polarization depend strongly on the numbers; physical properties of light from the sunlit sky are sensitive to the existence of aerosols in the atmosphere, and measurements of these quantities should provide a simple and useful method of characterizing atmospheric turbidity on a long-term basis.

MLO is an advantageous site for making skylight measurements for aerosol monitoring. Since the observatory is located in an oceanic setting far from major landmasses, the natural aerosol loading is minimal, and pollution from local sources is generally confined to the atmospheric layer below the temperature inversion associated with the trade wind regime. In fact, Mauna Loa is thought to have some of the cleanest atmospheric conditions to be found in the world. In addition, a large complement of mutually supporting measurements, such as incident solar radiation at different wavelengths, particle counts at the station, and lidar probes of the atmosphere, are made on a routine basis at the observatory.

The present investigation is designed to measure in detail the intensity and state of polarization of the light from the sunlit sky and to determine, if possible, the best method of using skylight data for characterizing atmospheric turbidity at the observatory.

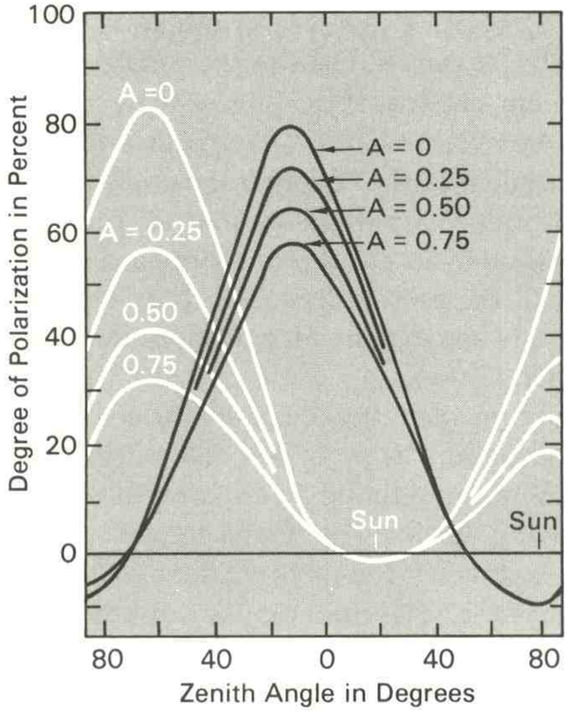


Figure 1. Polarization as a function of zenith angle in the plane of the sun's vertical for a plane parallel Rayleigh atmosphere at a wavelength of 0.365 μm and the altitude of MLO for four different values of surface albedo and for solar zenith distances of 78.5° (solid curves) and 23.1° (dashed curves).

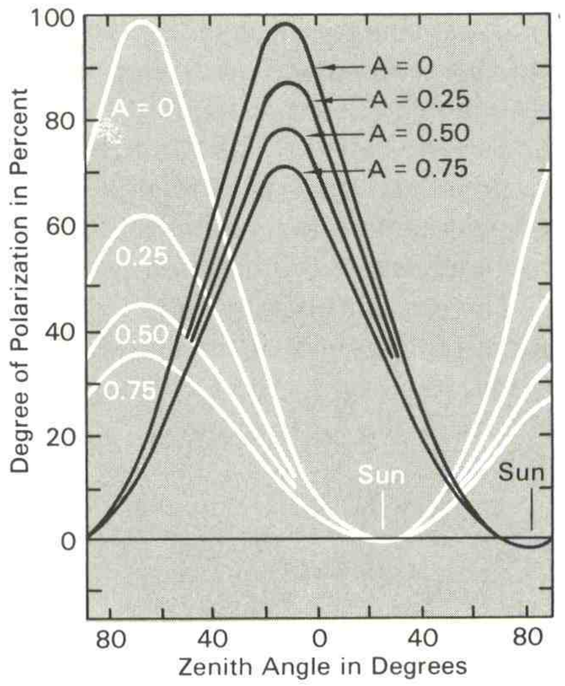
THEORETICAL EXPECTATIONS

Since the atmosphere at Mauna Loa is very clear, the Rayleigh approximation, in which all particles are assumed to be small in comparison with the wavelength of the radiation, should be a good theoretical model with which to evaluate the measurements. In preparation for this work an extensive set of computations of the intensity $I(\tau;\ \theta,\ \theta_0,\ \phi\text{-}\phi_0;\ A)$, degree of polarization $P(\tau;\ \theta,\ \theta_0,\ \phi\text{-}\phi_0;\ A)$, and angle $\chi(\tau;\ \theta,\ \theta_0,\ \phi\text{-}\phi_0;\ A)$ of the plane of polarization with respect to the vertical direction was carried out. Here $\tau = \tau(\lambda,\ h)$ is normal optical thickness of the atmosphere at the wavelengths λ and altitude h of the observatory; $(\theta,\ \phi)$ and $(\theta_0,\ \phi_0)$ are the zenith angle and azimuth of the observed direction and the sun, respectively; and A is albedo of the surface. The values of the different parameters used in the computations are listed in Table 1. The various combinations of the parameters resulted in a total of 159,936 individual values from the computations.

In the interest of brevity, emphasis here is confined to theoretical results for two wavelengths. The first, $\lambda = 0.365$ μm, is characterized by a relatively large optical thickness ($\tau = 0.333$) with much multiple scattering, whereas the second, $\lambda = 0.80$ μm, corresponds to a small optical thickness ($\tau = 0.015$) and a minor significance of multiple scattering effects in the atmosphere. Because of this change of scattering efficiency with wavelength for the Rayleigh atmosphere, it is to be expected that radiation is morensitive to aerosol effects at the longer wavelengths than it is at the shorter wavelengths. As will be seen below, this expectation is borne out by the measurements.

The degree of polarization as a function of zenith angle in the plane of the sun's vertical (plane defined by the sun and the zenith direction) for $\lambda = 0.365$ μm is shown for four values of surface albedo ($A = 0$, 0.25, 0.50, and 0.75) and two zenith angles of the sun ($\phi_0 = 23.1$ and 78.5) in Fig. 1. Multiple scattering is responsible for the decrease of the maximum polarization from 100% to about 80% and for the existence of the negative branches of the curves, with the attendant neutral points (points of zero polarization). Of particular interest are the depolarizing effects of surface reflection, the reflected radiation being assumed to be unpolarized and isotopic in the outward hemisphere. In all cases, increasing surface reflection decreases the magnitude of the polarization maximum, the decrease being most pronounced for the

Figure 2. Polarization as a function of zenith angle in the plane of the sun's vertical for a plane parallel Rayleigh atmosphere at a wavelength of 0.80 μm and the altitude of MLO for four different values of surface albedo and for solar zenith distances of 78.5° (solid curves) and 23.1° (dashed curves).



higher sun elevation. This increase of surface influence with increasing sun elevation is due to the efficient transmission of the direct solar beam through the atmosphere, and the consequent strong illumination of the surface, at the higher sun elevations. At the same time the efficient transmission causes less multiple scattering at the higher sun elevations, a feature which explains the increase of the polarization maximum with increasing sun elevation for the case of no surface reflection ($A = 0$).

Polarization curves for $\lambda = 0.80$ μm are shown in Fig. 2. The very high maxima here attest to the paucity of multiple scattering at this long wavelength, whereas the decrease of polarization with increasing surface reflection is evidence of the efficiency with which the direct solar beam is transmitted downward through the atmosphere to illuminate, and be reflected from, the surface.

Since the present investigation is emphasizing the polarization and intensity of skylight in the zenith direction for the case when the sun is very near the horizon, either above or below, the change of polarization maximum with sun elevation is of particular interest. In fact, the theoretical computations, being based on the assumption that the curvature of the atmospheric layers is negligible (a plane parallel atmosphere), do not apply at very low sun elevations. To obtain a qualitative estimate of the features to be expected in the extreme case when the sun is at the horizon, it is necessary to extrapolate the data beyond their region of theoretical validity. Although this is admittedly a questionable procedure, it does give some insight as to the probable effects of surface reflection in the measurements.

From curves such as those shown in Figs. 1 and 2 it is possible to determine the degree of polarization at the maximum as a function of the various parameters of the computations. In Fig. 3 the magnitude of the polarization maximum, P_{max}, is shown as a function of sun elevation for $\lambda = 0.365$ μm (dashed curves) and $\lambda = 0.80$ μm (solid curves) and for four different values of surface albedo. The extrapolation from a sun elevation $\alpha = 5.7°$ to $\alpha = 0°$ is shown by the dotted segments of the curves. It is evident that at $\lambda = 0.365\mu$m, surface reflection has a significant effect on P_{max} at all sun elevations, including $\lambda = 0°$, if the extrapolation is valid in any sense. Intuitive reasoning would indicate that even when there is no appreciable radiation incident on the surface from the direct solar beam, strong scattering by the optically thick atmosphere would cause a significant amount of diffuse illumination of the surface, and reflection of the diffuse radiation would produce the depolarizing effects shown in the diagram. At $\lambda = 0.80$ μm, on the other hand, there is little diffuse radiation to illuminate the surface, so at very low sun elevations, for which the energy in the direct beam is minimal, the effect of surface reflection must also be minimal. In the diagram, the curves for $A \neq 0$ have been extrapolated to closely approximate that for $A = 0$ for $\alpha = 0°$. This is undoubtedly an exaggeration, but the trend of the curves at $\alpha > 5.7°$ indicates that surface effects at the longer wavelengths must be very small at the time the sun is at or below the horizon. This fact will be used in the interpretation of the skylight measurements.

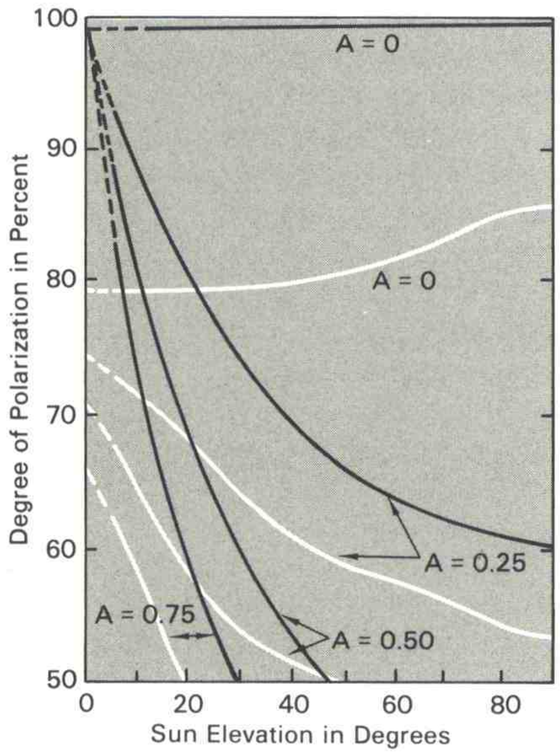


Figure 3. Maximum polarization versus solar zenith angle for a plane parallel Rayleigh atmosphere at wavelengths of 0.365 μm (dashed curves) and 0.80 μm (solid curves) and the altitude of MLO for four different values of surface albedo. The dotted extensions of the curves represent an extrapolation to a sun elevation of 0°.

RESULTS OF MEASUREMENTS

Mode of Operation

The normal mode of operation for measurements in the period from first light in the morning until the sun was a few degrees above the horizon was to orient the polarimeter in the direction of the zenith and step continuously through the four sets of color filters. A measurement of intensity, degree of polarization, and orientation of the plane of polarization in each of the eight wavelength ranges was obtained at approximately 50-s intervals throughout the period. The uncertainty in each measurement depends somewhat on wavelength, the sensitivity of the photomultiplier tubes decreasing strongly near the shortwave and longwave limits. Thus measurements at 0.32 and 0.90 μm have a probable uncertainty of perhaps $\pm 0.5\%$ during the dawn period, whereas those at the other wavelengths have a probable uncertainty of approximately $\pm 0.2\%$. In the post-sunrise period the uncertainties were somewhat less than these values.

Because of the large number of measurements made in this series, it is necessary for purposes of illustration to select cases that are typical of different types of atmospheric conditions. Cases of low atmospheric turbidity will be discussed first, and the data from these cases will be used for comparison with the measurements made under more turbid or anomalous atmospheric conditions.

Low-Turbidity Cases

All of the measurements made under conditions of low turbidity give results similar to those shown by the curves of Figs. 4 and 5, in which degree of polarization P in the zenith direction is plotted as a function of sun elevation. In the range of wavelengths from 0.32 to 0.50 μm, shown in Fig. 4, the polarization increases monotonically with increasing wavelength, and the behavior of P appears to be anomalous in some respects. It will be remembered that for Rayleigh scattering the maximum polarization is at 90°, or slightly less, from the direction of the sun, and many measurements, both in the past and in the present series, show this expectation to be closely approximated in the actual atmosphere when the sun is well above the horizon. Obviously, this would correspond to the zenith polarization maximum occurring at the time the sun is on or slightly above the horizon. The fact that the zenith polarization reaches its maximum when the sun is 2.5° to 3.5° below the horizon, or at scattering angles of 92.5° to 93.5°, must be brought about by the geometry of the sun-atmosphere combination in the sunrise period.

From intuitive reasoning one can obtain an idea as to the possible cause of the apparently anomalous behavior of the short-wavelength curves of Fig. 4. As the first direct rays of the sun illuminate the high atmosphere at solar depression angles of 6° to 4°, primary scattering by the tenuous upper atmosphere is predominant, and the angular dependence of the polarization is about as would be expected. However, as the solar depression angle decreases, the direct rays descend lower into the atmosphere, and the rapidly increasing atmospheric density causes a rapid transition from primary scattering to multiple scattering as the predominant feature of the radiation field. As the transition develops, the polarizing effects of multiple scattering overcompensate the normal increase of polarization to be expected as the scattering angle approaches 90°, thereby causing the indicated decrease of P. As the sun continues to rise to the horizon, the atmospheric pathlength of the incident rays through the spherical atmosphere tends to decrease, with the result that the depolarizing effects of multiple scattering combine with the regular increase of polarization to create the plateau shown by the curves. After sunrise the optical pathlength of incident radiation continues to decrease; multiple scattering is alleviated sufficiently to counteract the angular decrease of polarization as the sun moves to less than 90° from the zenith to cause the plateau of the curves to persist after sunrise for $\lambda = 0.365$ and 0.40 μm. At $\lambda = 0.32$ μm the optical pathlength is so large that a small change with sun elevation does not appreciably change the relative importance of multiple scattering, and the normal change of P with changing scattering angle proceeds about as expected.

There are obviously some features of the curves of Fig. 4 that these simple concepts do not explain. First, the change of position of the maximum with wavelength appears to be the reverse of what would be expected. Since multiple scattering increases with decreasing wavelength, one would expect the

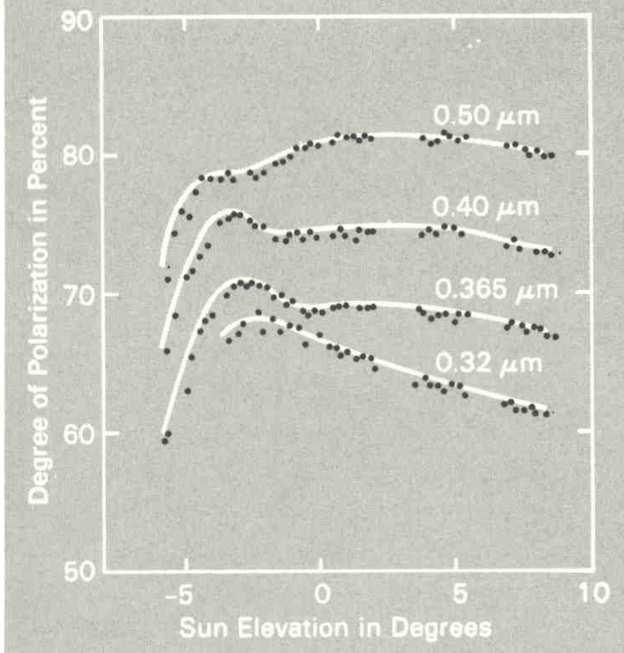


Figure 4. Polarization in the zenith direction as a function of sun elevation for four different wavelengths in the shortwave part of the solar spectrum. The data were taken in very clear atmospheric conditions on February 19, 1977.

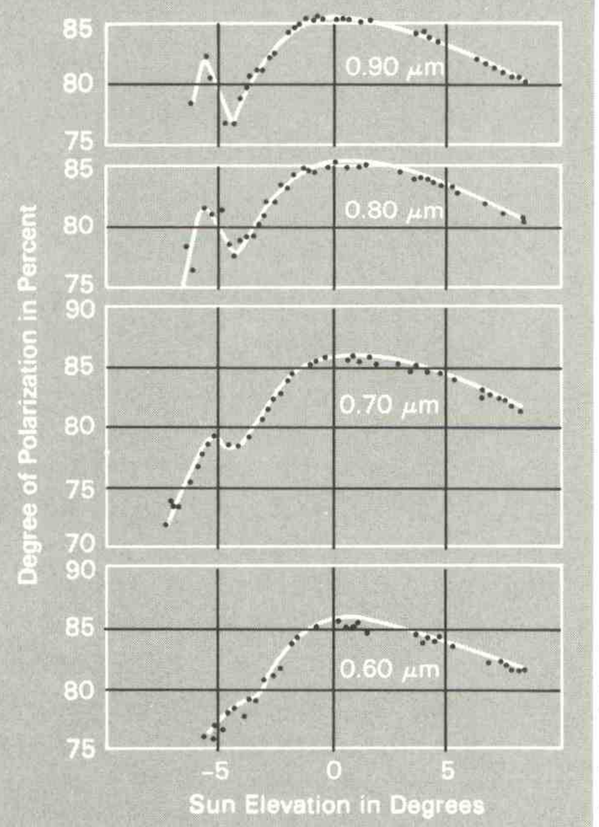


Figure 5. Polarization in the zenith direction as a function of sun elevation for four different wavelengths in the longwave region of the solar spectrum. The data were taken in very clear atmospheric conditions on February 19, 1977.

depolarizing effects to show up at larger solar depression angles for short wavelengths than for longer wavelengths, but the data do not bear out this expectation. Astronomical refraction would tend to cause a shift in the right direction to explain the observations, but the magnitude is probably too small. Second, the curve for $\lambda = 0.50$ μm appears not to follow the simple explanation proposed above, but in this case the effects of non-Rayleigh-type particles modify the behavior from what it would be for a pure Rayleigh atmosphere. This may indeed be the case for the shorter wavelengths as well, but, as discussed below, such aerosol effects are particularly evident as wavelengths $\lambda \geq 0.60$ μm.

The curves of zenith polarization versus sun elevation for the longer wavelength ranges are shown in Fig. 5. Here the scale of the ordinate is staggered so as to separate the curves. Two features of the diagram indicate that primary scattering dominates the radiation field at these wavelengths. First, the maximum is located at approximately 90° from the sun, the shift of its position, which was ascribed to multiple scattering effects at shorter wavelengths, being absent from these curves. Second, the magnitude of the maximum (about 85.5%) is essentially independent of wavelength in this range, a fact which indicates that multiple scattering effects must be very small. The high value of the maximum shows that atmospheric turbidity must have been very small, since scattering at these wavelengths is strongly dominated by the non-Rayleigh particles in the atmosphere.

Another interesting feature of Fig. 5 is the behavior of the zenith polarization at solar depression angles of 3° to 6°. The pattern shown by these curves is typical of that on almost all days for which the early morning measurements have been made at Mauna Loa, although, of course, the details vary. The magnitude of the secondary maximum, the magnitude of the minimum, and the position of the minimum all show day-to-day variations that seem to be associated with high-level, either stratospheric or upper tropospheric, layers of aerosols. If this is proved, by auxiliary measurements such as lidar probes, to be the case, then the measurement of zenith polarization should be a simple and valuable means of characterizing and monitoring turbidity of the upper atmosphere.

Under most conditions the minimum of a curve occurs at a solar depression angle of approximately 4°, and the secondary maximum occurs when the sun is 5.0° to 5.2° below the horizon. The solar ray tangent to the earth's surface is at heights of about 25 km and 16 km for solar depression angles of 5° and 4°, respectively. The polarization curves would thus indicate that an aerosol layer with a top at about 25 km and a maximum density at 16 km exists over Mauna Loa a large part of the time. In isolated cases the aerosol becomes relatively diffuse, its altitude varies somewhat from day to day, and occasionally it largely, but not completely, disappears. Some data to substantiate these statements are given below.

Average Low-Turbidity Curves

In order to have some standard curves for comparison purposes, 10 days on which the maximum polarization at 0.80 μm was at least 84.8% were selected as low-turbidity days, and average low-turbidity curves for $\lambda = 0.365$ and 0.80 μm were computed from the ten sets of data. The curves resulting from this process are shown in Fig. 6. Although slight variations of the position of the presunrise minimum at $\lambda = 0.80$ μm tend to broaden the outline of the average curve from its configuration on individual days, the feature is well defined in the average. Similarly, the secondary maximum is reasonably pronounced for the average. If the existence of these features is to be ascribed to an aerosol layer, as was postulated above, then the top of the layer would be at an average altitude of about 26 km and reach its maximum density at 16 to 17 km MSL in average low-turbidity atmospheric conditions at Mauna Loa. The primary maximum for the average at 0.80 μm occurs at the time when the sun is just on the horizon, as it would for predominantly primary scattering in a clear atmosphere.

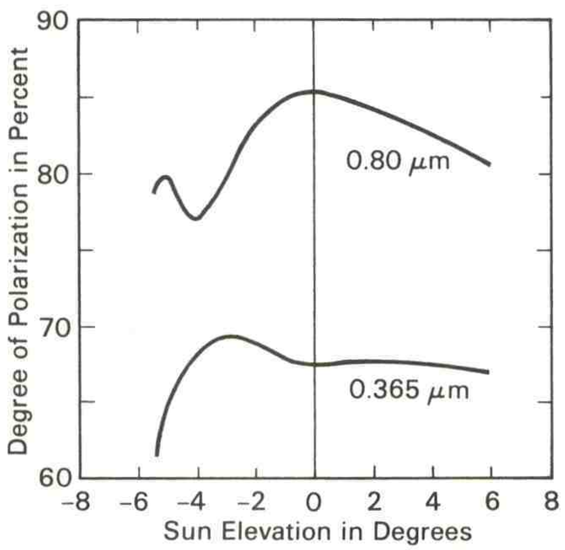


Figure 6. Polarization at the zenith as a function of sun elevation for average low-turbidity conditions at Mauna Loa. The curves were obtained by averaging the measurements taken on 10 days selected for atmospheric clarity (February 10, 15, 19, 21, 23, 26; March 4, 9, 10, 11, 1977).

The average low-turbidity curve for $\lambda = 0.365$ μm shows the primary polarization maximum in the zenith direction to occur at a solar depression angle of about 2.9°, with a very minor minimum at about sunrise. This curve is much more difficult to interpret than that for the longer wavelength, and there is a greater scatter in the data from which the average was determined. As was pointed out previously, the short-wavelength radiation is strongly influenced by the depolarizing effects of multiple scattering, and cloud reflection plays a very important role in determining the shortwave radiation field, even for very low sun elevations.

Zenith Polarization on Days with Moderate to High Turbidity

We are now in a position to characterize conditions of moderate to high atmospheric turbidity by comparison of zenith polarization measured in such cases with the average low-turbidity curves of Fig. 6. On February 17 there was evidence of dust, perhaps of volcanic origin, in the troposphere or lower stratosphere over the region of Hawaii. A layered structure was visible above the horizon in all quadrants. The yellow color was more pronounced than usual in the early morning sky, and a definite aureole was visible in the region of the sun. Unfortunately, the lidar system at the observatory was inoperable at the time, but measurements by the solar corona research project at the site indicated the skylight intensity at one solar diameter from the solar disc to be 3 to 4 times the average value during the morning of February 17. Such an intensity increase is associated with increased forward scattering of sunlight by particulate matter in the atmosphere.

The degree of polarization, as measured at the zenith during the sunrise period at a wavelength of $\lambda = 0.80\ \mu m$ on February 17, is compared with that for average low-turbidity conditions in Fig. 7a. The measurements indicate the high-altitude conditions to be near average, but the main aerosol layer at high altitudes appeared to be thinner than average. The flattening of the curve in the range of solar depression angles of $-4.2°$ to $0°$ indicates that the turbidity component has extended well below its average sunrise altitude in the atmosphere. The shift of the maximum from its average sunrise position to a solar depression of about $1.3°$, together with a decrease of polarization of over 5% after sunrise, would likewise indicate increased depolarization effects of aerosol scattering well down into the troposphere.

A second case of obvious atmospheric turbidity occurred on March 25. Cloudiness was very minor throughout the morning and forenoon of that day, but there was a considerable amount of dust or heavy haze in the atmosphere. Dust layers extending to several degrees above the horizon were visible, the sunrise sky was unusually yellow, and a definite solar aureole persisted throughout the forenoon. The zenith polarization measurements for March 25 are compared with the average low-turbidity curve in Fig. 7b. The behavior of the polarization field on that day is obviously anomalous, the position of the minimum being shifted to a solar depression angle of $3.5°$ and the magnitude of the maximum being decreased by about 3% from its low-turbidity value.

An even more anomalous case occurred on March 1, as shown by the curve of Fig. 7c. On that morning, however, there were wisps of cirrus clouds in various parts of the sky and considerable upslope motion carrying air from lower levels to the mountain top. Care was taken to make sure that there were no visible clouds near the zenith as the measurements were made, but there may well have been some depolarization effects introduced by reflection from higher-level clouds or by effects of particles that had not yet formed visible clouds. The curve shows obvious optical instability which may have been produced by either actual or nascent clouds. Whether or not such particulates constitute atmospheric turbidity depends on the definition of the term, but they certainly do have a major effect on the field of skylight polarization.

The period from March 31 to April 7 was characterized by strong vertical motions in the atmosphere as a weather system moved over the area. Large cumulus clouds with occasional thunderstorms were prevalent, and upslope motion on Mauna Loa brought clouds over the observatory by midforenoon on most days. The data points for this period are much more scattered than usual, an indication of optical instability in the atmosphere. In Fig. 8, polarization curves derived from zenith measurements at $\lambda = 0.80\ \mu m$ are shown for three days of the period (April 2, 3, and 4). As in the previous diagram, the dashed curves represent the low-turbidity average for the same wavelength. The curves of Fig. 8a show the degree of polarization to be up to 4.5% lower than the low-turbidity average. By April 3 (Fig. 8b), however, the minimum was very pronounced and was shifted to occur at a solar depression angle of about $2.9°$. These features would seem to indicate an increase of tropospheric turbidity between April 2 and 3, although the polarization maximum was slightly higher on April 3 than on the previous day. The most anomalous case of the period occurred on April 4, as shown in Fig. 8c. Here the polarization maximum was about 8.5% lower than the average for low-turbidity conditions, and the early morning minimum bears little resemblance to that of more normal atmospheric conditions. Measurements not shown here indicate that by April 7 the atmosphere had returned to a more nearly normal turbidity situation.

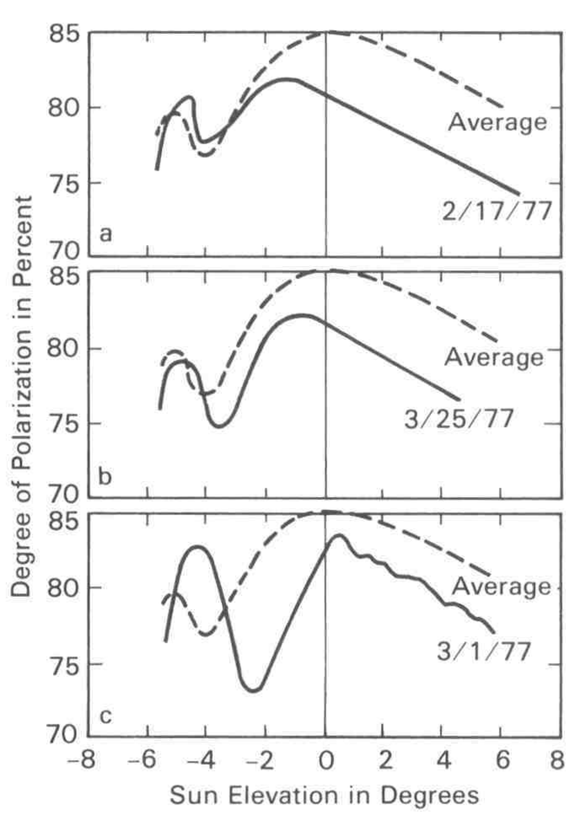


Figure 7. Polarization at the zenith as a function of sun elevation as measured at a wavelength of 0.80 μm on days with moderate to high atmospheric turbidity (solid curves) compared with that for average low-turbidity conditions (dashed curves).

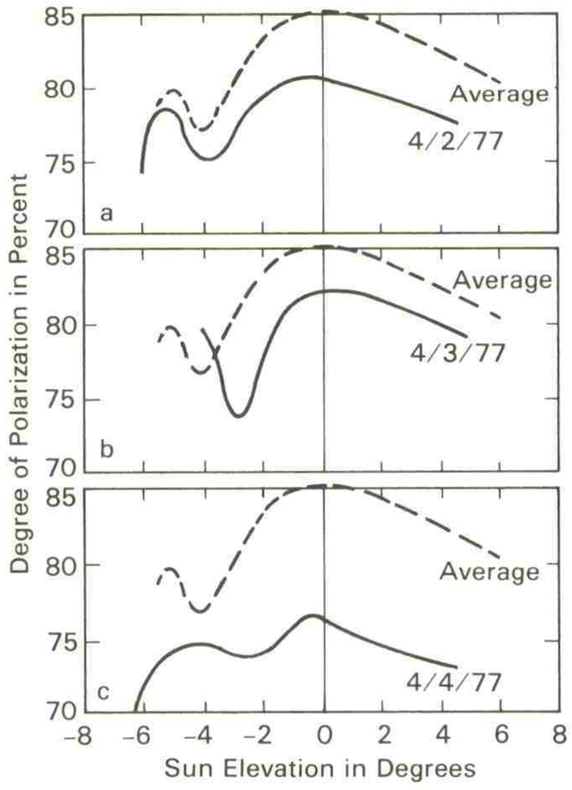


Figure 8. Polarization at the zenith as a function of sun elevation as measured at a wavelength of 0.80 μm on days with moderate to high atmospheric turbidity (solid curves) compared with that for average low-turbidity conditions (dashed curves).

Table 1. Values of Parameters Used in Computations for the Rayleigh Model

λ (μm)	τ	θ (degrees)			θ_0 (degrees)	ϕ-ϕ_0 (degrees)	A
0.32	0.625	90.0	68.9	43.9	0	0	0
0.365	0.333	88.3	67.0	41.4	23.1	0.30	0.25
0.40	0.246	86.6	65.2	38.7	36.9	60	0.50
0.50	0.098	84.8	63.3	35.9	53.1	90	0.75
0.60	0.047	83.1	61.3	32.9	66.4	120	
0.70	0.025	81.4	59.3	29.5	78.5	150	
0.80	0.015	79.6	57.3	25.8	84.3	180	
0.90	0.009	77.9	55.2	21.6			
		76.1	53.1	16.3			
		74.3	50.9	8.1			
		72.5	48.7				
		70.7	46.4				

DISCUSSION

The possibility of using measurements of skylight polarization in the zenith direction during sunrise or sunset periods to characterize turbidity conditions in the upper atmosphere has long been recognized. Linke (1951) made a long series of observations of zenith skylight measurements by both visual and photoelectric means. Fesenkov (1961) has studied the problem by means of some theoretical approximations applied to twilight phenomena but concluded that zenith twilight phenomena are unsuitable for studying the optical properties of the atmosphere at high altitudes. Dietze (1963), on the other hand, has used zenith polarization measurements to study the penetration of cosmic dust into the upper atmosphere and attributed a decrease of polarization, observed to occur at solar depression angles of 6° to 12°, to concentrations of cosmic dust in the 80- to 100-km region of the atmosphere. A discussion of the entire twilight problem has been given by Rozenberg (1966).

Although the concept of using zenith skylight measurements for characterizing atmospheric turbidity is not new, there are certain aspects and results of the present series of measurements that do appear to be unique to the series. First, the measurements made here extend to wavelength ranges longer than those of previous investigations. For instance, the measurements and theory on which Fesenkov based the opinion of zenith twilight phenomena being unsuitable for studying atmospheric properties were for radiation at visible wavelengths, in which case multiple scattering of the primary twilight component introduces extreme complexity into the problem. In the infrared region, however, the multiple scattered component is essentially negligible in comparison with that arising from primary scattering, and so the problem is comparatively much simpler at the longer wavelengths. A second feature of the present series is the high altitude of the observatory at which the measurements were made. The two aspects of high altitude and long wavelengths combine to make a very small normal optical thickness of the atmosphere above the site. For instance, at a wavelength of 0.80 μm and an altitude of 3460 m the normal optical thickness of the Rayleigh atmosphere is only 0.015. The optical thickness discussed by Fesenkov (1961) was over 13 times this

(0.20), and so, of course, multiple scattering effects are much more important in his results.

Although further work, both experimental and theoretical, needs to be done to arrive at a more complete physical understanding of the field of skylight polarization when the sun is very near the horizon, the measurements made here indicate that a useful index of atmospheric turbidity can be obtained very simply by routine monitoring of the degree of polarization in the direction of the zenith during the early morning period. Although similar measurements near sunset should yield similar results, local turbulence brought about by daytime heating would tend to introduce pollution from local sources and thereby render the polarization field during the period near sunset less representative of overall atmospheric turbidity than that which occurs in the sunrise period.

ACKNOWLEDGMENTS

The support for this investigation, which was provided jointly by the Resident Research Associateship Program of the National Academy of Science, the University of California, and MLO, is gratefully acknowledged. Special thanks go to the director, Dr. John Miller, and staff of the MLO for their excellent cooperation and support of the skylight measurements, as well as for their personal kindness and hospitality. Computations of skylight parameters for the Rayleigh atmosphere were performed by Bruce Fitch. The work was carried out while the author was on a 6-month sabbatical leave from the University of California, Davis.

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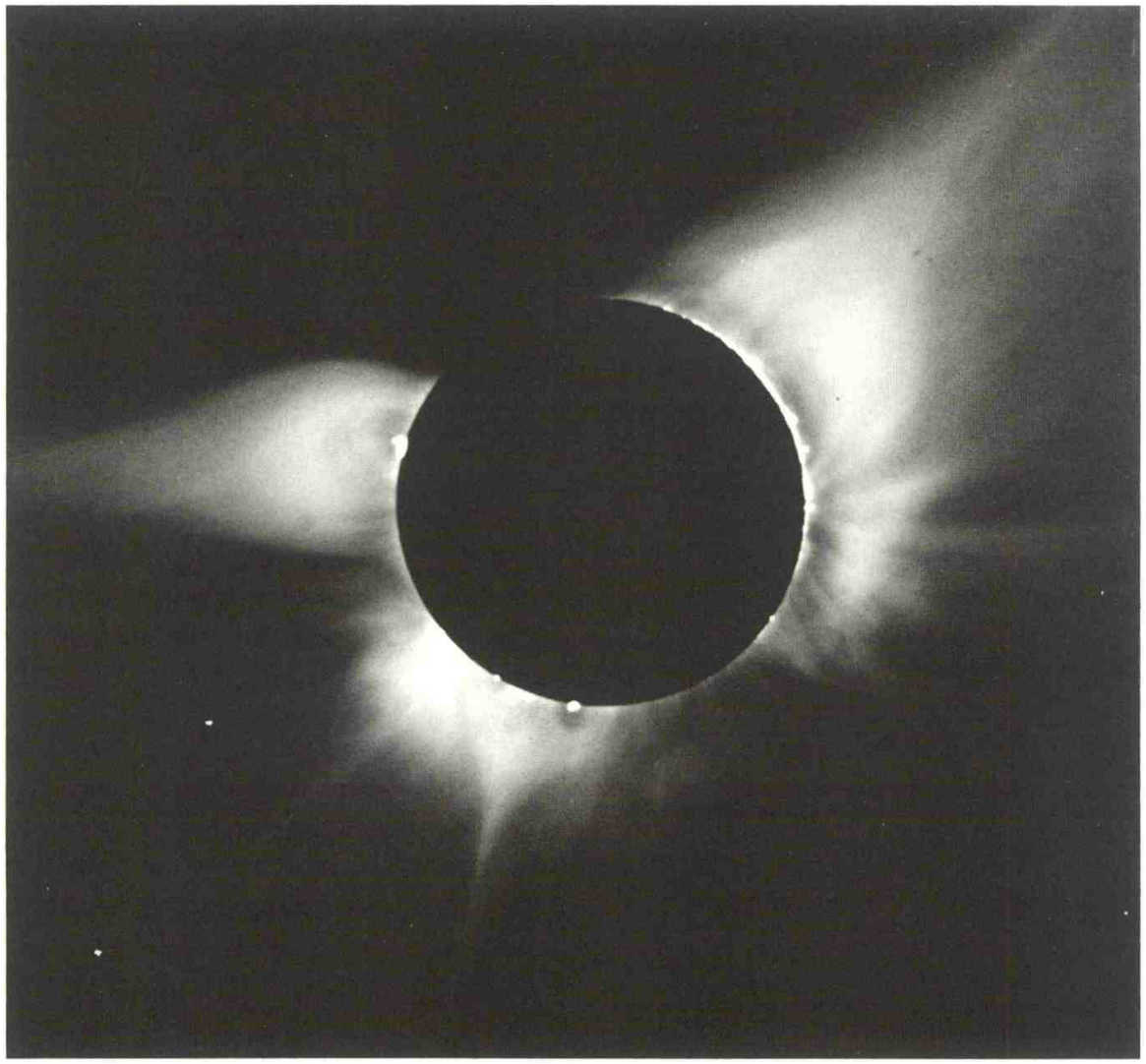

1966 eclipse photograph.

OBSERVATIONS OF THE SOLAR CORONA AT MAUNA LOA

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The sun's corona is best observed at times of total eclipse, when the moon, appearing almost identical to the sun in diameter, blots out the overwhelming brilliance of the solar disk (a million times that of the corona), and when the earth's atmosphere along the eclipse path is also in shadow and interference from scattered sunlight is much reduced. But however breathtaking and however useful to science they may be, total eclipses are so infrequent and of such short duration that they cannot really give us an accurate picture of the long-term behavior of the corona.

Invention of the coronagraph in 1930 by the French astronomer Bernard Lyot made day-to-day observations of the corona possible, and this instrument has been used to document many aspects of coronal activity that earlier were unknown or only suspected. Even in the thin clear air of high altitudes, atmospherically scattered light degrades coronagraph observations; nevertheless, they have been invaluable in portraying the corona's behavior in a continuous rather than piecemeal fashion.

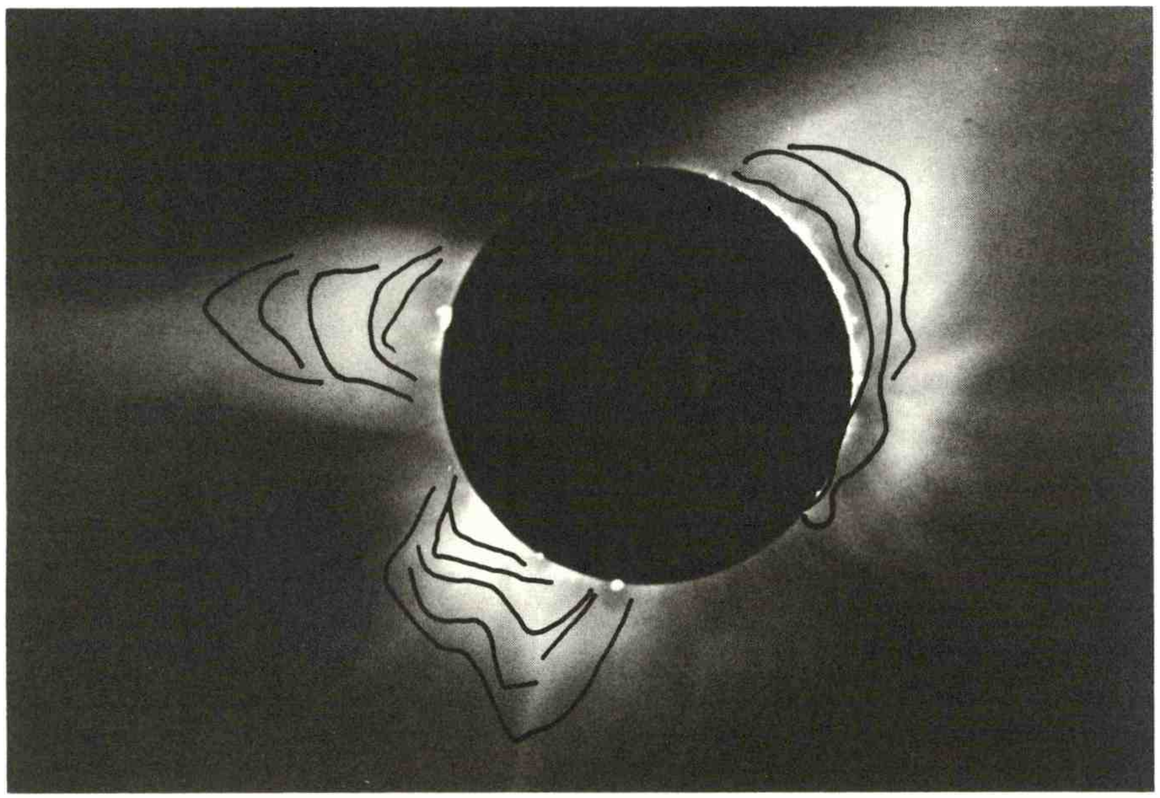


Figure 1. Mauna Loa K-coronameter observations superposed on HAO's 1966 eclipse photograph. The lines are intensity plots and correspond well with the principal coronal features (streamers, condensations, holes, etc.). The K-corona is composed of white light scattered by free electrons in the sun's atmosphere, and its radiance is a measure of electron density in the corona.

SOLAR CYCLE CHANGES IN THE CORONA

Basic changes occur in the appearance of the corona during the 11-year solar sunspot cycle. Near solar maximum, when 100 or more sunspots may be visible at one time, the corona appears to be almost circular, with brilliant streamers radiating from all latitudes. At solar minimum, when few sunspots develop, equatorial streamers predominate, polar features are much reduced, and large rifts often appear near the poles. At this time, total coronal radiance is less than half as great as it is during solar maximum.

Solar cycle changes in the corona were originally discovered by piecing together data from drawings and written descriptions of total eclipses. The advent of eclipse photography in 1851 introduced a more reliable method of recording eclipses and revealed also the difference in total radiance between solar maximum and minimum. Solar cycle changes have now been documented photographically and spectroscopically on a continuing basis with coronagraphs at high-altitude sites in France, Switzerland, Germany, Czechoslovakia, the USSR, Japan, and the United States.

MAUNA LOA OBSERVATORY STUDIES

Richard and Shirley Hansen, Charles Garcia, and Eric Yasukawa, working at the High Altitude Observatory (HAO) site on Mauna Loa, Hawaii, are studying features of the inner corona with two highly specialized coronagraphs, the K-coronameter and the Coronal Activity Monitor. These instruments, developed by HAO engineers, are especially adapted to map coronal radiance photoelectrically. They measure the polarized K-component of the corona, i.e., light scattered by free electrons in the sun's atmosphere. Both the K-coronameter and the Coronal Activity Monitor measure this radiation by

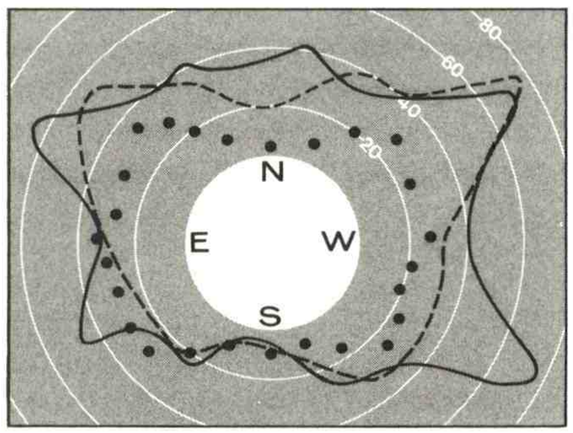


Figure 2. K-coronameter July monthly averages for 1964 (dot), 1966 (dash), and 1967 (solid) depict solar cycle changes in corona. Radial distance from the edge of the circle is proportional to radiance at 0.125 solar radii from the limb of the sun. Note that these are radiance plots and not diagrams of the shape of the corona.

making concentric small-aperture scans around the sun at predetermined distances above the edge, or limb, of the sun while the solar disk is occulted as in other coronagraphs (Fig. 1).

Mauna Loa data verify that pronounced changes occur in the distribution of radiance in the corona during the solar cycle. For example, during the ascending phase (from 1964 to 1967) of the recent solar cycle the total radiance of the lower corona doubled, and there was a progressive migration of zones of enhanced activity toward the poles, as shown in Fig. 2. During July of the solar minimum year 1964 the general level of radiance was low and day-to-day changes were slight. In 1966, zones of increased activity appeared in the Northern Hemisphere. The general level of radiance was two to three times as great as that during solar minimum. In 1967, radiance had increased in the southern quadrants also, although a relative void remained over the south pole.

EVOLUTIONARY CHANGES

From the wealth of synoptic observations being made at Mauna Loa, the evolution of individual coronal features such as the streamers seen in eclipse photographs can be related to other solar phenomena. The corona appears to increase in radiance with the emergence of an active center, a localized region containing sunspots, and other manifestations of strong magnetic fields. Such an active center, which develops at a low latitude, gradually disperses, and a portion of its magnetic field migrates poleward, trailing behind the equatorward portion because of the differential rotation of the sun. For a time, magnetic field lines connect the two regions, but as the trailing field spreads poleward and eastward, field lines also join this region to the polar field. A filamentary, or quiescent, prominence typically divides the regions of opposite polarity. As the sun's rotation brings active centers near the limb of the sun, the association between active centers and coronal features becomes evident. When seen at the edge of the sun, these features are broad helmet-shaped structures; at greater heights above the sun's surface they taper to narrow streamers.

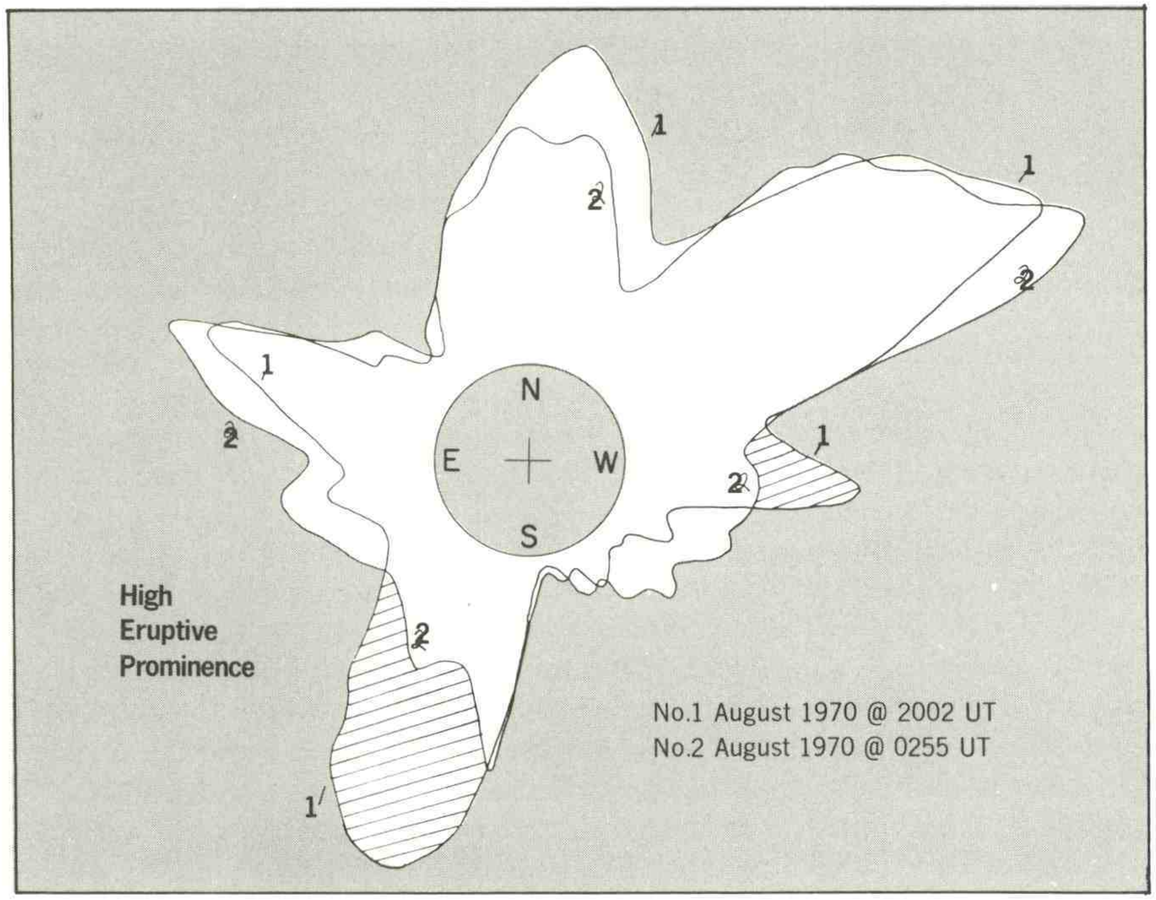
Ultimately, the trailing poleward end of the system appears to break its ties with the equatorward portion and to line up magnetically with the polar field. A long magnetic tunnel arches over the filamentary prominence that separates the trailing field from the polar field, and a helmet streamer extends outward as part of the polar corona. The equatorward end of the original active region, now magnetically unbalanced, may form a transequatorial arch if a similar region of opposite polarity exists at nearby longitudes in the opposite hemisphere.

SOLAR ROTATION

The sun's rotation causes systematic and recognizable changes in the appearance of coronal features as they move into and out of the plane of the sky, projecting for several days above the solar limb. Occasionally, very-high-latitude features may be followed continuously as they rotate around the pole.

CORONAL TRANSIENTS

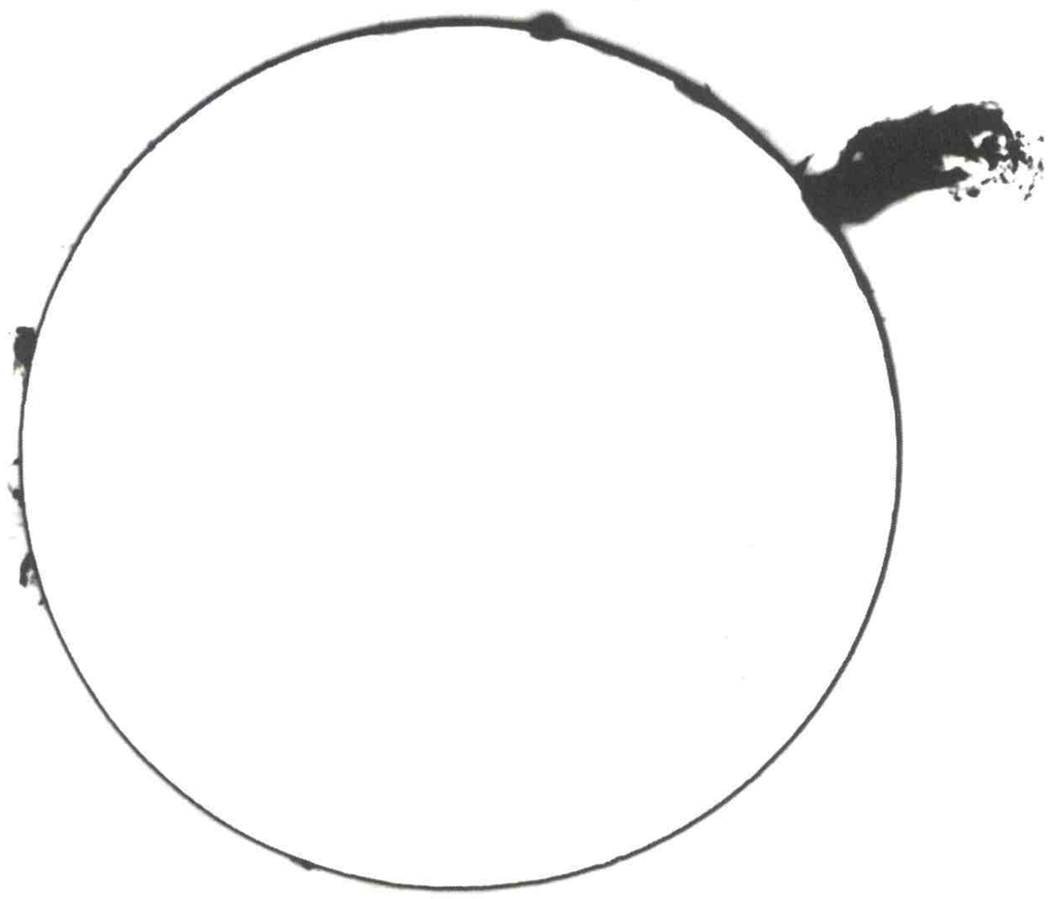
From 1970 to 1973, more than a dozen major abrupt depletions of the inner corona were observed at Mauna Loa. This coronal material, expelled from the sun, was almost invariably associated with eruptive hydrogen alpha



prominences and correlated in both position and time with outward moving type-1V radio sources as seen with a coronagraph aboard the OSO-7 satellite, operated by the Naval Research Laboratory. These coronal transients are abrupt and short lived, and occur in localized regions of the corona (Fig. 3).

Several coronal transients observed at Mauna Loa have also been recorded by the radioheliograph at Culgoora, Australia, operated by the Commonwealth Scientific and Industrial Organization (CSIRO). On March 21, 1970, for instance, the radioheliograph recorded three distinct radio sources, one of which moved to a distance of six solar radii from the limb of the sun. Mauna Loa data suggest that then, as well as during several other transient events, the loss of material blown out into space depleted part of the corona temporarily, for radiance was markedly reduced in the immediate area of the eruption. Recovery was rapid, however, and by the next observing day the coronal structure had returned to its preflare shape and brightness (Fig. 4).

Figure 3. Example of coronal depletions at 0.75 solar radii from the limb of the sun, obtained from K-coronameter records. Brightness of the corona is represented by radial distance from the circle. During the interval between these measurements (about seven hours), a large prominence erupted from the SE limb with attendant depletion of the coronal streamer (cross hatching) and also in a separate event a flare occurred near the west limb with a somewhat smaller depletion of coronal ray.

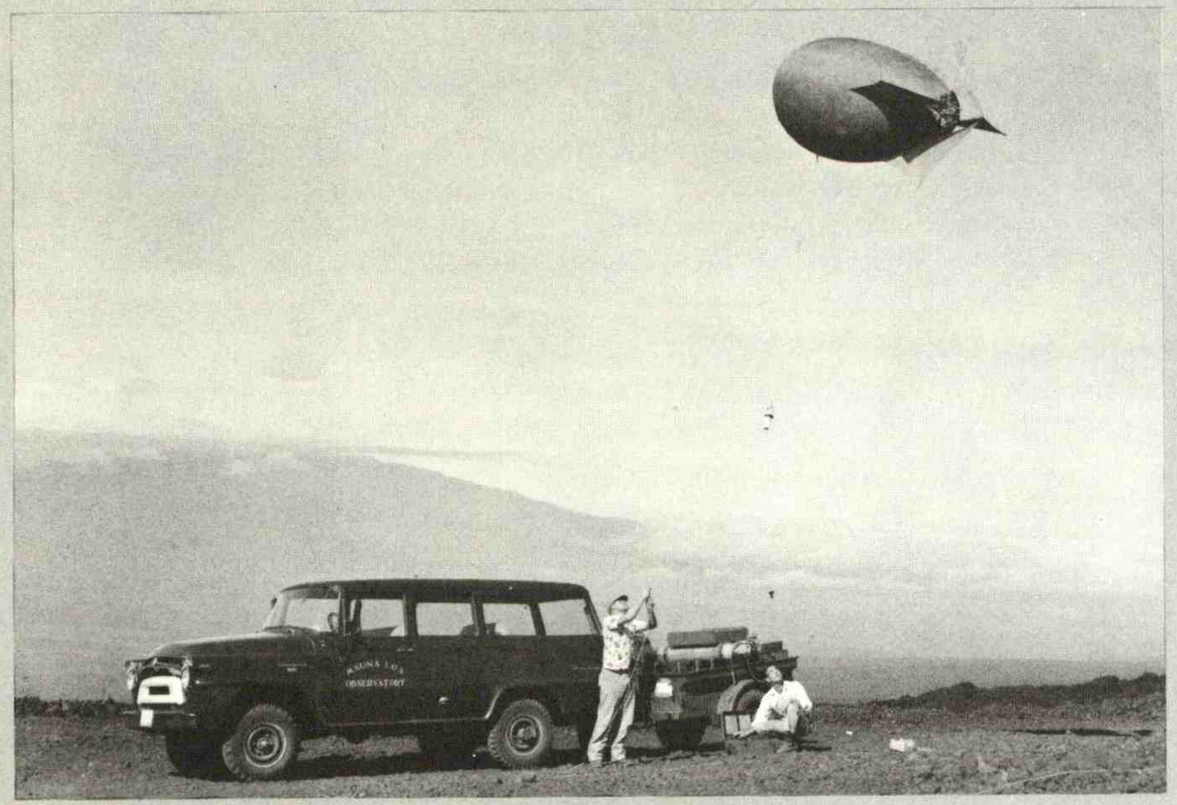


NEW INSTRUMENTATION

The 11-year cycle of solar activity will reach a maximum in 1979. A large effort will be made by HAO to study events occurring on the active sun. HAO will have a solar coronagraph on the Solar Maximum Mission satellite due to be launched into circular orbit in late 1979. To support and complement the SMM coronagraph, a new K-coronameter and a prominence monitor are being built by HAO in Boulder, Colorado, for use at Mauna Loa, Hawaii.

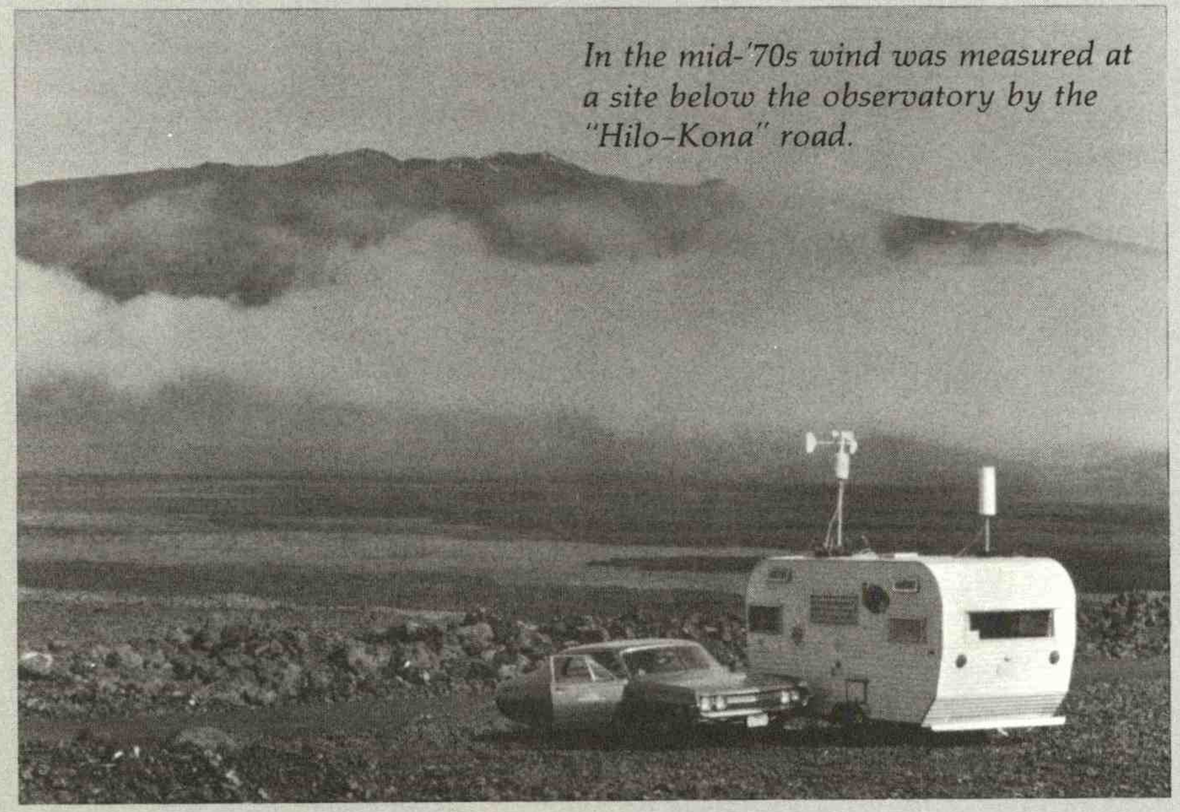
Time resolution will be improved by a factor of several hundred over that of the telescope now used at Mauna Loa. All scan heights will be measured simultaneously at a number of scanned position angles. Computers will control much of the telescope operation and digitize the data on magnetic tape. Together these instruments will measure and interpret coronal electron density and magnetic field structures on a rapid time scale to provide a better understanding of the dynamics of coronal transients.

Figure 4. Eruptive prominence seen with the Mauna Loa Hα coronagraph on October 28, 1972. This eruption caused a depletion in the solar corona as coronal material was carried outward from the sun during the eruptive phase of the prominence.



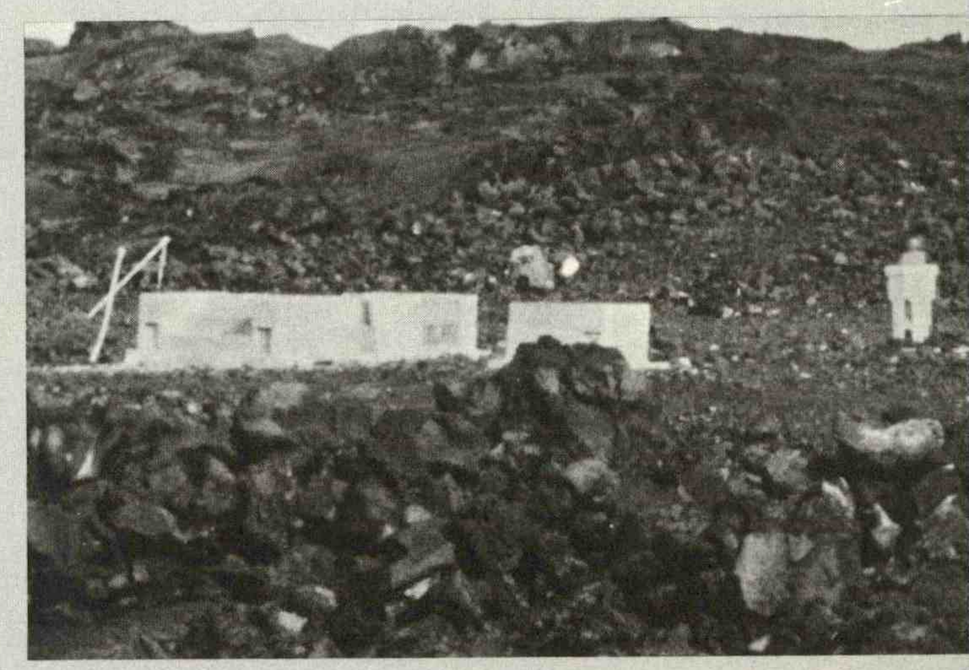
Saul Price and Jack Pales used a tethered balloon for meteorological sounding of the atmosphere (1958).

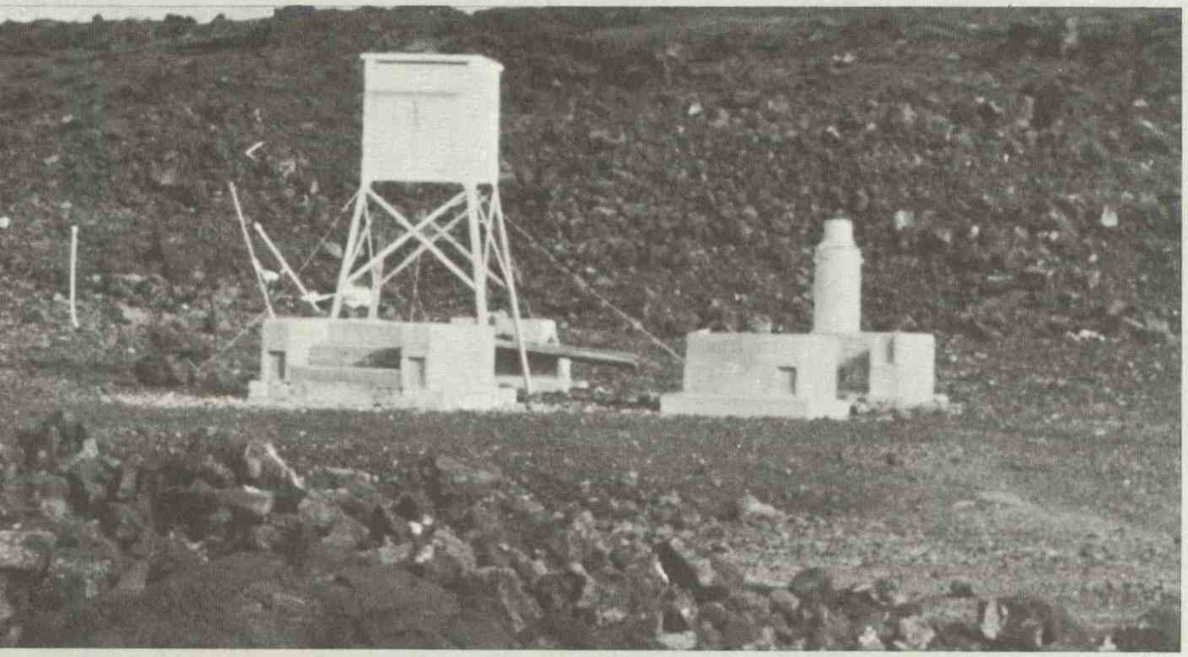
Weather-releated equipment at MLO includes (left, from top) microbarograph, wind-speed and -gust and direction recorder, and operations recorder, and (right, from top) temperature, and solar radiation records.



In the mid-'70s wind was measured at a site below the observatory by the "Hilo–Kona" road.

Kulani Mauka, MLO's climatological station at 8300-ft elevation.





Meteorological measurements

The Complexity of the Wind Patterns at Mauna Loa Observatory

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Hilo, Hawaii 96720

INTRODUCTION

The purpose of the U.S. baseline stations (Mauna Loa, Samoa, Barrow, and South Pole) is to monitor trace materials in the atmosphere that may cause climatic change. In order to interpret these data, meteorological parameters such as surface measurements, vertical soundings, and air trajectories have been employed (Keeling et al., 1976; Pack et al., 1977; and others). A parameter that has been used in interpreting the Mauna Loa Observatory (MLO) data is the surface wind direction and speed.

The wind regime at MLO consists of two major components—local and synoptic. The local upslope (northerly wind)-downslope (southerly wind) system at the observatory has frequently been described (Lavoie, 1967; Mendonca, 1969; and others). The daytime upslope flow is not, however, a simple anabatic flow, because the strength of either the low-level trades on the east side of the island or the sea breeze on the west side determines whether the upslope has a westerly or easterly component (Fig. 1).

The second wind system, i.e., the large-scale synoptic flow, which reflects global circulation and usually has an easterly or westerly component, occurs also at the site. The difficulty of determining which system prevails arises when the winds come from the SE., SW., NE., or NW. To distinguish between the local wind systems and the synoptic flow is one aspect of establishing whether a given measurement is representative of a global or local value.

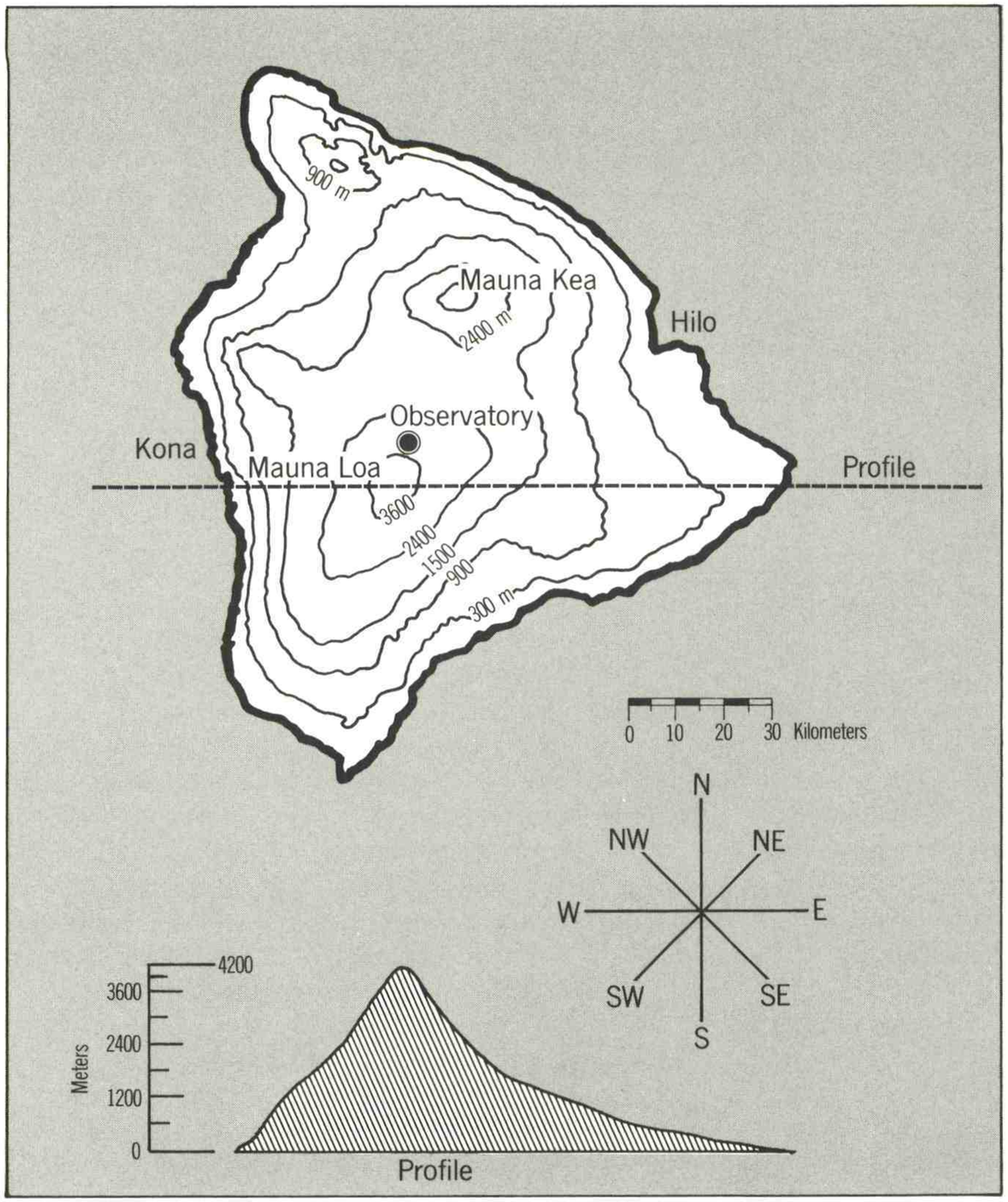


Figure 1. Topography and profile of the island of Hawaii.

MEASUREMENTS

For approximately 20 years, wind measurements at MLO have been made with a cup anemometer and recorder using a digital system to eight points of the compass. For an evaluation of this record, a 2-year period (February 1, 1975 to January 31, 1977) was chosen, and the hourly averaged wind direction and speed were summarized.

WIND DIRECTION

The average hourly wind direction over the 2-year period is plotted in Fig. 2. The most obvious feature of this figure is the regularity of the upslope direction, or northerly component, of the wind. This anabatic wind, which prevails only during the daytime period (0800–1900 LST), may, however, be influenced by the northeasterly trades progressing up the Saddle area from the Hilo side or by the westerly sea breeze from the west Kona coast of the island. These two regimes fight a daily battle to impose on the upslope winds an easterly or a westerly component. In addition, a synoptic flow may sometimes be imposed on local wind systems and thus complicate the picture.

The southerly, or downslope, component is present during the evening and early morning. However, even though winds with a southerly component may prevail throughout the day during some months, i.e., September 1975, 1976, and May 1977 (Fig. 1), the synoptic pattern interferes with the katabatic winds in many cases. The diversity of the wind patterns at the same time of the year can be seen by comparing the January patterns.

The large-scale synoptic systems leave a significant imprint on the MLO surface winds. Meteorologists have divided the synoptic patterns that affect the Hawaiian Islands into two simple categories—summer and winter (Worthley, 1967). During the winter period (October–April) the intertropical convergence zone moves farther south allowing the more westerly flow associated with extra-tropical disturbances to prevail. The summer period (June–August) is characterized by the semipermanent high-pressure situation to the north and east of the Hawaiian Islands. May and September are considered periods of transition.

As the local winds accentuate the north and south components of the winds, the synoptic flow strengthens the easterly and westerly directions. During the winter period the west winds are increased. The easterly component is strongest during the summer period but may appear throughout the year depending on the position of the intertropical convergence zone. During the transition period between summer and winter seasons, the best upslope-downslope pattern exists. A summary of the local flow patterns and the regional synoptic patterns is given in Table 1.

WIND SPEED

Over the 20 years of wind measurements, moderate to strong winds at MLO (speeds > 10 mph (4.5 m/s)) have been observed to indicate a dominance of the synoptic pattern over the local wind system. Even during these strong wind periods, the upslope has enough influence to swing the westerly flow from south to north during a given diurnal period. A similar effect is seen in the shift from south to north during the strong easterly flow, although this effect is less pronounced (Fig. 2).

A typical case of how the wind speed may help to differentiate between synoptic and local winds is shown in Fig. 3. The wind direction data for January 1976 are separated into two classes; all cases above 10 mph show the predominance of the southeasterly flow throughout the whole day and indicate a strong synoptic influence on the wind pattern. This synoptic situation occurs typically in the winter with a west-east polar front north of the islands but a southeasterly flow over Hawaii.

SUMMARY

The Mauna Loa wind system is a complex interaction of both the local flow systems and the regional synoptic patterns. To determine whether the MLO trace material measurements represent global or local values, an analysis of the wind speed and direction is a useful method.

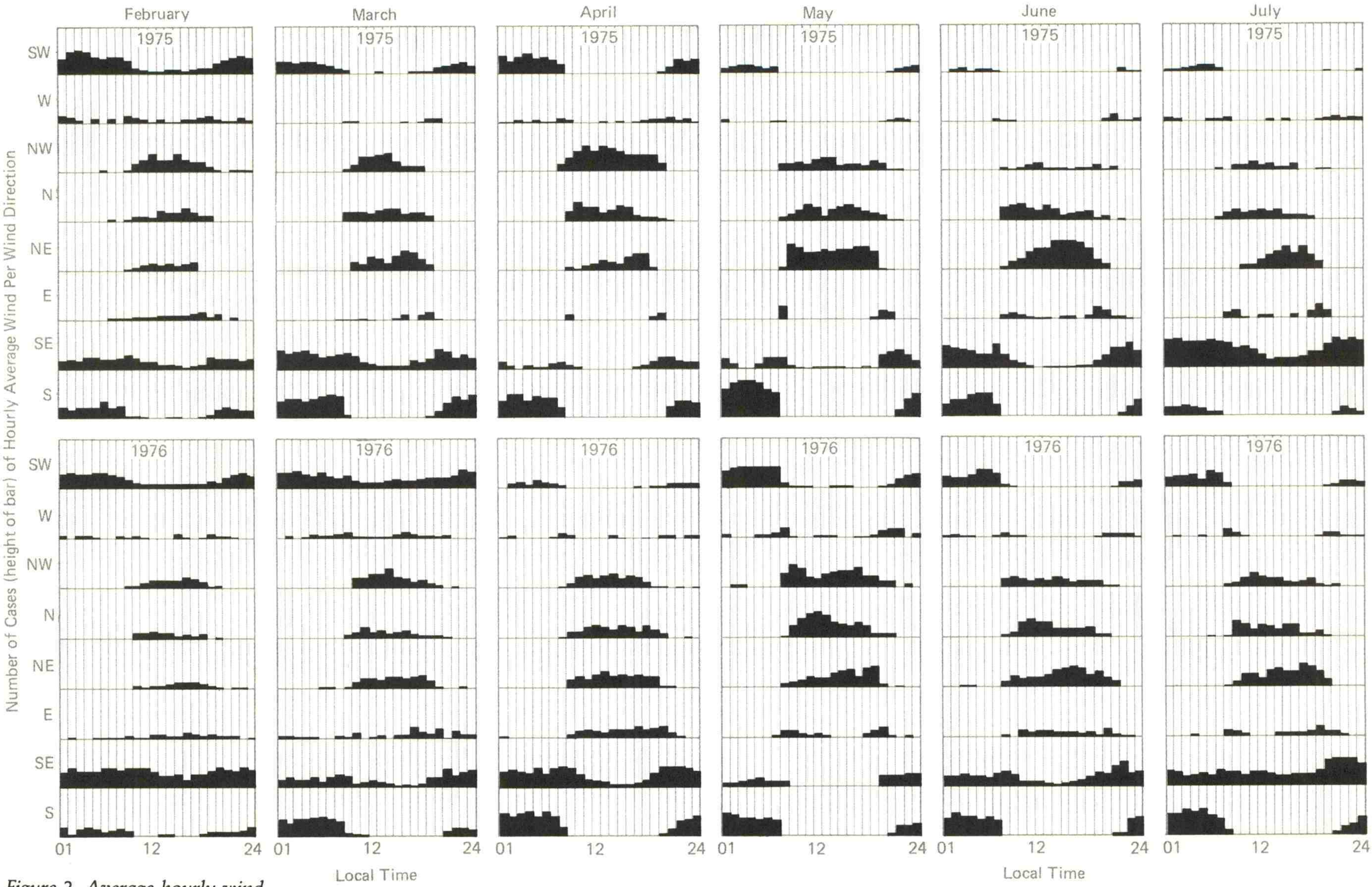
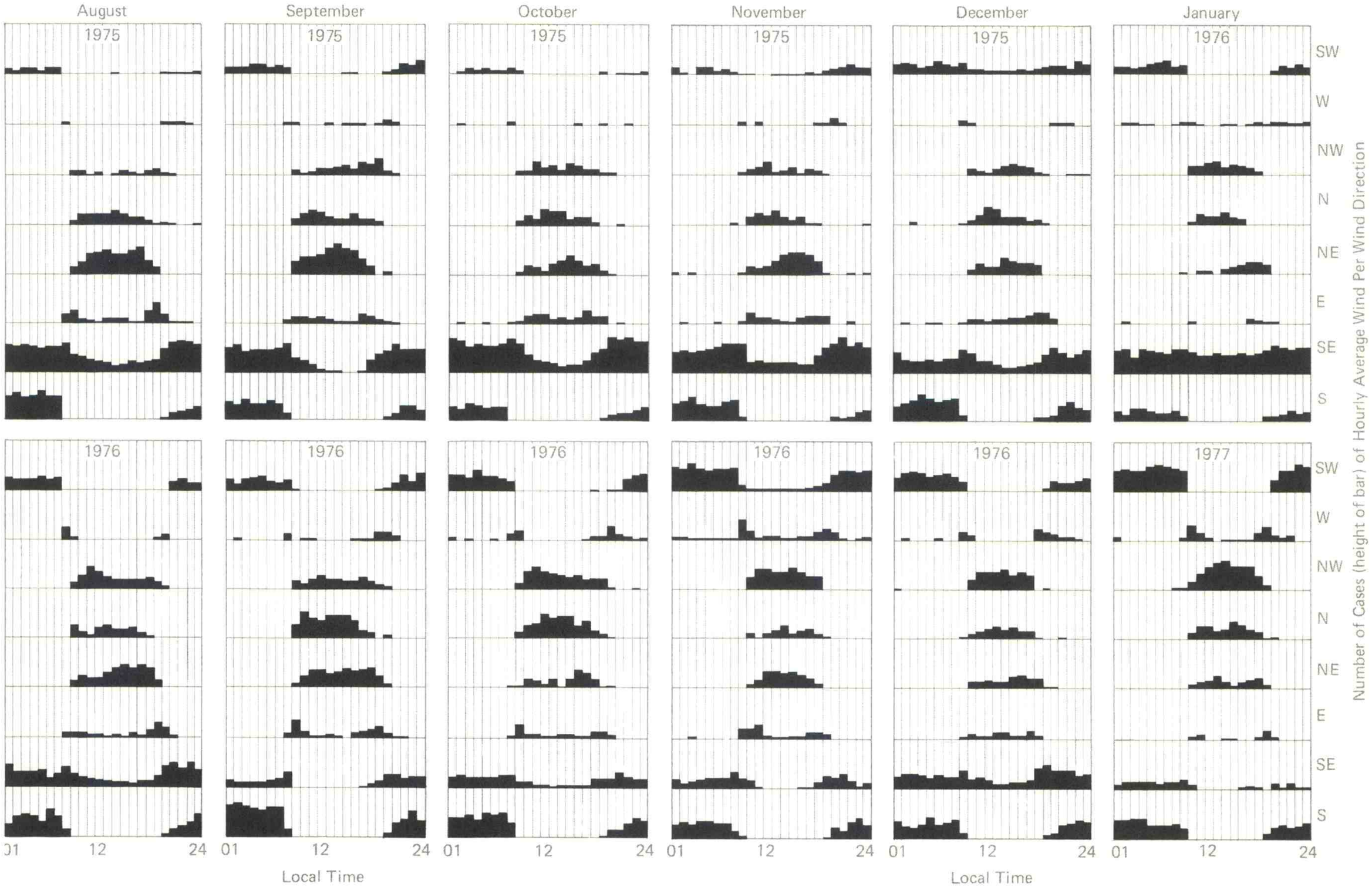


Figure 2. Average hourly wind directions at Mauna Loa. Averages are compared for two years.


August
1975
September
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November
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1976
1976
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Local Time
Number of Cases (height of bar) of Hourly Average Wind Per Wind Direction

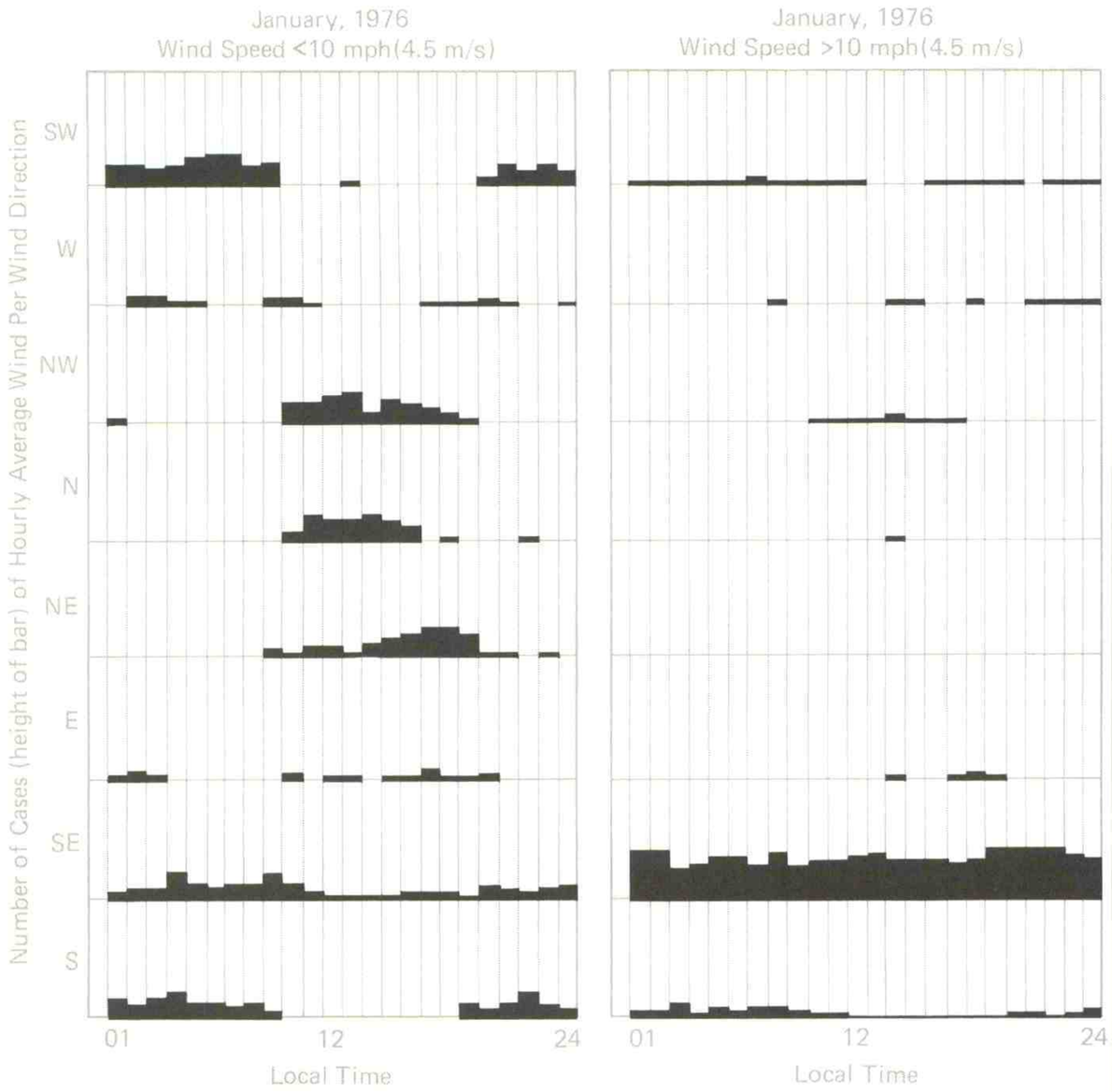

Figure 3. Comparison of hourly average winds per wind direction as separated into winds below and above 10 mph.

Table 1. Interpretation of Surface Wind Directions at Mauna Loa Observatory

Direction	Time		Prevailing Season
	0800–1900 LST	1900–0800 LST	
Southwest	Occurs only with strong synoptic component	Combination of downslope and synoptic component	Winter
West	Insignificant, recorded during wind shifts	Insignificant	None
Northwest	Major occurrence during this period, effect of local sea-breeze plus some support from synoptic	Insignificant	None
North	Local upslope flow, no synoptic component	Insignificant	None
Northeast	Local upslope flow plus a synoptic component	Insignificant	Slightly more often in summer
East	Mainly synoptic plus some local effects	Insignificant	Slightly more often in summer
Southeast	During strong synoptic flow from east	Local effect fortified by synoptic	All year long with slightly more cases in summer
South	Insignificant	Local downslope flow with little synoptic influence	All year

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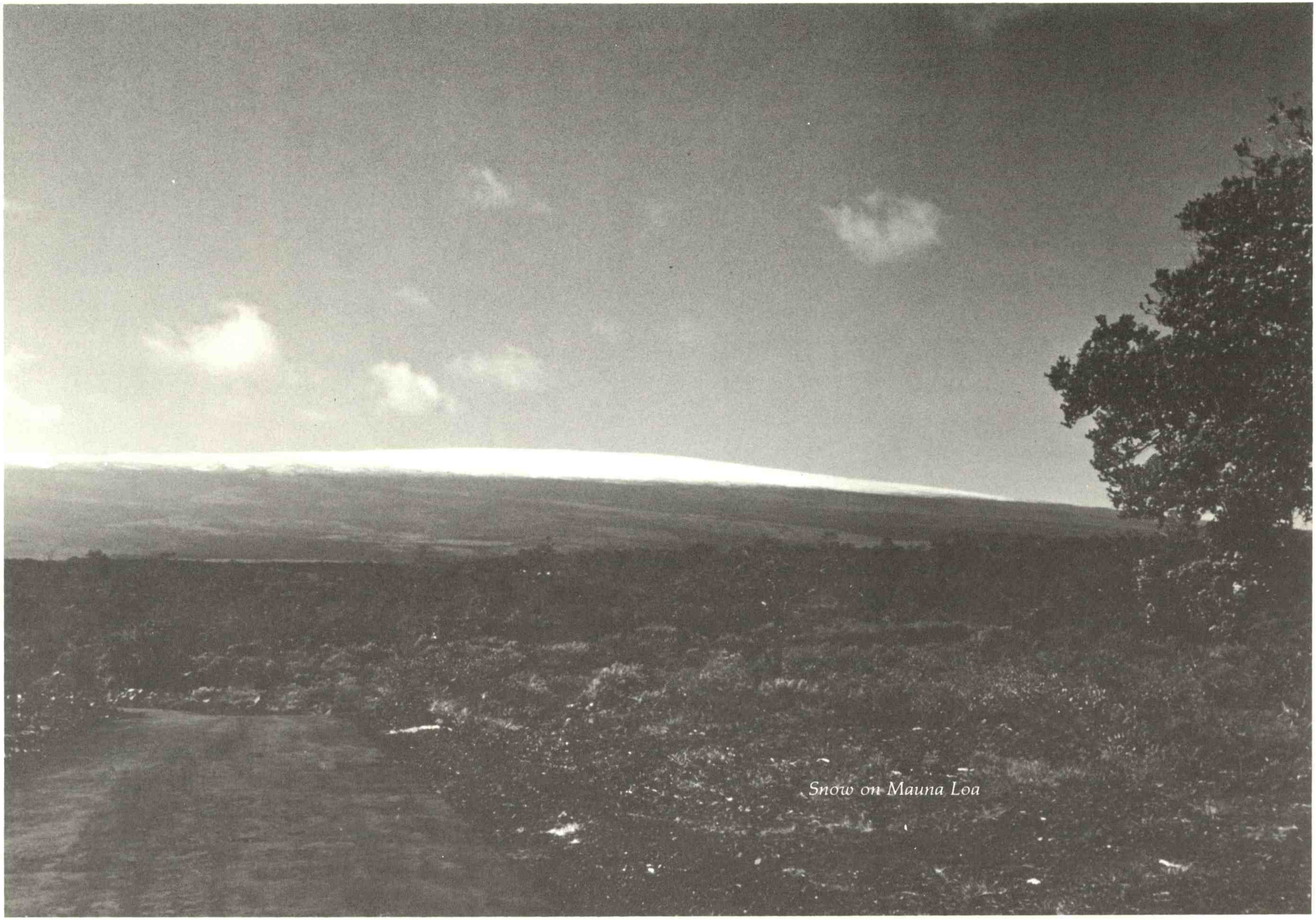

Snow on Mauna Loa

CLIMATE AND WATER BALANCE ON THE ISLAND OF HAWAII

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INTRODUCTION

The island of Hawaii, with a surface area of only 10,455 km², exhibits a spectacular range of climatic diversity comparable with that found on large continents. Three major factors contribute to this climatic diversity:

1. Topographic relief. The volcanic mountains of Mauna Kea and Mauna Loa reach summit elevations of 4,205 m and 4,168 m, respectively. The altitudinal range provides for a diversity of temperatures, and the mountains themselves are barriers that induce orographic precipitation.

2. Large-scale synoptic wind field. The strong and persistent northeast trade winds interact with the island topography to produce distinctive windward and leeward climates. The associated upper-level trade wind inversion exerts a particularly strong control on mountain precipitation gradients.

3. Local circulation. Differential heating and cooling of the land, water, mountain, and lowland areas on Hawaii give rise to localized wind regimes which add to the island's climatic diversity.

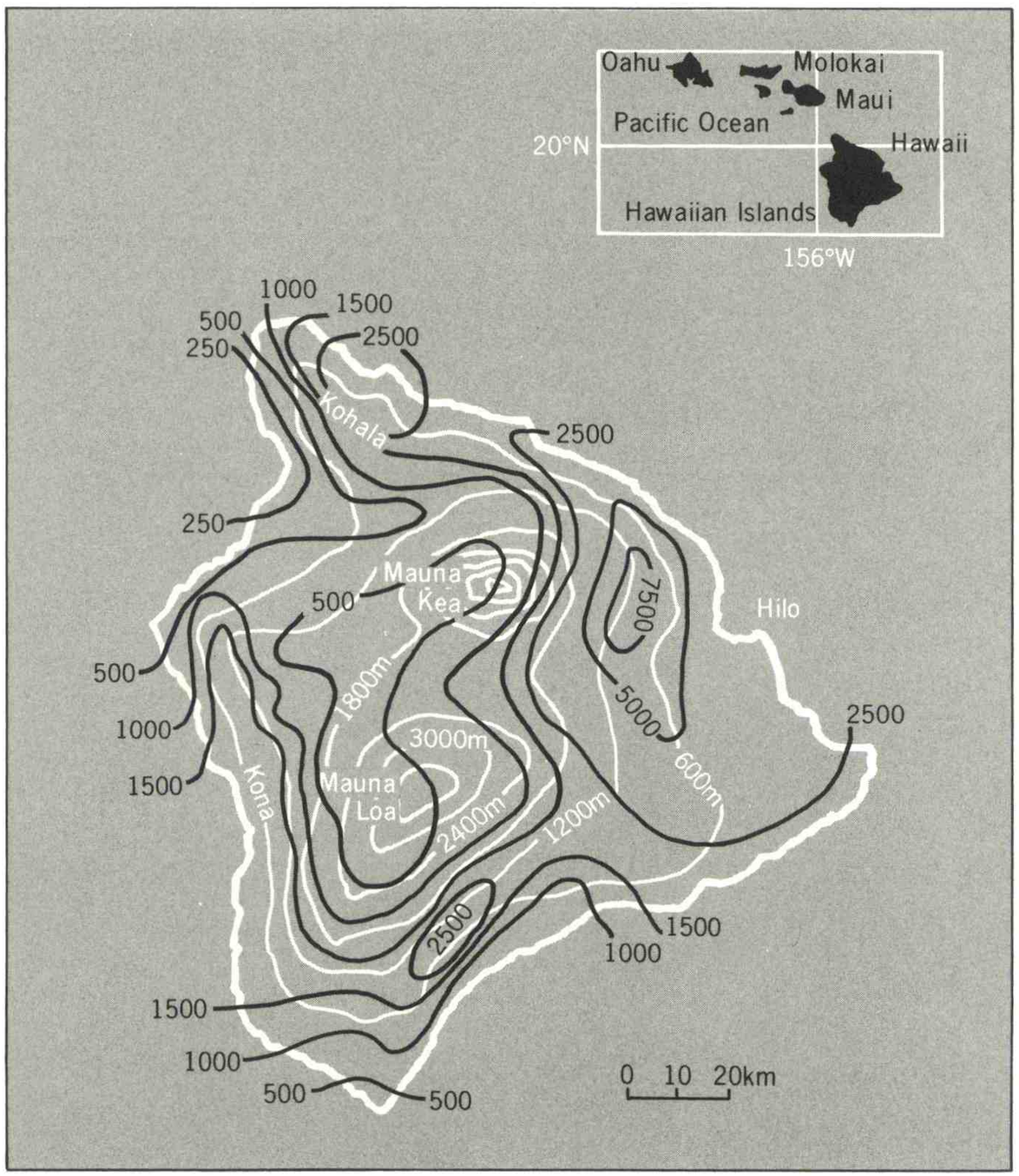


Figure 1. Distribution contours of mean annual rainfall (mm), superimposed on topographic map of the island of Hawaii. (Redrawn from Taliaferro, 1959; State of Hawaii, 1970.)

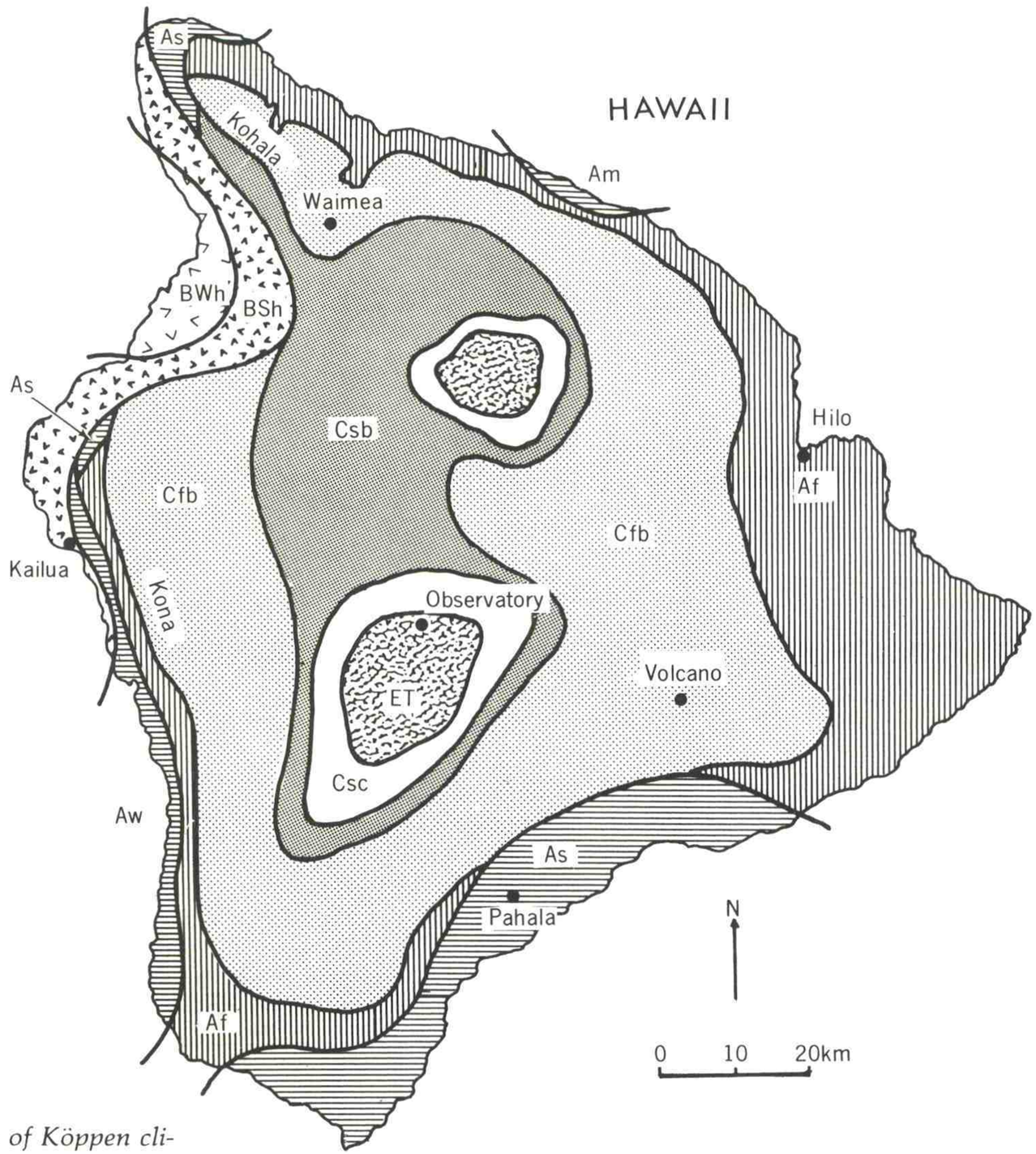


Figure 2. Distribution of Köppen climate types on the island of Hawaii.

A HUMID TROPICAL CLIMATES
(All monthly mean temp 18 °C) >
- Af TROPICAL CONTINUOUSLY WET (Each month mean rainfall 6 cm)
- Aw TROPICAL WINTER-DRY (At least one winter month mean rainfall < 6 cm)
- As TROPICAL SUMMER-DRY (At least one summer month mean rainfall < 6 cm)
- Am TROPICAL MONSOON (High annual rainfall with short dry season)

B ARID AND SEMI-ARID CLIMATES
(Annual evaporation exceeds precipitation)
- BSh HOT SEMI-DESERT (Moderate rainfall, mean annual temp. > 18 °C)
- BWh HOT DESERT (Low rainfall, mean annual temp. > 18 °C)

C TEMPERATE CLIMATES
(Mean temp. of coldest month between −3° and +18 °C)
- Cfb CONTINUOUSLY WET WARM TEMPERATE (At least four months mean temp. > 10 °C < 22 °C)
- Csb SUMMER-DRY WARM TEMPERATE (Temp. as above, 70% of annual rainfall in six winter months, dryest summer month rainfall < 3 cm)
- Csc SUMMER-DRY COOL TEMPERATE (Precipitation as above, less than four months mean temp. > 10 °C)

D COLD CONTINENTAL CLIMATES
(None in Hawaii)

E ICE CLIMATES
- ET PERIGLACIAL CLIMATE (Warmest mean monthly temp. between 0° and 10 °C)

KÖPPEN CLIMATIC ZONES

Integrating the altitudinal temperature gradients with the annual, seasonal, and spatially variable rainfall regimes results in a diverse combination of climatic environments. The Köppen climate classification uses monthly temperature and precipitation characteristics in a descriptive system that distinguishes broad regional and global climatic zones. The system has been often criticized for its empirical approach and lack of emphasis on "dynamic processes" (e.g., Carter and Mather, 1966); however, as a "first approximation" the Köppen classification offers useful insights into regional climatic patterns.

Four broad Köppen climatic zones are distinguished on the island of Hawaii. They are organized primarily as concentric altitudinal bands on the mountain slopes. Fig. 2 illustrates the spatial distribution of these Köppen climatic types on the island. The map was constructed on the basis of temperature (absolute or extrapolated) and precipitation data from 55 island stations. Discussions of the zones follow.

Humid Tropical Zone (*A* climates).

Characterized by warm temperatures throughout the year and relatively high annual rainfall, humid tropical climates occupy the lower slopes of the island from sea level to about 450 m (slightly higher in warmer areas of leeward Kona). This tropical zone may be further differentiated on the basis of rainfall seasonality. Large-scale synoptic disturbances in winter (mid-latitude cyclonic storms) produce substantial rainfall that is to some extent independent of slope aspect or elevation, and as a result most locations on the island exhibit an absolute winter maximum in rainfall. However, windward areas of Hawaii also receive substantial orographic rainfall throughout the year, with the result that there is no distinct dry season (*Af* climate). Lowland areas on the island that are transitional in location between windward and leeward receive less orographic rainfall (since they are not oriented normal to trade wind flow) and exhibit a distinctive summer dry season (*As* climate). Humid summer-dry climates are not common anywhere in the world, since for most tropical locations rainfall is at a maximum in the summer, the result of increased convective instability in the high-sun period. Outside of Hawaii the *As* climate type occurs only in southern Madras (India) and adjacent northern Sri Lanka.

The leeward or Kona coast of Hawaii contains the only extensive area of summer maximum rainfall in the Hawaiian archipelago (*Aw*, winter-dry climate). Isolated from the prevailing trade wind flow by intervening high mountains, the Kona coast's dominant circulation pattern is formed by a localized land-sea breeze regime. Increased land surface temperatures in summer strengthen the daily sea breeze regime and increase convective instability, leading to a high frequency of afternoon thundershowers. The vertical structure necessary for thundershower development is further assured by the high mountains, which exclude the trade wind aloft and limit the potential for strong vertical wind shear. The presence of a strong shearing force would otherwise tend to destabilize these leeward convectional cells. Although there is generally a summer rainfall maximum throughout Kona, the *Aw* climate gives way to *Af* at elevations above 400 m, where, by virtue of general orographic position, there is adequate precipitation in all months.

Arid and Semi-Arid Zones (*B* climates).

A classic rain shadow desert exists on the leeward side of the Kohala mountains. Smaller and lower (maximum elevation 1,670 m) than Mauna Kea and Mauna Loa, the Kohala mountains are incapable of blocking out trade wind flow to leeward. Having become depleted of moisture during windward ascent, the trades warm adiabatically to leeward, promoting a hot, arid zone. With only 190 mm of annual rainfall, Kawaihae on the leeward Kohala coast is the driest location in the Hawaiian archipelago. The Köppen system distinguishes two climatic subtypes, the true desert (*BWh* climate) and the semidesert (*BSh* climate) on the basis of relative aridity. In leeward Kohala the true desert gives way to semi-desert at higher elevations.

Temperate Zone (C climates)[1]

Average air temperature in Hawaii decreases with altitude at the rate of about 0.55°C/100 m (Price, 1973). When the criteria of the Köppen classification are used, at elevations above 400–500 m on the mountain slopes, tropical climates grade to temperate as a result of decreasing average temperatures. As a result of the moderating influence of altitude, almost two-thirds of the "tropical" island of Hawaii possesses a temperate upland climate. The majority of this zone is characterized by warm summers and adequate precipitation in all months (*Cfb* climate). Except for the absence of a stronger season variability the upland Hawaii climates are analogous to those of similar Köppen designation in Pacific coastal areas of North America. Ascending orographic clouds compressed between the rising mountain slope and an upper-air temperature inversion produce frequent ground level mountain fog, an important moisture source for upland vegetation (Juvik and Perreira, 1974). At still higher elevations on Mauna Kea and Mauna Loa (above 2,000 m) there is a tendency toward summer drought. The increased strength and frequency of the trade wind inversion in summer (modal elevation 1,800 m) inhibits the vertical penetration of orographic clouds and precipitation to the higher slopes. This summer-dry zone (*Csb* climate) also occurs at a lower elevation in leeward Kohala, Mauna Kea, and Mauna Loa, where summer orographic precipitation is largely absent. Above 2,500 m on both Mauna Loa and Mauna Kea the summer-dry regime changes from warm to cool (*Csc* climate).

Alpine (periglacial) Zone (*E* climates).

Above 3,200-m level on Mauna Kea and Mauna Loa all months have a mean temperature below 10°C, and the climates are classified as periglacial (*ET*). Nighttime freezing is common throughout the year. Although it exhibits a winter maximum, annual rainfall is very low (200–400 mm) and variable. Above the 3,500-m level, winter snowfall accounts for a substantial portion of the seasonal precipitation. Köppen used the 10°C (warmest month) boundary to separate the *C* and *E* climates on the basis that trees will not normally grow where mean temperatures fall below this level. Hence *E* climates characterized the treeless arctic tundra. The upper tree line of Mauna Kea (3,000 m) corresponds fairly closely to the *C/E* boundary mapped in Fig. 2. On Mauna Loa the tree line is much lower for edaphic reasons (recent lava).

WATER BALANCE

The preceding discussion of Köppen climatic zones on Hawaii provides a general overview of the dramatic range in regional climatic diversity found on the island. However, this descriptive approach says little about the direct linkage of climate to physical and biological processes at the earth/atmospheric interface.

An integration of seasonal moisture supply (precipitation) with the evaporation and transpiration demands of the environment (determined primarily by solar energy inputs) provides an index of moisture surplus or deficit. Such indices can illuminate direct process/response relationships between climate and the terrestrial ecosystem.

In an initial survey of water balance climatology on the island of Hawaii, Mueller-Dombois (1966) constructed a series of climate diagrams 21 stations (see Fig. 3). This type of diagram, popularized by Walter and Lieth (1960), portrays seasonal curves of mean monthly temperature and precipitation. According to Muller-Dombois (1976) an index of precipitation efficiency is built into the diagrams by making one degree of temperature (Celsius) equal to two millimeters of precipitation in the scaling of the two ordinates. This is based on the assumption that monthly potential evapotranspiration (in millimeters) is roughly equal to twice the mean monthly temperature (Gaussen, 1954). Wherever the precipitation curve drops below the temperature curve, a drought season is indicated. Thus the graph is transformed into a water balance diagram with the temperature curve interpreted as an index of potential evapotranspiration.

A serious problem inherent in this graphing technique is the tendency to approximate evapotranspiration with a simple linear function of air temperature (i.e., the 2:1 ratio). Chang (1959, 1968) has reviewed the problems of temperature-based estimations of potential evapotranspiration and points out

[1]The Temperate (*C*) and Polar (*E*) climates as originally proposed by Köppen were not applied in high-altitude tropical environments, which, because of their orographic complexity, lack of meteorological data, and absence of strong seasonality, were simply designated as highland climates (*H*). In more recent global and regional climatic maps of the tropics, highland *C* and *E* climatic areas are frequently portrayed in order to show approximate altitudinal analogs for these broad latitudinal climatic zones.

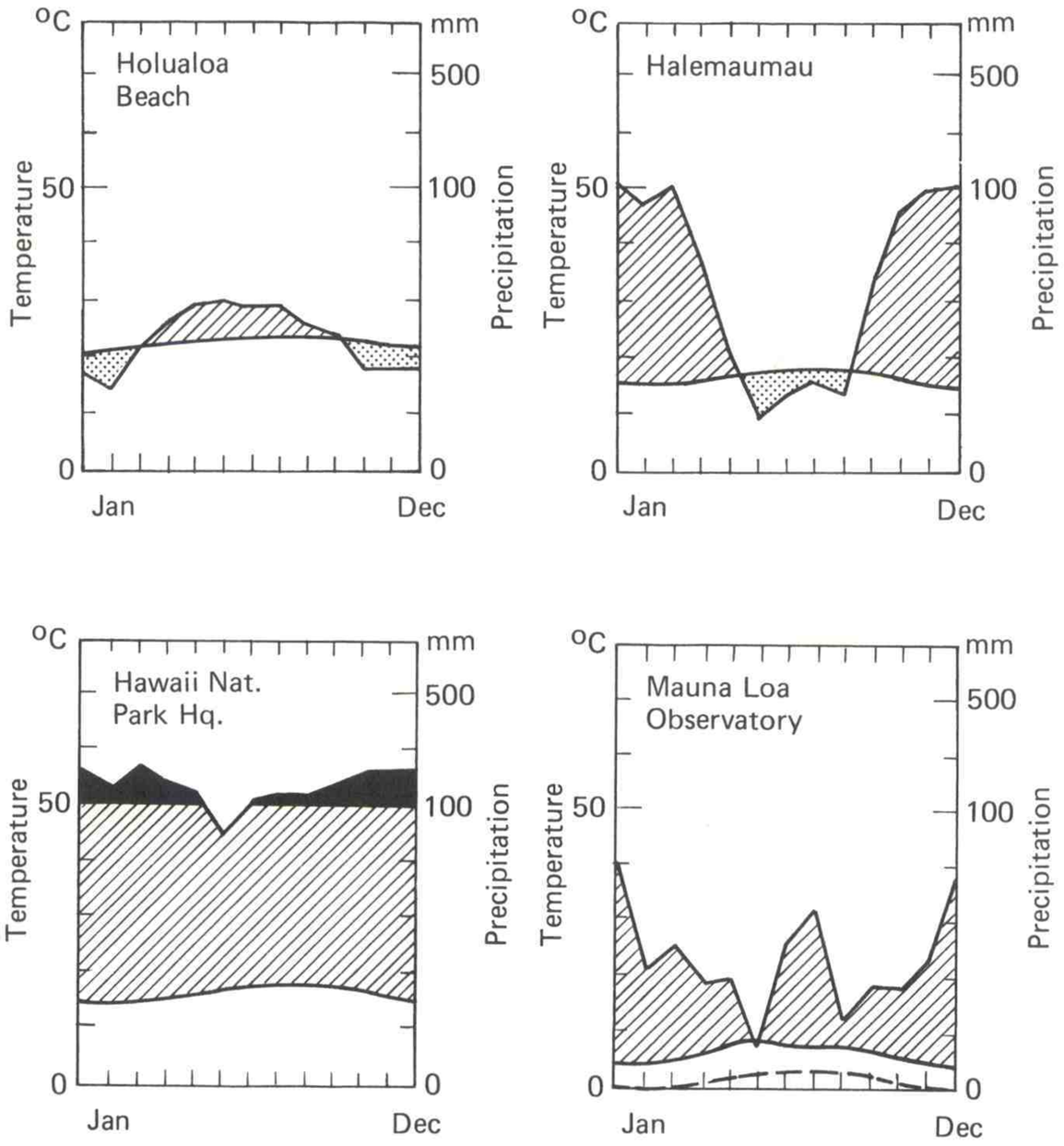


Figure 3. "Walter" climate diagrams for four Hawaii island stations (From Mueller-Dombois, 1966).

that solar radiation rather than temperature is the primary forcing function in the evaporative process. Temperature-based estimates of evaporation implicitly assume a strong correlation between temperature and solar radiation. In Hawaii, as a result of advection and the buffering effect of the surrounding marine environment, there is generally poor correlation between solar radiation and temperature. In Hilo, for example, the range in mean monthly air temperature is only 1.4°C between June (24.2°C) and December (22.8°C). By contrast, the receipt of solar radiation in June (563 Ly; see solar radiation data for 1965 from Löf et al, 1966) is more than twice that in December (263 Ly).

It is obvious from the above comparison that temperature-based estimates of evapotranspiration cannot be expected to portray realistically the seasonal fluctuations implied in the radiation data. However, in the absence of a dense network of solar radiation monitoring stations on the island, upon which more sophisticated spatial modeling of evapotranspiration might be based, it is necessary to revert to some form of temperature-derived estimation in a "first approximation" of water balance regimes.

Thornthwaite (1948) has developed perhaps the most widely adopted method of estimating potential evapotranspiration. His empirical formula is based essentially on air temperature:

$$E = 1.6\,(10T/I)^a. \qquad (1)$$

Potential evapotranspiration E is computed from mean monthly temperature T and an empiric "heat index" I, which itself is an exponential function of temperature; a is a constant.

To obtain mean monthly evapotranspiration, the values derived from eq. (1) are corrected for mean daylength and number of days in the month. The Thornthwaite equation, although subject to the general limitations of all temperature-based methods, might be expected to give better results than the Walter method in Hawaii, since potential evapotranspiration is expressed as an exponential rather than linear function of temperature.

Figure 4. Monthly estimated potential evapotranspiration and measured pan evaporation for Hilo and Pahala data.

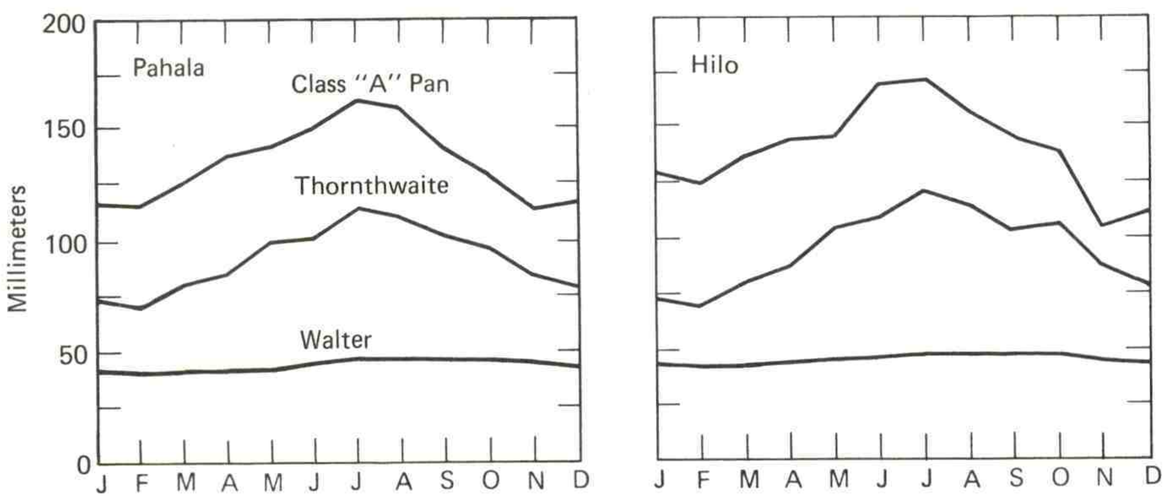
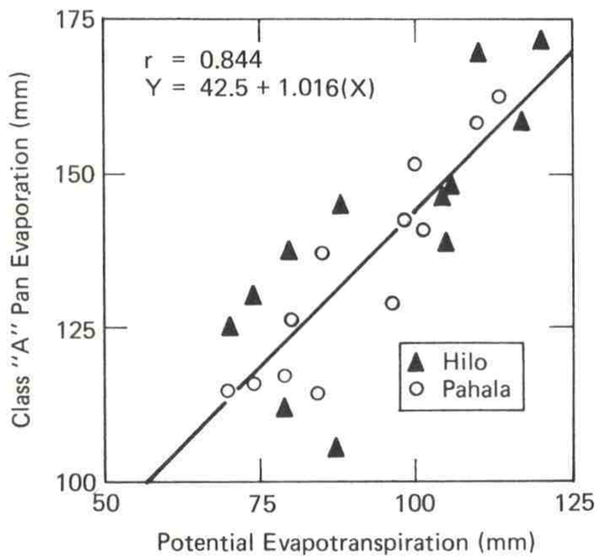


Figure 5. Relationship between monthly class "A" pan evaporation and estimated monthly potential evapotranspiration (Thornthwaite) for Hilo and Pahala data.



In Fig. 4, monthly values of potential evapotranspiration derived by both the Walter and the Thornthwaite methods have been plotted along with class "A" pan-evaporation data for Hilo and Pahala. It is evident that Walter grossly underestimates pan evaporation (here assumed to be equal to potential evapotranspiration) and also fails to detect the seasonal rhythm apparent in the pan data. Thornthwaite also underestimates pan evaporation but does so in a fairly consistent manner and achieves a strong covariation with the pan data in seasonal rhythm. This suggests that the Thornthwaite method might be useful in Hawaii if a correction factor could be derived to compensate for the consistent underestimation exhibited in Fig. 4.

In Fig. 5, monthly values of the Thornthwaite potential evapotranspiration estimate are plotted against pan evaporation for Hilo and Pahala. With a regression coefficient of 0.844, approximately 71% of the observed variation in pan evaporation can be explained by variation in the Thornthwaite estimate. (The regression coefficient is significant at 0.01 level.) Potential evapotranspiration Y can thus be reasonably predicted from the Thornthwaite values X by the linear regression equation

$$Y = 42.8 + 1.016\,(X) \qquad (2)$$

Before eq. (2) can be applied as a general (island-wide) correction factor for the Thornthwaite potential evapotranspiration estimate, it must be verified that the relationship established in Fig. 5 (for two lowland locations) is equally valid for mid- and high-altitude areas of the island

There are no class "A" pan evaporation data for inland mountain areas of Hawaii with which the lowland-derived correction factor might be compared. However, Juvik and Clarke (1976) have accumulated limited experimental data on mountain evaporation gradients in Hawaii Volcanoes National Park on the east flank of Mauna Loa. These data were obtained by using four constant-level pan evaporimeters (Fig. 6) situated along an altitudinal transect between sea level and 2,000 m.

In Fig. 7, measured mean daily evaporative rates (averages from 133 days of simultaneous readings taken from September 1974 through May 1975) are

Figure 6. Constant-level pan evaporimeter. a) field installation with inner tube reservoir; b) evaporimeter detail. Note foam insulation around evaporation pan.

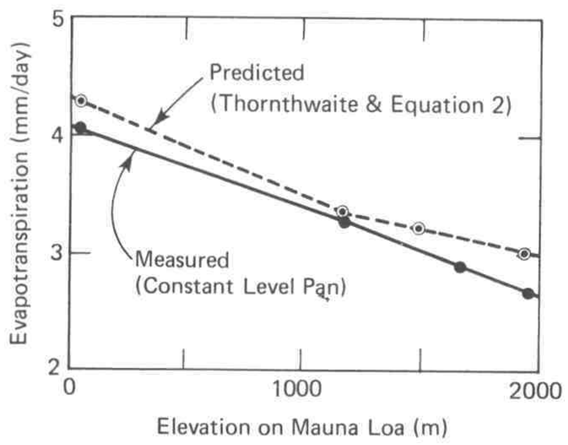
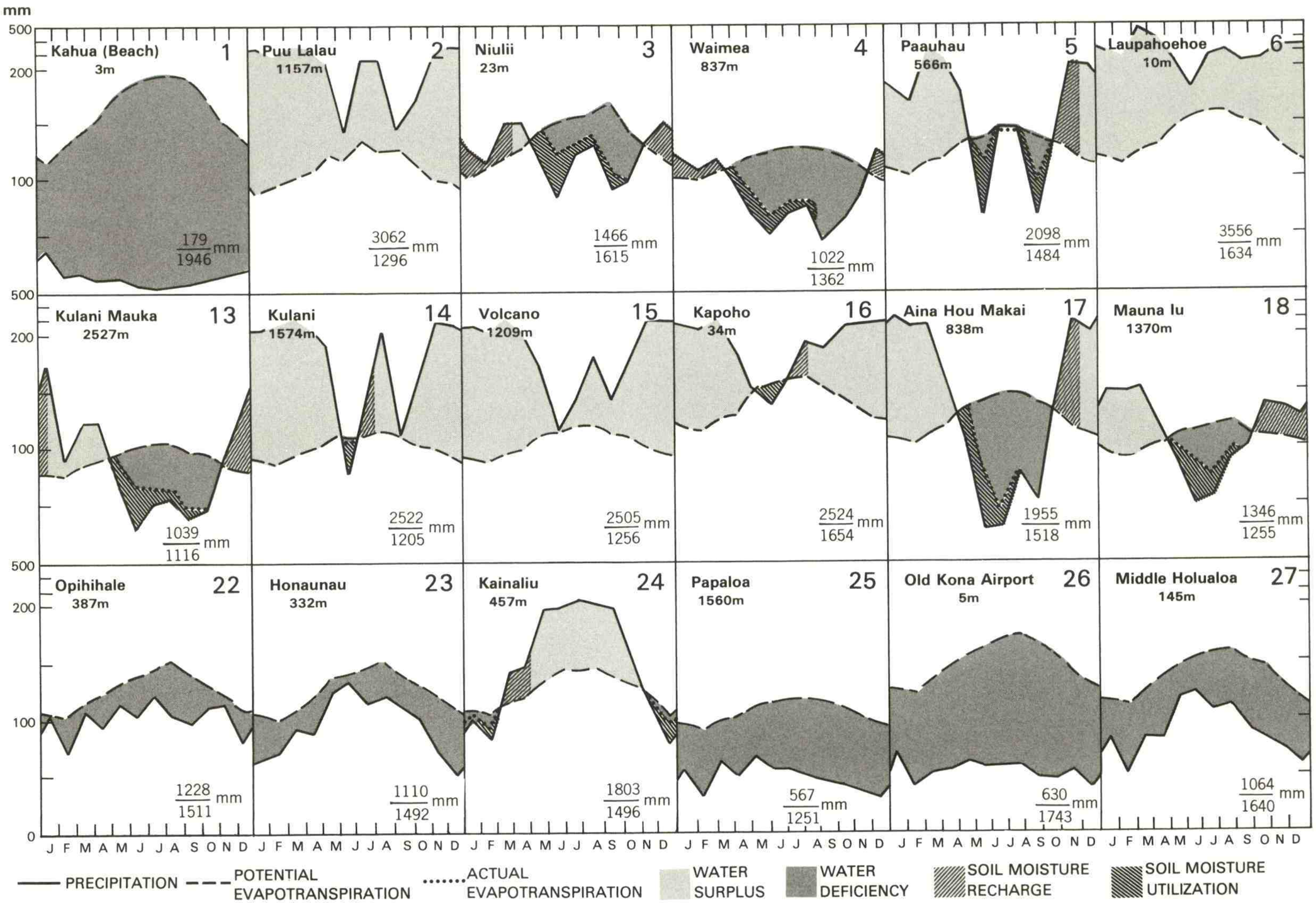


Figure 7. Relationship between measured and predicted evapotranspiration along an altitudinal transect in Hawaii Volcanoes National Park on the east flank of Mauna Loa (pan data from Juvik and Clarke, 1976).

plotted against elevation. There is a clear linear decrease in evaporation over the altitudinal range surveyed (approximately 0.72 mm/day/1,000 m). Fig. 7 also shows the corrected (eq. 2) Thornthwaite potential evapotranspiration values (mean of 9 months, September to May) derived from temperature-recording stations that occur near the evaporimeter transect. There is good agreement between the Thornthwaite and the evaporimeter values (differences range from 1% to 12%), largely because air temperature also decreases linearly with elevation. On the basis of the close agreement in Fig. 7, the corrected Thornthwaite estimate was considered acceptable to use for all areas of the island in the derivation of monthly and annual potential evapotranspiration from temperature data.

Corrected Thornthwaite estimates of monthly and annual potential evapotranspiration were computed from standard tables (Thornthwaite and Mather, 1975) and eq. (2), for 30 stations on the island of Hawaii. The evapotranspiration data were then integrated with monthly precipitation values to produce seasonal water balance diagrams (Fig. 8). Because some of the water surplus received in the wet season is stored as soil moisture for utilization during dry periods, the computation of seasonal water balance must incorporate a parameter describing the moisture storage capacity of the soil.

On the geologically youthful island of Hawaii, soils are not generally well developed except for limited areas where ash deposits occur in high-rainfall zones. Recent lava flows exhibiting little or no soil development cover substantial portions of the island. The average depth to bedrock for 75 different Hawaii island soil types and subtypes has been calculated at 0.89 m with only moderate variation (Sato et al., 1973), lending quantitative credence to this stated geological youthfulness of the island. Soil moisture storage capacity has not been well studied for most Hawaiian soil types. A value of 125 mm/m is the average moisture capacity for ten different soil types for which data are available. If this is assumed to be representative, then the average soil moisture storage capacity for all Hawaii island locations would be 111.2 mm (i.e., 0.89 $\times$ 125). In the construction of water balance diagrams for all island stations this value was rounded off to 100 mm so that standard moisture depletion tables could be employed in water balance calculations (Thornthwaite and Mather, 1957).


mm
500
200
100
0
1 Kahua (Beach) 3m
179/1946 mm
2 Puu Lalau 1157m
3062/1296 mm
3 Niulii 23m
1466/1615 mm
4 Waimea 837m
1022/1362 mm
5 Paauhau 566m
2098/1484 mm
6 Laupahoehoe 10m
3556/1634 mm
13 Kulani Mauka 2527m
1039/1116 mm
14 Kulani 1574m
2522/1205 mm
15 Volcano 1209m
2505/1256 mm
16 Kapoho 34m
2524/1654 mm
17 Aina Hou Makai 838m
1955/1518 mm
18 Mauna Iu 1370m
1346/1255 mm
22 Opihihale 387m
1228/1511 mm
23 Honaunau 332m
1110/1492 mm
24 Kainaliu 457m
1803/1496 mm
25 Papaloa 1560m
567/1251 mm
26 Old Kona Airport 5m
630/1743 mm
27 Middle Holualoa 145m
1064/1640 mm
J F M A M J J A S O N D
PRECIPITATION
POTENTIAL EVAPOTRANSPIRATION
ACTUAL EVAPOTRANSPIRATION
WATER SURPLUS
WATER DEFICIENCY
SOIL MOISTURE RECHARGE
SOIL MOISTURE UTILIZATION

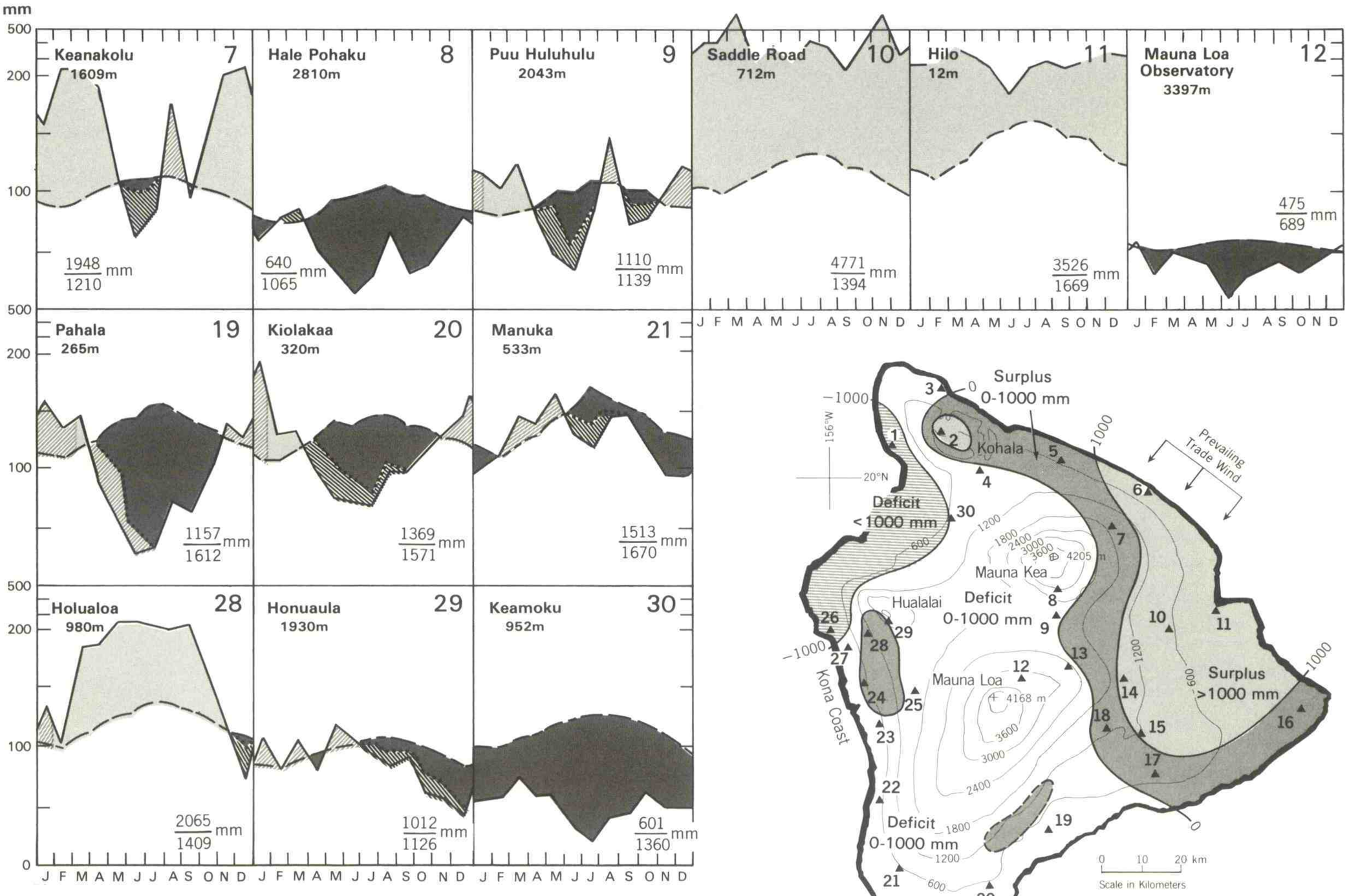


Figure 8. Annual water balance on the island of Hawaii. Ratios are mean annual precipitation over mean annual potential evapotranspiration in millimeters.

The 30 water balance diagrams constructed for the island depict both steep gradients and pronounced regional differences in seasonal moisture surplus and deficit. In Fig. 8 the difference between annual precipitation and potential evapotranspiration has been mapped in four zones:

1. Annual surplus exceeding 1,000 mm. This zone comprises 20% (2,100 km²) of the island area and is restricted to the high-rainfall regions of windward Mauna Kea, Mauna Loa, and the summit area of Kohala. The annual moisture surplus in this zone ranges as high as 3,377 mm (station 10) at middle elevations. All stations within this zone (stations 2, 6, 10, 11, 14, and 15) exhibit an absolute winter maximum in precipitation, and a secondary summer maximum also occurs at elevated stations where summer orographic precipitation is exaggerated (e.g., stations 2 and 14).

2. Annual surplus between 0 and 1,000 mm. This zone comprises 21% (2,200 km²) of the island area and extends from middle to high elevations on the windward slopes down to sea level in those areas where slope aspect is not oriented perpendicular to prevailing trade wind flow, and thus the orographic rainfall component is diminished. For the windward stations there is typically a moderate summer drought (stations 5, 7, 9, 13, and 17) from 2 to 5 months long. The increased strength of the trade wind inversion in particular limits summer rainfall at higher elevations. The localized core area of high convectional rainfall in Kona also falls within this moisture zone. However, here the deficit period occurs in winter (stations 24, 28, and 29) and is not severe.

3. Annual deficit between 0 and 1,000 mm. This zone comprises 54% (5,600 km²) of the island area and occupies a predominantly leeward location on Kohala, Mauna Kea and Mauna Loa. The drought period may be concentrated in either the summer (on the windward side) or the winter (on the Kona side) and is typically 6 to 12 months long.

4. Annual deficit exceeding 1,000 mm. This zone comprising 5% (550 km²) of the island area is restricted to leeward Kohala and north Kona. The annual moisture deficit may exceed 1,900 mm (station 1).

SUMMARY

The Thornthwaite water balance diagrams and map demonstrate graphically the tremendous climatic diversity on the island of Hawaii. Although the Köppen map (Fig. 2) shows only a relatively small portion of the island to be arid or semi-arid (*Bwh* and *BSh*), from the water balance analysis it is evident that nearly 60% (zones 3 and 4 above) of the island experiences an annual moisture deficit.

ACKNOWLEDGMENTS

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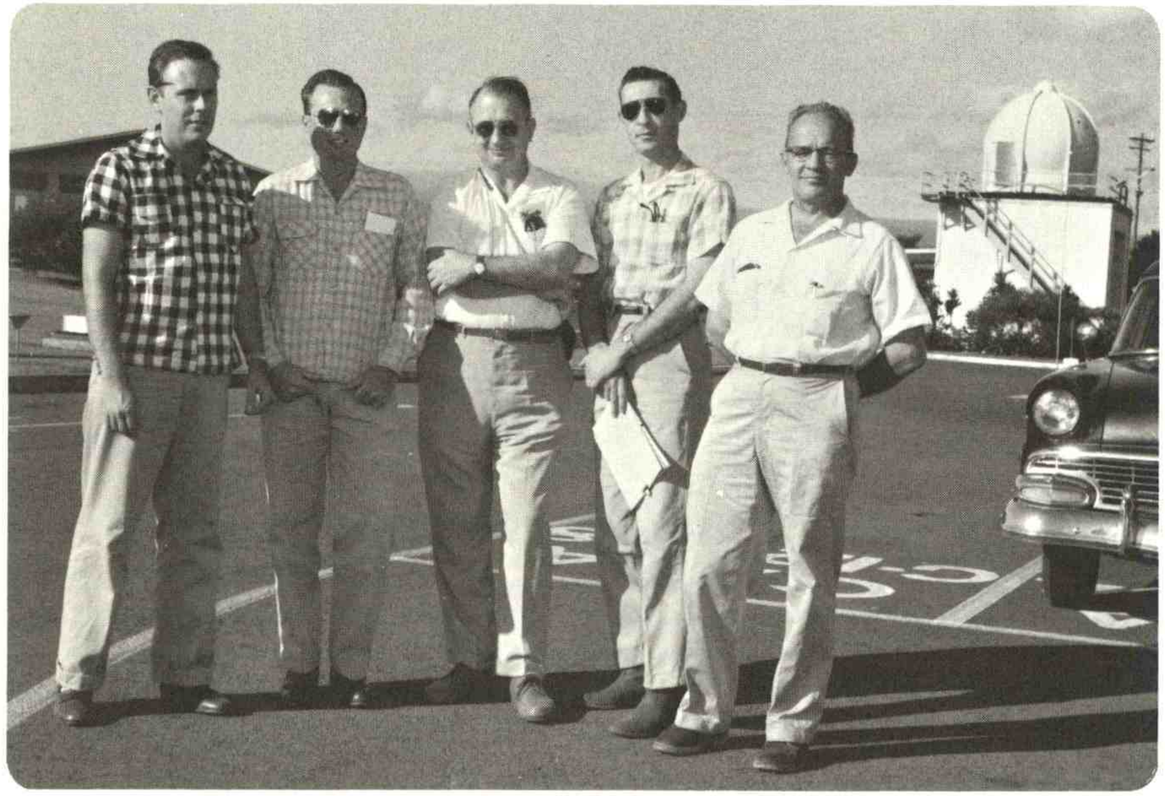
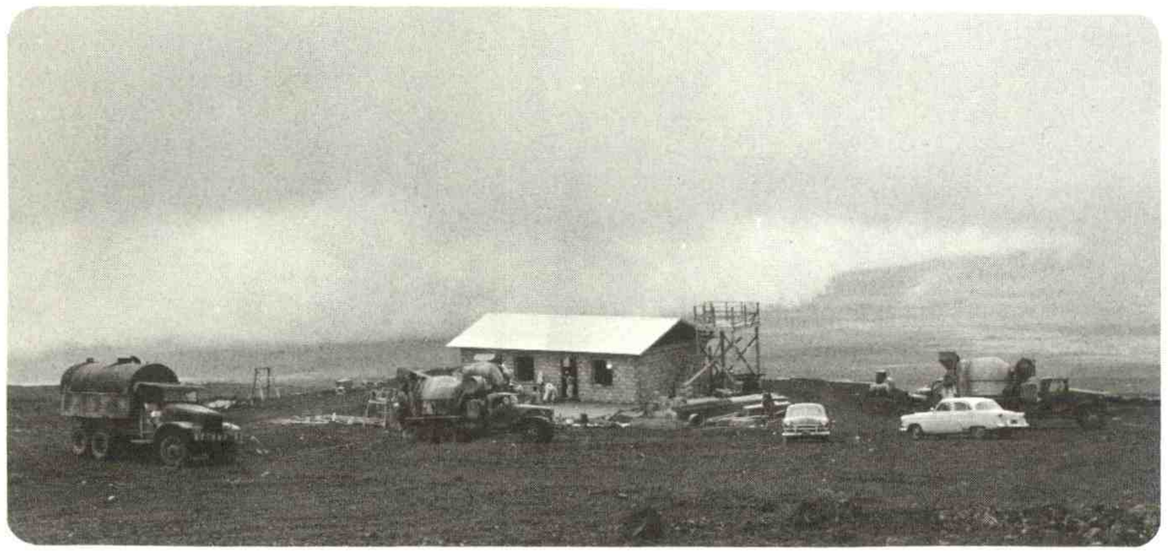


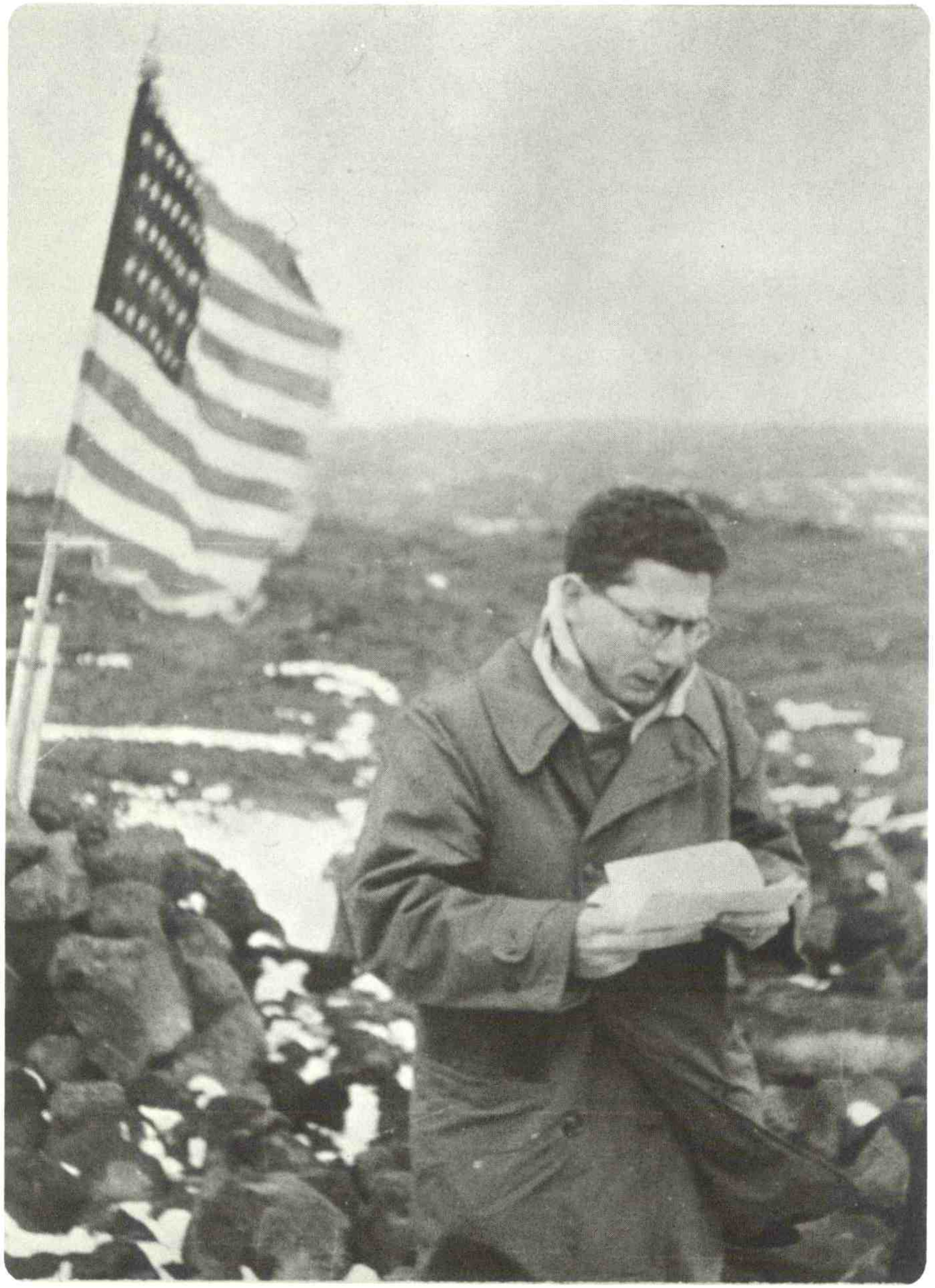
Howard Tatum (now Meteorologist-in-Charge at Hilo), Bob Williams, Harry Wexler, Jack Pales, and "Doc" Colby Foss at the Hilo airport, 1959.

This pyrheliometer, attended in 1959 by Jack Pales, is still in use. To the right are early radiometers, no longer used. The generator building is visible behind Pales (Official U.S. Navy Photograph).



The observatory building in June 1956.

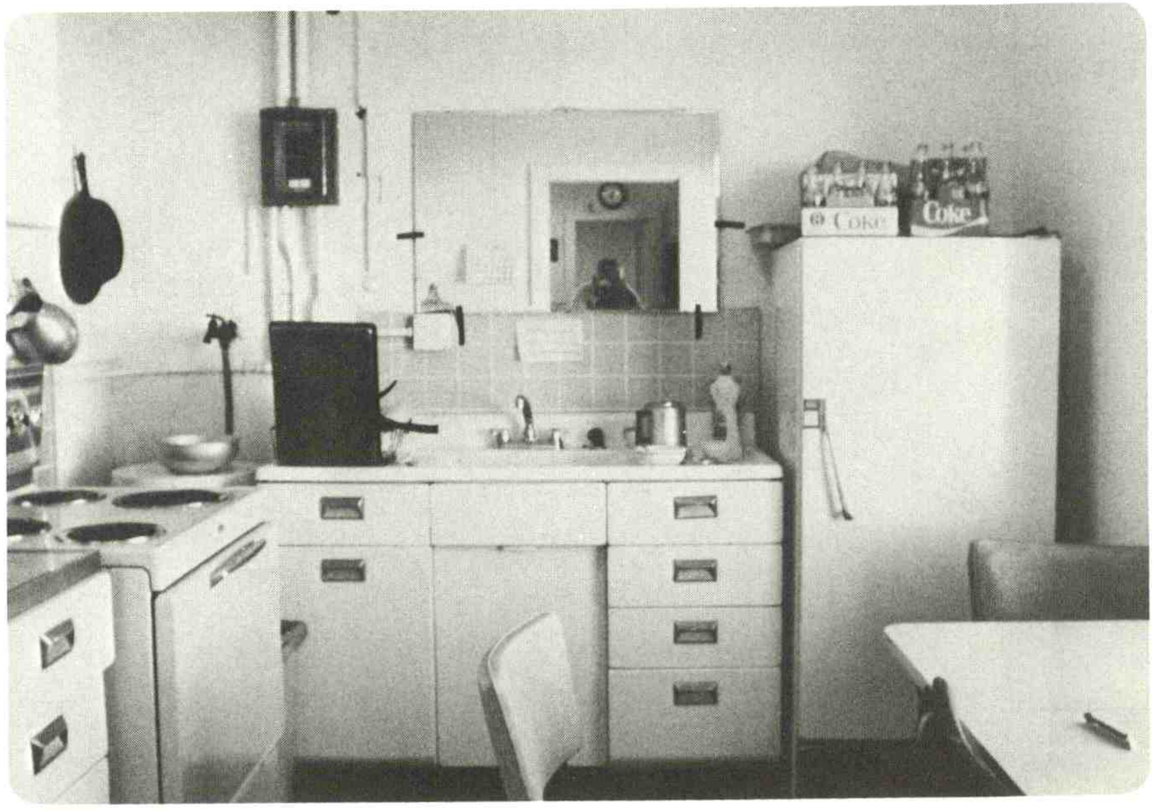
A pictorial history of Mauna Loa Observatory

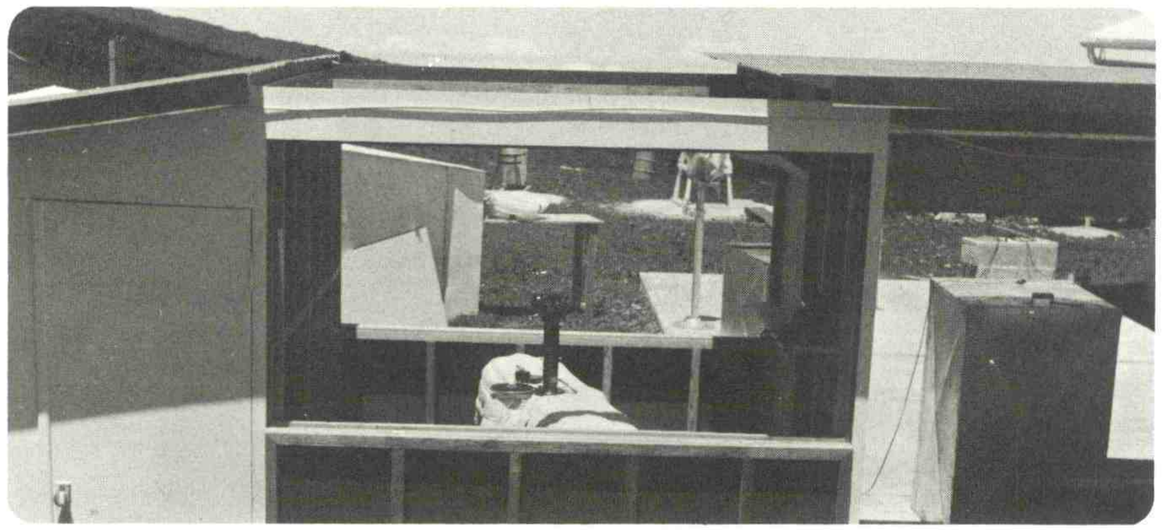


Saul Price at the dedication of the summit weather station in 1954.

Mauna Loa and Weather Bureau personnel in November 1959. Standing: Bill Cobb (MLO), Ray Busniewski (WB), Nels Johnson (WB), Cliff Kutaka (MLO), (a Weather Bureau visitor?), and Jack Pales (Director, MLO): kneeling: Tom Tyrrel (MLO).

The kitchen and two bunk rooms at MLO (1973) have been displaced as walls have been relocated and new equipment has been installed.

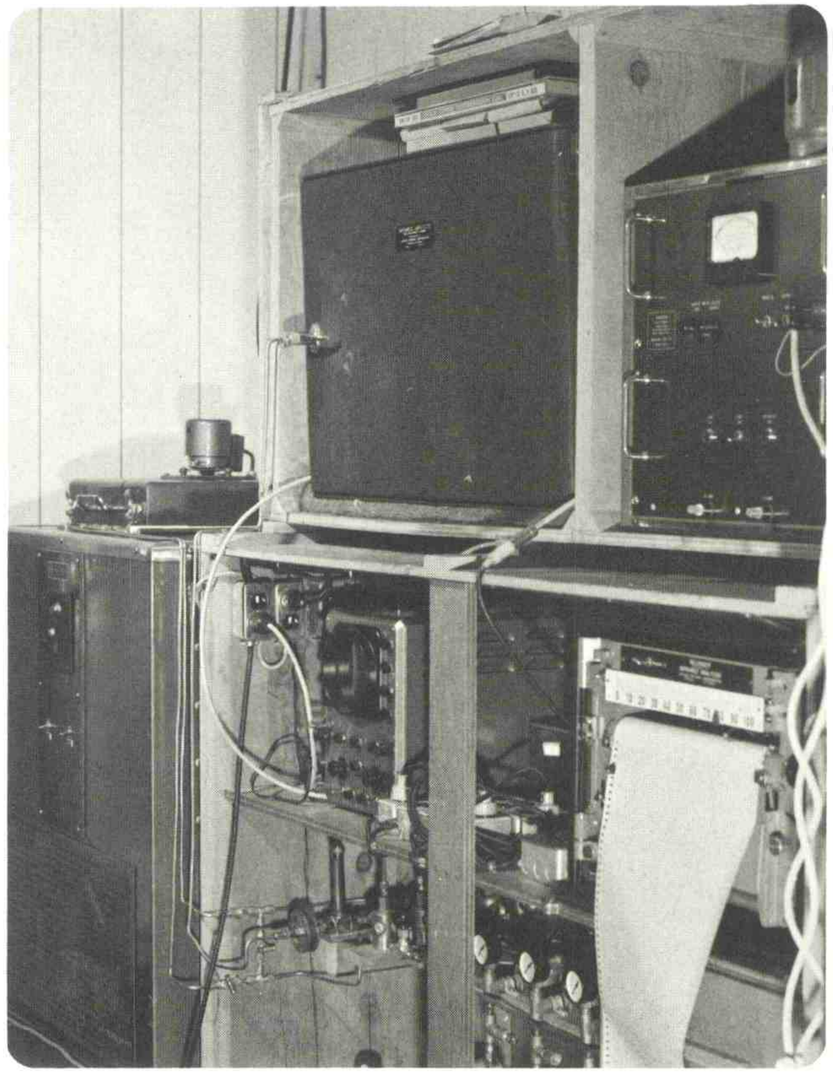


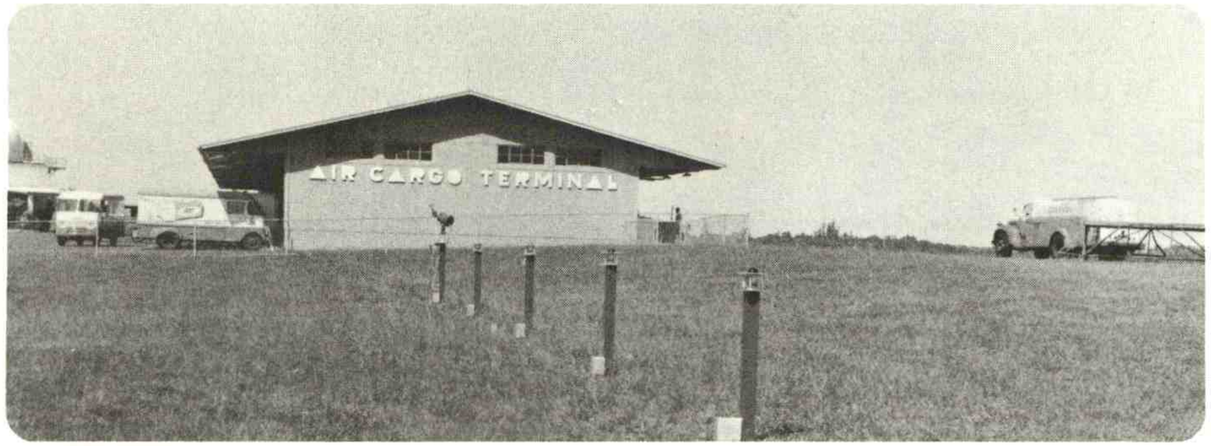


The Dobson shelter (with sliding roof) in April 1958.

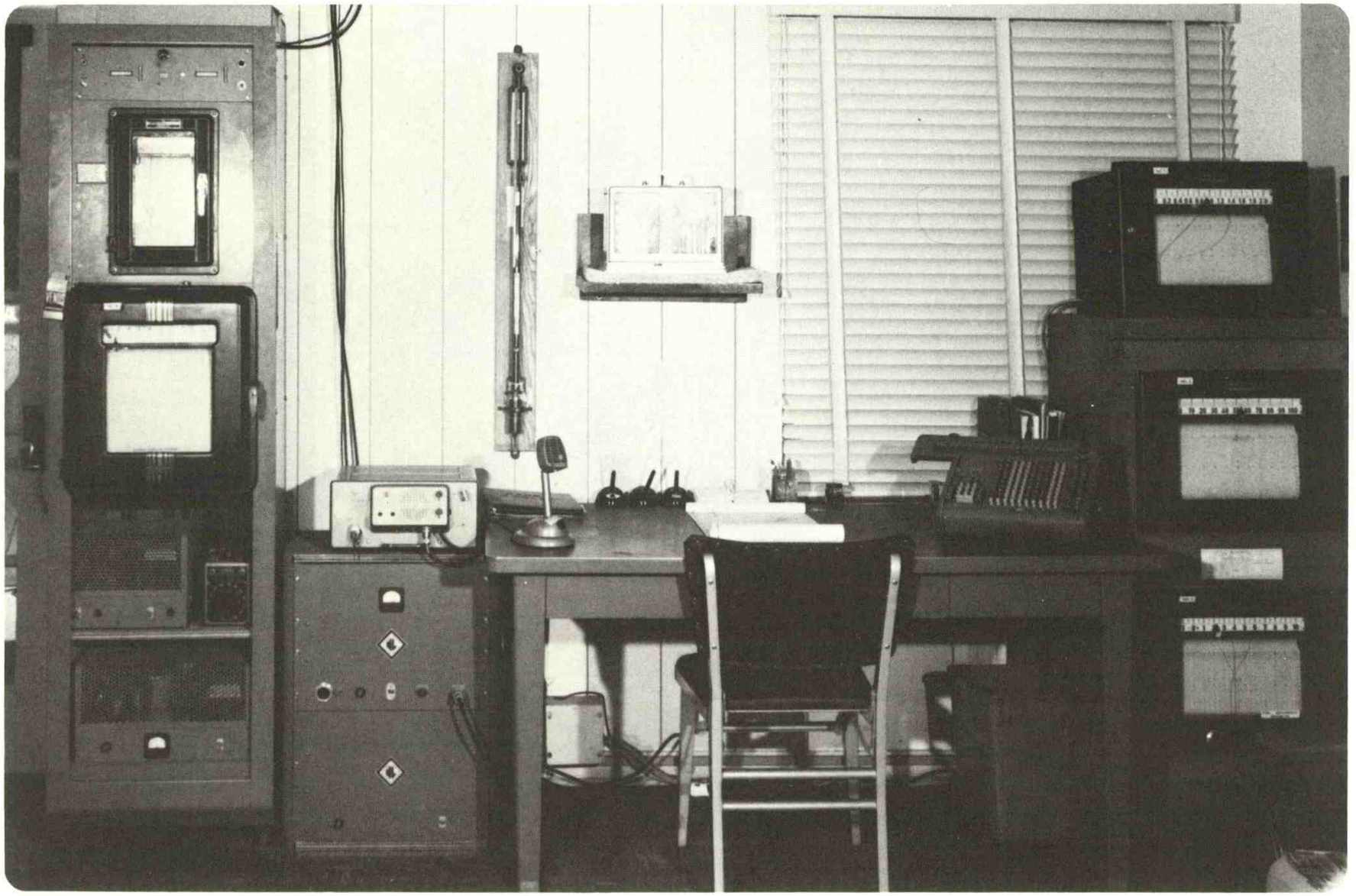
Cliff Kutaka taking a Dobson spectrophotometer measurement at the observatory in the late 1950s.

The CO_2 instrumentation at MLO in September 1959.

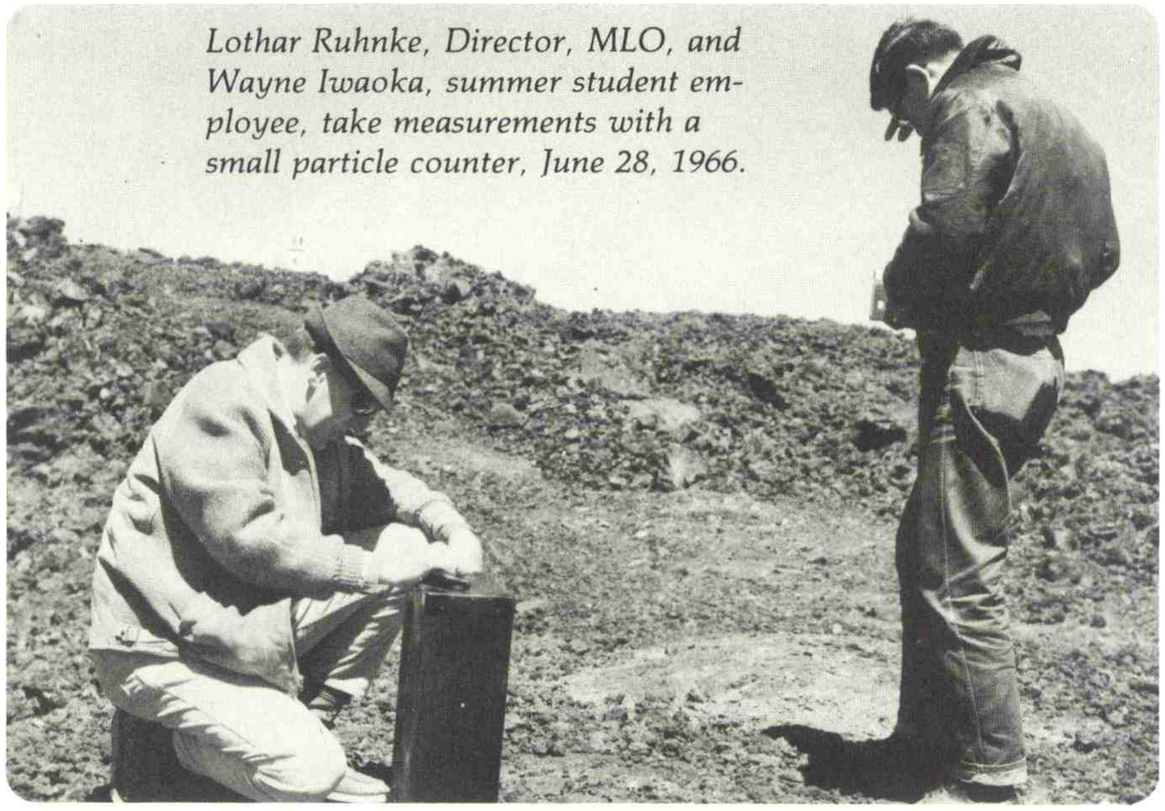




Solar radiation instruments at the Hilo Airport, 1960. MLO's Hilo offices were in the Air Cargo Terminal building.



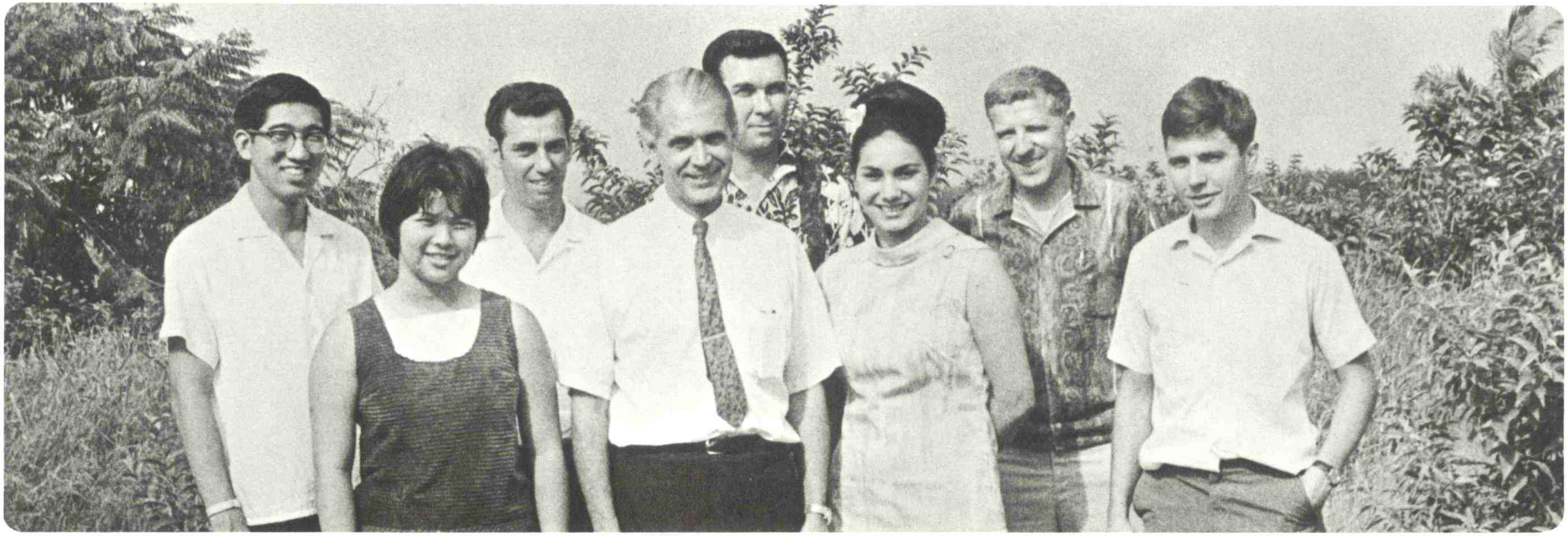
MLO interior in the early 1960s. The hand calculator is still part of the equipment. The microphone and transceiver were used to communicate with those traveling between the observatory and Hilo, in case of trouble on the road.

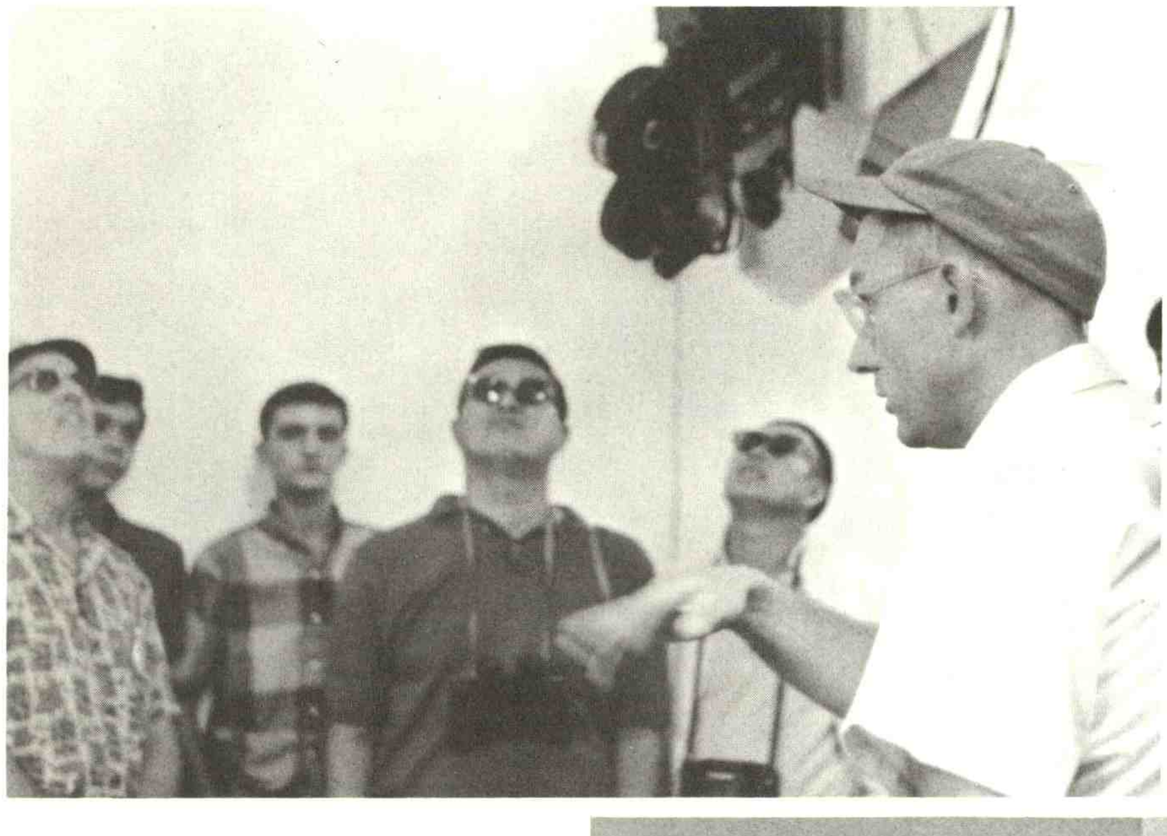


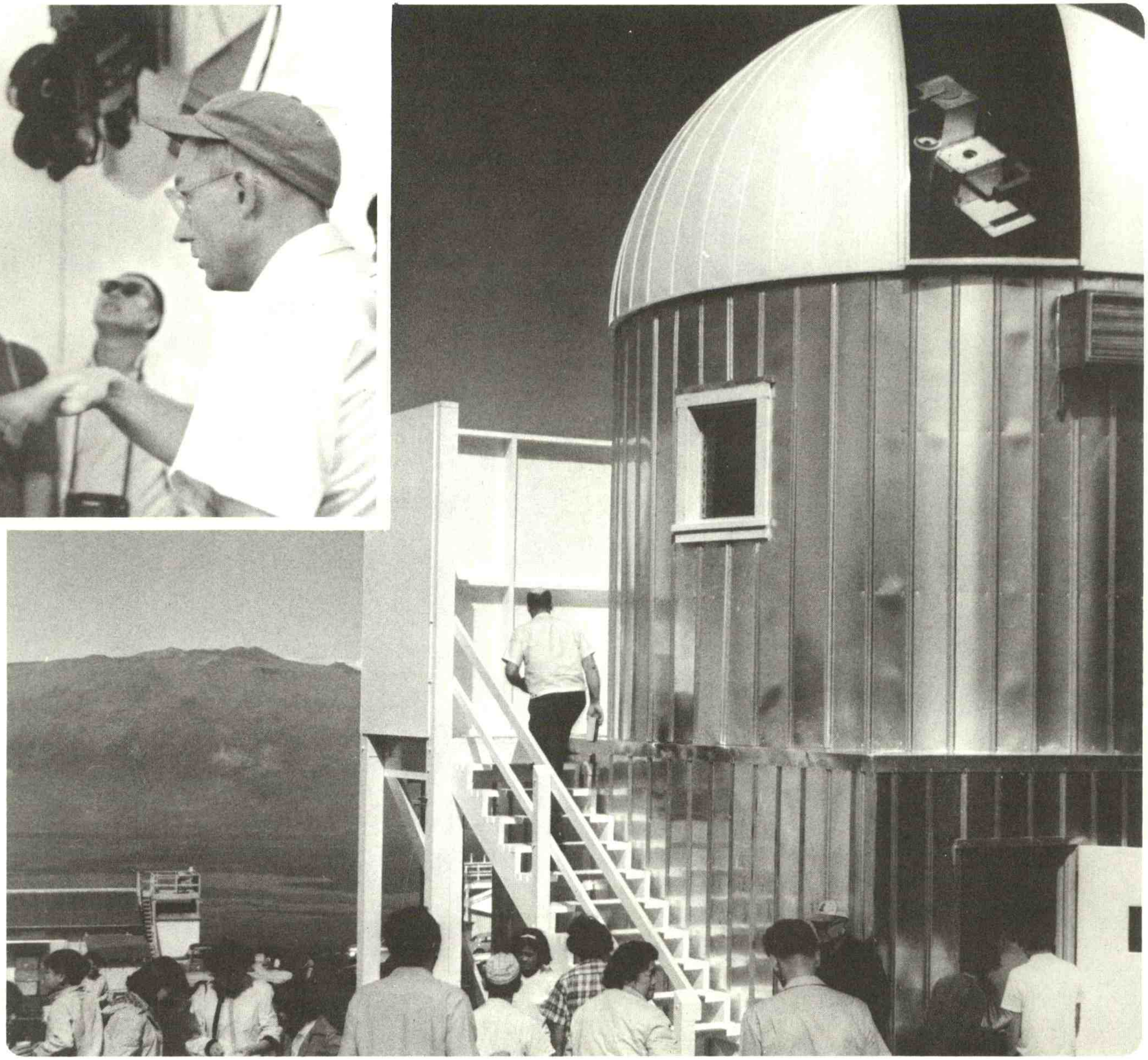
Lothar Ruhnke, Director, MLO, and Wayne Iwaoka, summer student employee, take measurements with a small particle counter, June 28, 1966.

In the main building of MLO, August 1966: Bill Waters, Ralph Stair, Mrs. Stair, and Howard Ellis.

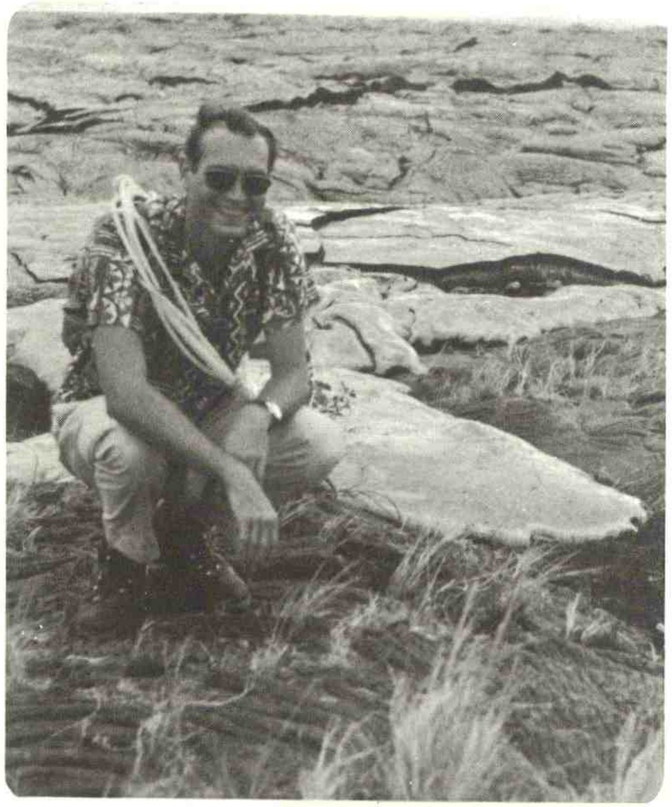
At MLO in June 1967 (left to right): Wayne Iwaoka, Sharon Nagata, Bernard Mendonca, Helmut Weickmann (Director, APCL), Howard Ellis, Judy Bright, Lothar Ruhnke, and Josef Mueller.





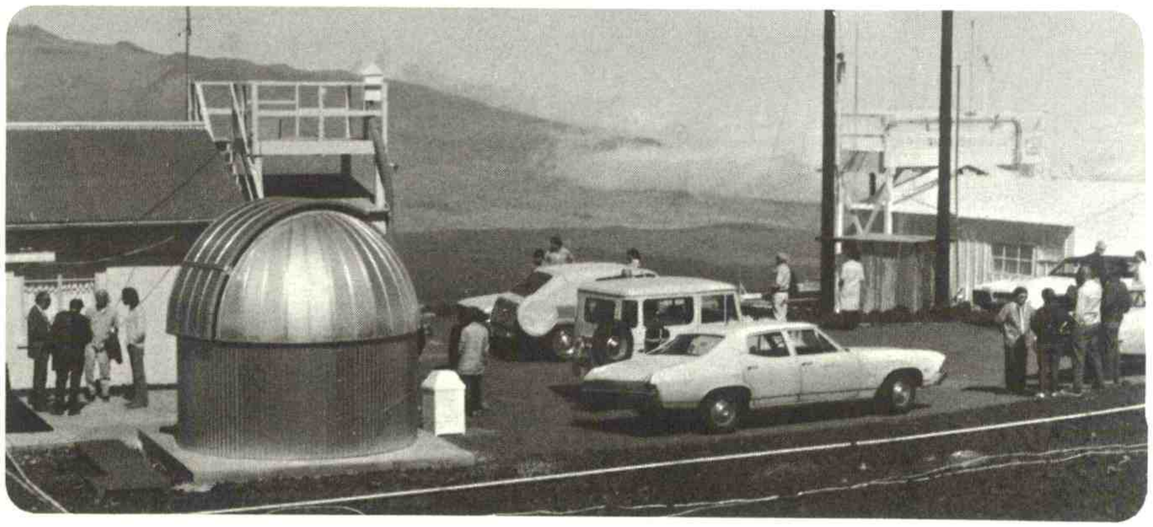


MLO/HAO Open House, December 4, 1966. Dick Hansen (in baseball cap) conducts a tour.



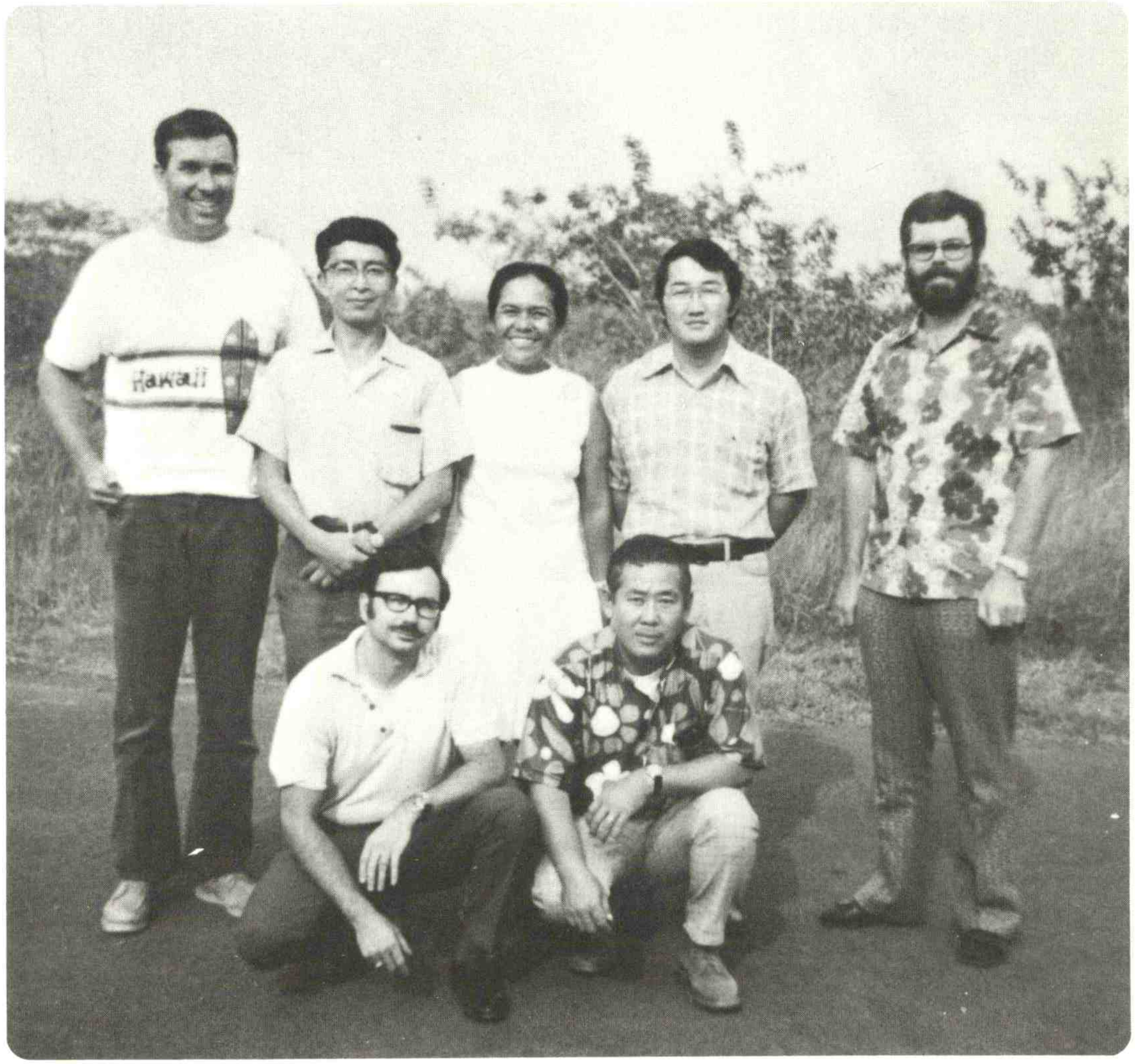
Jim Simpson (NRC Resident Research Associate) at lava flow, Kalapana National Park, September 1970. MLO followed the flow of lava for a laboratory experiment and measured the gaseous effluent on site as the lava entered the sea.

MLO staff during visit of Deputy Director of ERL, in front of the Cloud Physics Observatory in Hilo. Left to right: John Chin, Rudolf Pueschel (Director, MLO), Bernard Mendonca, Judy Bright Pereira, Robert Knecht (Dep. Director, ERL), Howard Ellis.



Mauna Loa Observatory entertains visitors on its 15th anniversary.

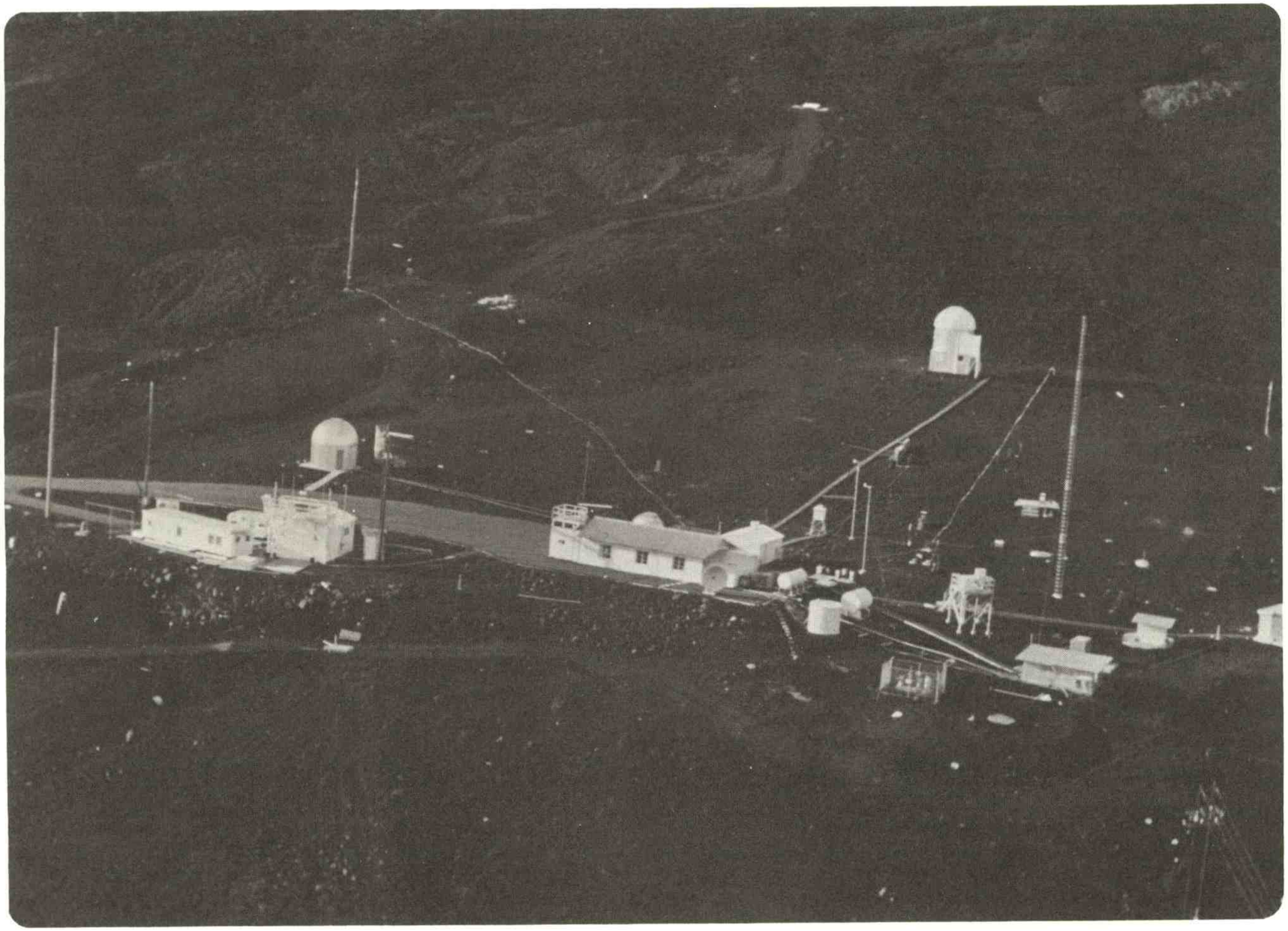
Don Pack, Rudy Pueschel, and Larry Mehau (Island Land-Use Committee member) at MLO's 15th Anniversary open house, January 9, 1972.



MLO staff in 1972. Standing: Howard Ellis, John Chin, Marge Kealanahele, Alan Yoshinaga, Ronald Fegley, Kneeling: Mark Goldman, Al Shibata.

Student Aides Charmaigne Makanui and Leona Ferreira, August 1976.

Mauna Loa Observatory staff members and visitors in February 1972. Back row: Visitor (?), Charles Garcia, Bernard Mendonca, Dick Proulx, Visitor (?), and Earl Barrett. Front row: Visitor (?), Eric Yasukawa, Barry Bodhaine, Walter Komhyr, John Chin, Bob Grass, and Al Shibata. The front dome houses the Dobson spectrophotometer. The NCAR coronagraph is in the rear dome.



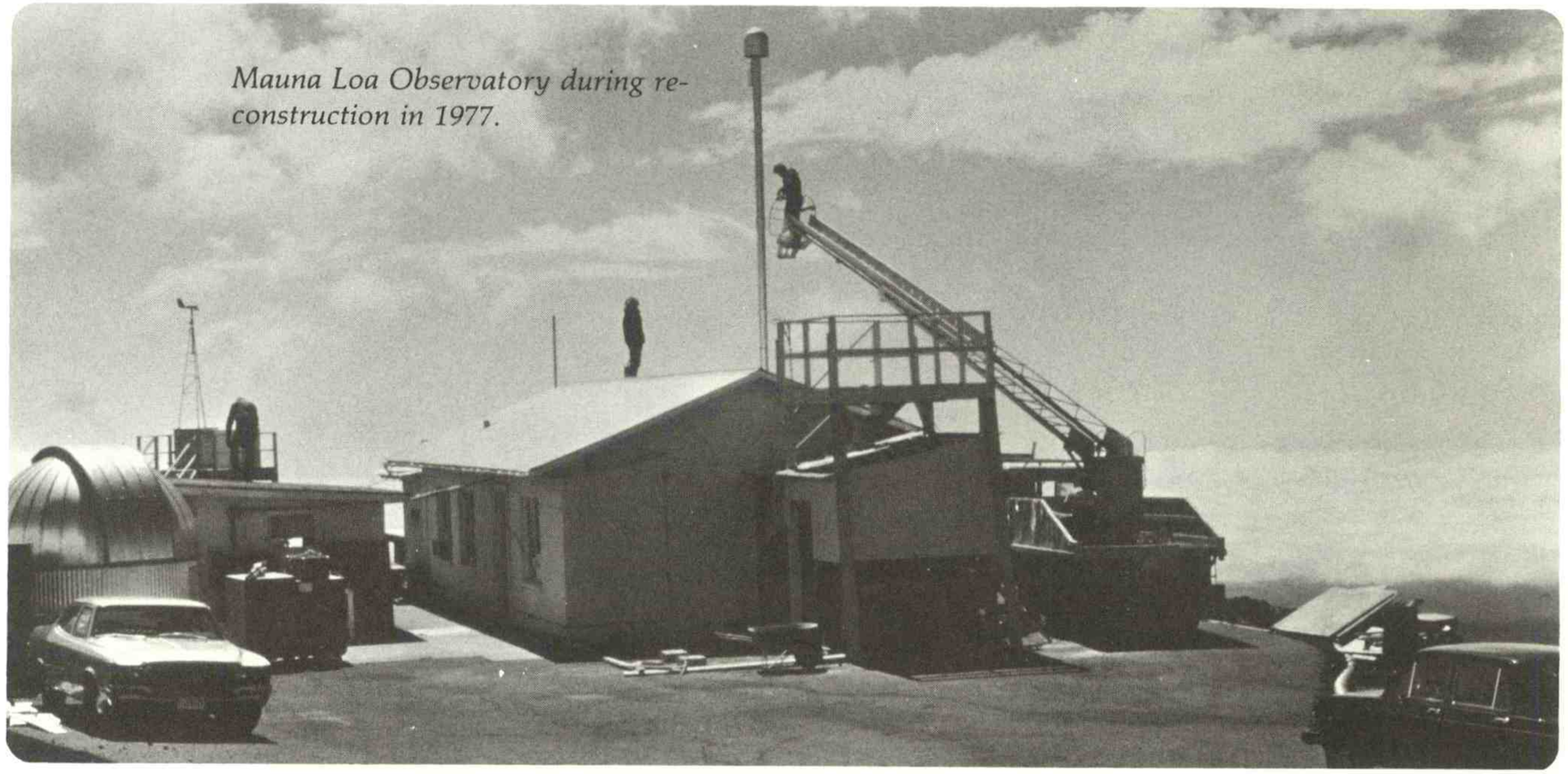
By April 1975 facilities and equipment had proliferated to include towers, trailers, diesel fuel tanks, domes, antennas, and signs of a multitude of individual experiments (photo by Robert K. McGill).

Judy Bright Pereira

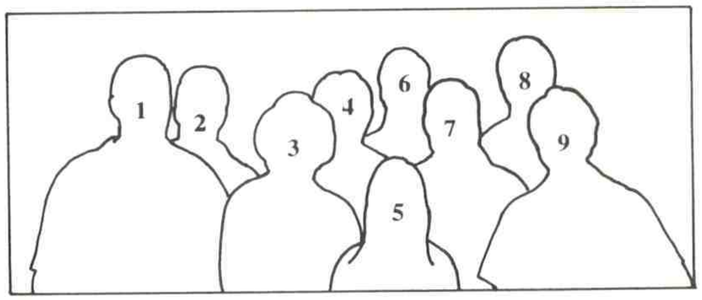
Margie Kealanahele

Kin Coulsen, U. of California at Davis, was Senior Scientist at Mauna Loa Observatory for six months in 1977.

The new solar radiation array, 1977. Mauna Kea is in the background.



Mauna Loa Observatory during reconstruction in 1977.



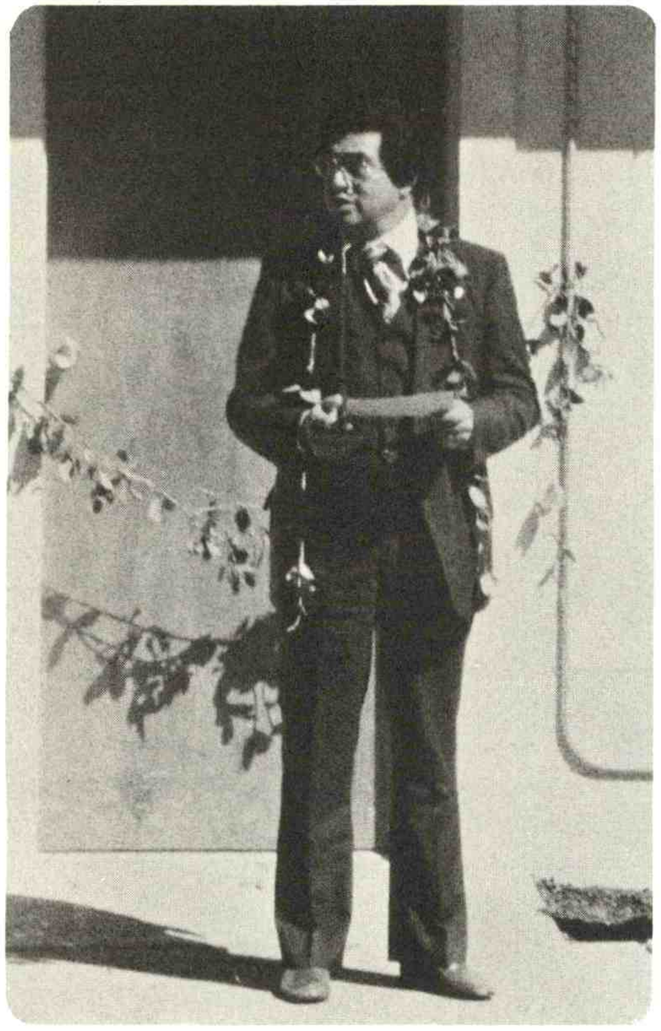
Mauna Loa staff in March 1978: 1. Howard Ellis 2. Mamaru (Al) Shibata 3. Judy Pereira 4. Alan Yashinaga 5. Cynthia Aki 6. John Chin 7. Dick Cram 8. Duane Harding 9. John Miller. Missing: Sandra Ireland, Lily Kam, and Dan Nakamura.

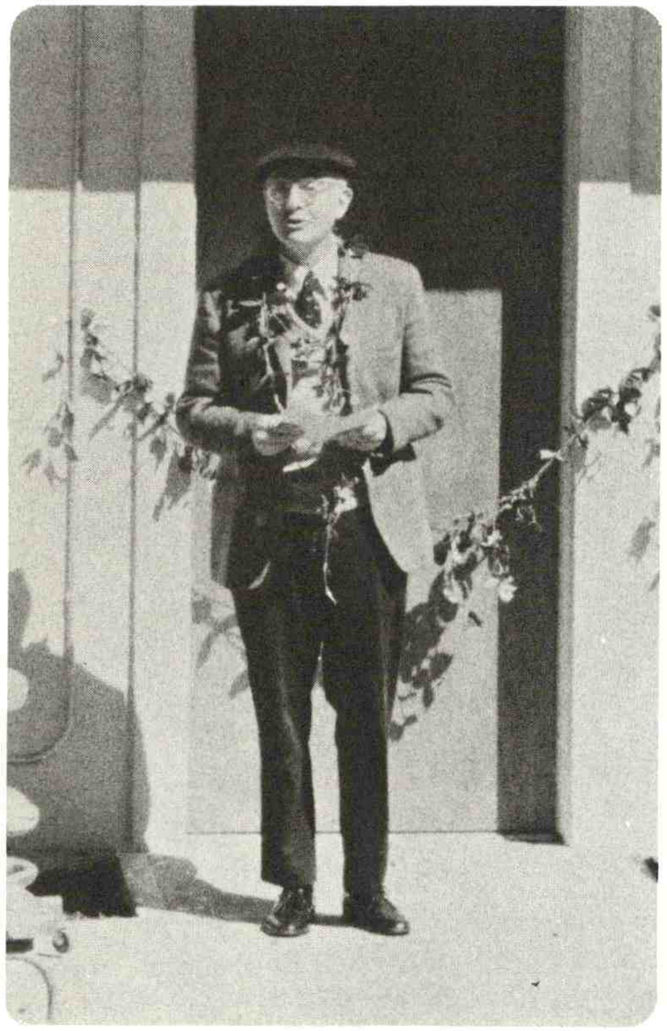
Mauna Loa Observatory in March 1978 had a new tower for measuring solar radiation, and a new 40-ft air sampling intake stack, looking here almost as tall as the 80-ft tower in the background.

In 1978, in the newly modernized main building, Alan Yoshinaga is checking air inflow from the air sampling intake stack.

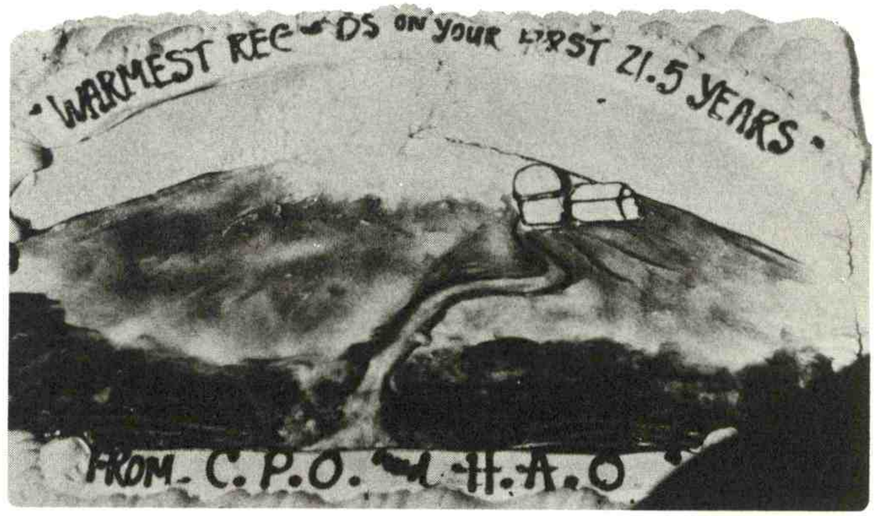
Mauna Loa Observatory 20th anniversary celebration, January 28, 1978.

The Rev. Edward Kealanahele blessed the observatory, staff members, and visitors participating in the celebration.





The Honorable Daniel Akaka, U.S. Representative from Hawaii, and Dr. Lester Machta, Director, Air Resources Laboratories, addressed the gathering.



A cake to celebrate the anniversary.

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