Climate Control

Deliberate and inadvertant actions that change the atmosphere are becoming increasingly crucial to the welfare of man and his environment. Theories of climate control are numerous but unsatisfactory. The Global Atmospheric Research Program will reveal new answers to the problems.

by Walter Orr Roberts

LIFE IN A TECHNICALLY advanced society like ours is increasingly dependent on an understanding of atmospheric behavior. Food, travel, recreation, commerce—these and many other major aspects of the daily duties of men are strongly affected by the vicissitudes of weather and climate. Even the subtle joys of life turn upon wind and storm, as with the smell of rain in a wheat field, the flowers on a mountain hillside, the beauty of a sunset or even the opportunity to see a sunset at all.

Moreover, man himself is a growing force in the atmospheric environment. For example, increasing jet travel may be altering the atmospheric radiation processes. Anyone living at the end of a long atmospheric sewer, such as a New Yorker, finds it easy to realize that the pleasures of clear, crisp air have become a rarity, have yielded to the fouled, odorous, heated air of the city and its environs. The changes do not look at all pleasant.

Man appears, indeed, already to be influencing his climate, his atmospheric environment, to an alarming degree. If this is actually so, it suggests that international regulation of deliberate and inadvertent actions that change our atmosphere has become a necessity, and that major measures should be taken for the welfare of mankind. The problem may soon be even more pressing than that of the A-bomb!

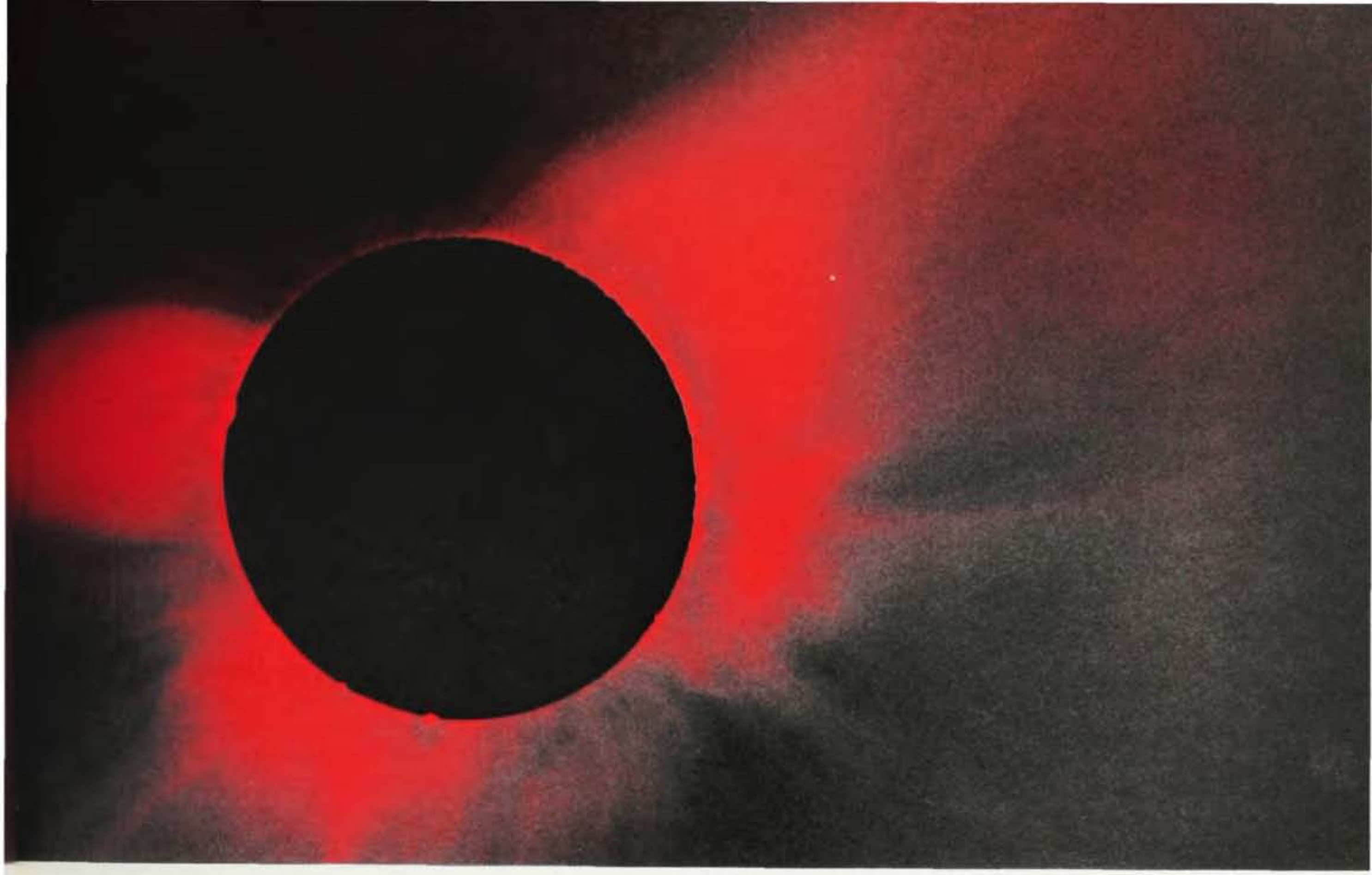
The problems of the atmosphere—its circulation, stability and mechanisms—are so complex that it may take years to unravel theoretically the cause-effect relationships.

Although many theories have been advanced in favor of a particular cause of climate changes (such as ocean currents, volcanic dust or solar activity), no single explanation has offered a wholly satisfactory solution. Explaining the mysteries of hurricane formation or the clustering of severe rainfalls could possibly elucidate the problem. But in order to make real progress we must examine the processes of the atmosphere in such a way that we may approximate the complex interactions of the atmosphere itself. At present, this is the direction that atmospheric explorations are taking. Many of us hope that the Global Atmospheric Research Program, an international effort to be initiated in the 1970's, will at last bring the weather system under a realistic scale of observation. Then perhaps, through intensified research, we will gain a more comprehensive understanding of the way in which man inadvertently or deliberately controls climate.

Historical climates

The development of civilization has always been connected with the history of climatic changes. In a sense, atmospheric researchers are becoming historians in their efforts to unravel the mysteries of climate. While the astronomer looks through the murky clouds of the earth's atmosphere to determine the answers of deep space, the atmospheric researcher is interested in the murk itself: clouds, dust and shimmering air. The history of this murk is derived from historical records. Man's struggle for existence has been played out within the framework of vast and powerful environmental forces such as droughts, tornadoes and hurricane disasters. All these forces are products of fascinating and subtle changes in the circulation of the earth's atmosphere.

One might compare the 11th and 16th centuries to see some of the strik-



SOLAR CORONA during a total eclipse. The complex structure is derived from irregular distribution of electrons.—FIG. 1

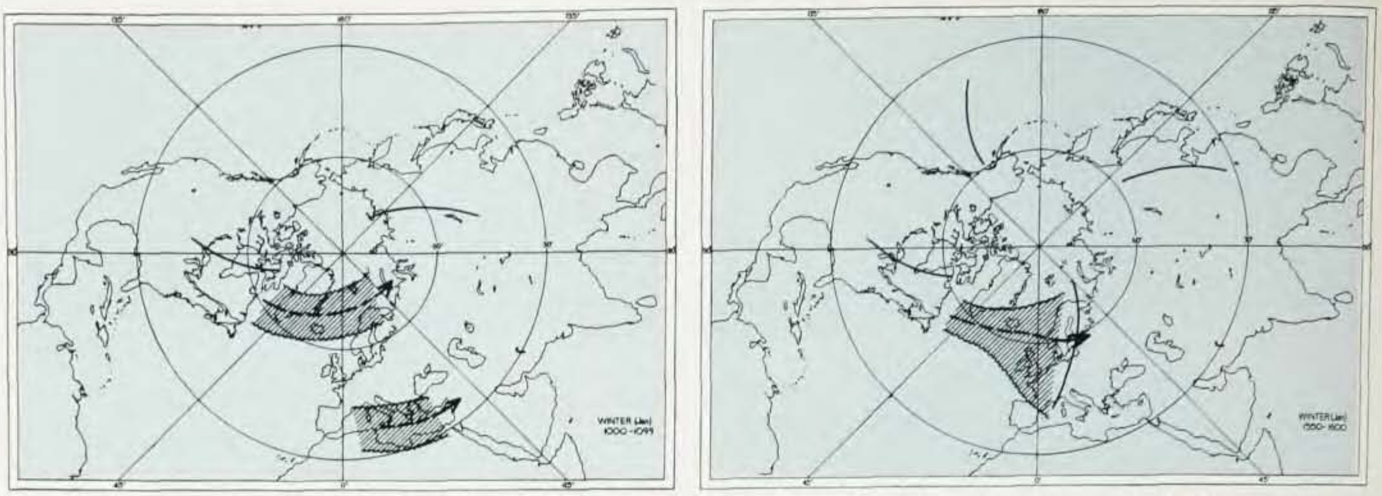
ing and spectacular changes that have occurred. Figure 2 shows average winter storm tracks deduced in detailed fashion for Europe during the period 1000–1099. For this century there were two belts of principal storm activity: one in the Mediterranean and one north of most of central Europe. Around the middle of the 16th century, as shown in figure 3, the principal winter storm tracks appeared almost in the center of the 11th century pattern. The causes of these changes are still matters of some scientific speculation. It seems reasonable to believe that the 11th-century pattern arose from a pattern of weather characterized by a persistent jet stream with but two nodes or troughs—one over Siberia and one over North America. From 1550 to 1600, on the other hand, the average jet stream pattern for winter months seemed to be more undulatory, with four waves or troughs instead of two. But the why of it all remains a mystery.

There are many other examples of large and interesting climatic changes. For example, the archeological museum in Plovdiv, Bulgaria, which I recently visited, contains a panorama of the trend of civilization in that particular spot, stretching continuously backward for 10 000 years. This period spans many extremes of climate and war—products of the tyrannies of nature and of man.

The legend of the twilight of the gods, which concerns the events occurring around 550 B.C., may have been the result of a sudden and drastic worsening of climate in northern Europe. At this time the growing season abruptly shortened by many days. This shorter growing season, which persisted for many centuries, was possibly a major factor in changing the locus of a flowering of civilization from northern and central Europe to the Mediterranean. Historians often largely disregard the influence of climate on history. I suggest that it merits more scholarly attention.

J. Titow, an English historian, found that by using the account rolls of the Bishopric of Winchester for the 13th and 14th centuries he could reconstruct month by month trends of weather. From the records he determined the number of bushels of each crop, the number of chickens, etc., that tenants rendered to their lords. From this chronology he could reconstruct a time sequence of climatic trends. Hubert H. Lamb reconstructed the trend of climatic patterns for the same period from the chroniclers of the 13th and 14th centuries. These patterns show much correlation with the trends derived from Titow's records. Pall Bergthorsson has also studied the history of climatic change in Iceland from records of fishing fleets and from studies of skeletal remains of Icelanders adversely affected by famine periods.[1]

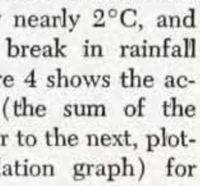
In our own country, Harold E. Malde has summarized climatic changes in North America.[2] He describes, for example, the fields that grew 13 000 years ago near Fort Collins, Colo. The temperature apparently averaged some 8.5°C cooler, and the rainfall some 30 cm greater. About 5000 years ago this was supplanted by a hot, dry climate that gave rise to an economy based on corn, beans and squash, a system that



WINTER STORM TRACKS deduced from historical records of 11th and 16th centuries.—FIGS. 2,3

still persists in primitive areas of the Southwest.

Between 1900 and 1950 another significant example of major climatic change occurred in our region of the world and particularly in the northeastern United States. The winter mean temperature rose by nearly 2°C, and there was a sharp break in rainfall around 1900. Figure 4 shows the accumulated rainfall (the sum of the rainfall from one year to the next, plotted on an accumulation graph) for two selected stations, one in the Nile River Valley and the other on the Carolina coast around 1900. Both stations show increasing rainfall to around 1900 with a persistent and continuous trend in the opposite direction following thereafter. Since 1950 it appears that the upward trend of temperature in the northeastern United States has reversed. It may even be that, with this reversal of the warming trend, there is a trend toward drier weather in major parts of our country.



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Perhaps the most striking fact about climate trends is that they are not more violently changeable. This climatic stability makes the circumstances of life on our planet favorable. The sun itself, giver of the life and warmth of earth, is indeed itself stable, a precondition for a stable pattern of earthly weather. Galileo wrote, "The sun is a star and all the stars are suns." But many of these suns are not nearly so stable as our sun, which radiates its light with almost perfect constancy. There is only a small percentage variation, if any, in sunlight from month to month and year to year.

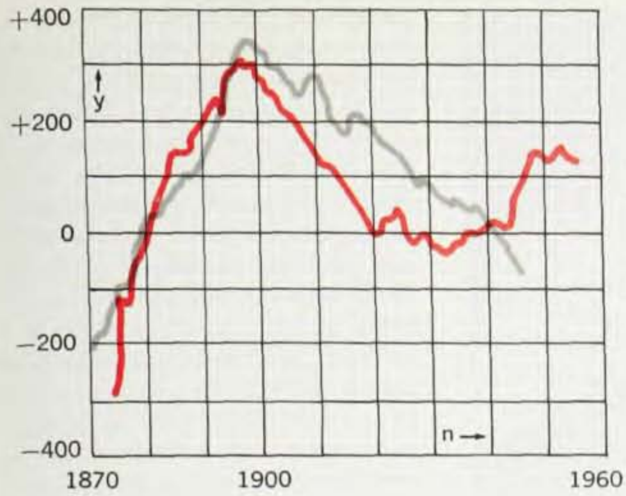
A stable sun and a nearly circular orbit of earth around its sun is only a precondition for stable climate. The climate might vary widely even with a stable sun: We cannot state for sure why this is so. Indeed, the records of geologic ages give evidence of climatic extremes far greater than those of historic times. There are many fascinating future chapters to be written in this story.

Theories of climatic change

The driving force of atmospheric circulation is the sun. Certainly the evaporation of ocean water, the subsequent development of clouds and the very force of the winds derive their energy from the sun. But the wanderings of the jet streams, the variations of persistent storm tracks in different regions and the changing patterns of drought and flood originate changes of a subtle origin and nature. The very delicacy of the balance of the forces of weather, and the magnitude of the energies involved, make possible the development of major dynamical instabilities that produce vast weather changes. Therefore, large climatic changes can be triggered off by small causes. Moreover, these causes are, at present, largely unknown and unpredictable.

The theories of the cause of climatic change appear to be almost as numerous as the people working in the field. Maurice Ewing, William C. Donn, Joseph Fletcher and many others have worked on theories that the equilibrium between ocean currents and polar ice sometimes becomes unstable, leading to major climatic changes. This may even be the best theory for certain time scales of climatic change, but there are many other alternatives, and each has its adherents. For example, there are theories dealing with unstable, long-term, feedback oscillations from wind-driven ocean currents interacting back on the atmospheric circulation; the action on the atmospheric circulation changes the driving wind. Many other theories deal with natural oscillations of an irregular nature.

Some years ago, the late Harry Wexler of the US Weather Bureau proposed a theory dealing with volcanic dust as an initiator of climatic change. It is definitely known that the Krakatoa volcanic explosion in the last century, and the 17 March 1963 volcanic explosion in Bali, threw large amounts of dust into the high and middle atmosphere. In the Bali instance, this resulted in a 3% decrease



ACCUMULATED RAINFALL for the Nile River Valley (red line) and the Carolina coast (gray line). There is an increase in rainfall followed by an opposite trend. —FIG. 4

in the solar radiation incident in the southern hemisphere shortly after the explosion. The decrease persisted for several years and is now trailing off to the preëruption normal. In this case, volcanic dust certainly had an altering effect on the radiative balance of the atmosphere, but we do not know that it actually caused climatic changes of measurable magnitude.

Similar theories have been advanced regarding falling meteoric and cosmic dust. When it began to snow in Fred Hoyle's science fiction novel, *The Black Cloud*, this change was the first evidence of the arrival of the catastrophic Black Cloud. Fred Hoyle's book is no more science fiction than many theories of climatic change. For example, one theory suggests that (in some mysterious, subtle way unexplained by theory or experiment) cosmic rays are changing the ionization in the stratosphere, and that this change has an influence on climatic trends.

Solar activity

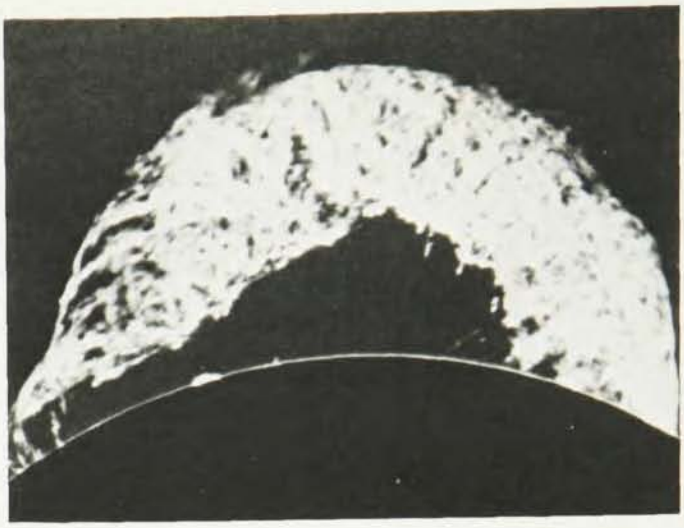
Some years ago I did some work on how solar-activity variations might possibly influence weather and climatic trends. Solar activity was at the heart of my approach. The variable activity of the sun, as I have implied above in speaking of the sun's constancy, represents but a small fraction of the total energy output of the sun. But percentage changes can be large in certain wavelength regions (as in the region from 50 to 300 angstrom units, in the soft x-ray region of the solar spectrum). Similarly, the changes in the flux of charged particles from the sun can be enormous. These emissions are selectively absorbed at different levels of the atmosphere; thus these layers can be subjected to great changes in temperature or motion as a result of the changeable solar input. This is at the core of my work. I must admit at once, however, that there is a long, obscure history of researches in this field, much of poor quality and dubious conclusiveness. There is also a fascinating modern history by persons such as E. R. Mustel of the Soviet Union, Hurd Willet at MIT, and Pierre Bernard in France. This research has a far sounder scientific base but still leaves more questions unsolved than explained.

Let me start this part of the story by reference to figure 1, which shows the solar corona, the luminous atmosphere of the sun seen during a total eclipse. The corona is highly irregular in structure and in particle emission. This is implied in the photo, whose complex structure derives from the irregular distribution of the electrons of the corona, the source of the scattered white light seen beyond the edge of the eclipsed sun. Figure 5 shows a giant solar prominence, an ejection of hydrogen gas with a velocity on the order of a million miles an hour. Such ejections, on occasion, blast into interplanetary space great clouds of electrified particles that interact with the magnetosphere to produce auroras at the earth.

Figure 6 shows a brilliant aurora photographed in College, Alaska. We are beginning to understand how this phenomenon arises at the time of arrival of ionized particles streaming at high velocity from the sun. Figure 7 shows a significant but theoretically unexplained change in weather patterns accompanying great auroras (or their related "magnetic storms"). What is represented is a "persistence correlation" figure, representing the stability of day-to-day pressure changes over a network of 19 North American weather stations on the days preceding and following brilliant auroras. This work, which was done by Ralph A. Shapiro and colleagues at the Air Force Cambridge Research Laboratories,[3] shows that a rapid and large decline occurs in the persistence of the barometric pressure patterns from about the fifth day to about the 14th day following the aurora. This was dug out of a great deal of statistical noise, but is of great theoretical interest.

It is simple enough to try to correlate the trends of sunspot cycles with the weather, and many have done it. It is also easy to try to find relationships between particular features of the circulation and particular changes in cosmic-ray intensity. Yet all of these efforts fail to reveal simple, straightforward results. Where there appear to be significant effects, they are usually complicated ones, and they vary from place to place and from time to time. The response of the atmosphere to incident energy is complex. No simple-minded effort to uncover a straightforward correlation will find the answers.

The energetics of the problem are also crucial. The changes of energy incident on the atmosphere that are involved in the changes of solar activity are infinitesimally small compared with the energies of the atmospheric circulation systems themselves. Therefore the causes, if they are really to be found in solar activity, must involve some kind of trigger mechanism that sets off a reaction when the atmosphere is in equilibrium. A good deal of the history of the search for physical relationships is a story of people trying to develop mechanisms by means of which small forces can release large changes throughout the atmosphere.



HYDROGEN GAS ejected into space at a velocity on the order of a million miles an hour. —FIG. 5

AURORAS of this type occur at the time of arrival of ionized particles streaming from the sun. —FIG. 6

Atmospheric stability

Perhaps the most promising research pathway in this area is to study the stability of general atmospheric circulation and to find ways to upset the stability, and thus to change the number of waves that show up in global jet-stream trajectories or lower stratospheric pressure patterns. Big southward excursions of the so-called polar jet stream (at the "polar front") of the northern hemisphere are a major feature of northern hemisphere weather. They cause "polar outbreaks" that are apparently due to the release of inherent instabilities in the circulation. They usually bring extremely cold weather to the central US. In fact, they bring about most major storm systems of late winter and spring.

What exactly is the driving force? What singles out one particular small oscillation to grow into a large eddy? And what singles out one period of years to have a much larger percentage of these small irregularities in circulation that will grow into large ones? The answers are still unknown, but my own work suggests that the phenomenon may be triggered by something associated with an aurora.

Direct conversion of the kinetic energy represented by an aurora would yield something like 3000 ergs/sec/cm^2 in the most favorable location directly underneath the aurora at very high atmospheric levels like 100 km. This is to be compared with ergs per square centimeter per second, penetrating to lower stratospheric levels. The radiant energy falling on the earth, represented by full sunlight, for comparison, is more than a million ergs per square centimeter per second. The energies in both the normal circulation and the perturbed circulation are many orders of magnitude larger than the few ergs per square centimeter per second of auroral energy at the stratosphere. If brute-force heating were the cause of atmospheric changes at these levels, the energy would have to be far greater than the energy represented by the aurora itself. For my own part, I am convinced that some subtle change of the stratospheric ionization may, in selected terrestrial locations, cause cirrus cloud banks to form. These, in turn, may change the radiation balance of the atmosphere enough to provide substantial heating or cooling of the atmosphere, whence, in my speculation, come the weather changes. But I must admit my chain of reasoning is still far too speculative to be good science.

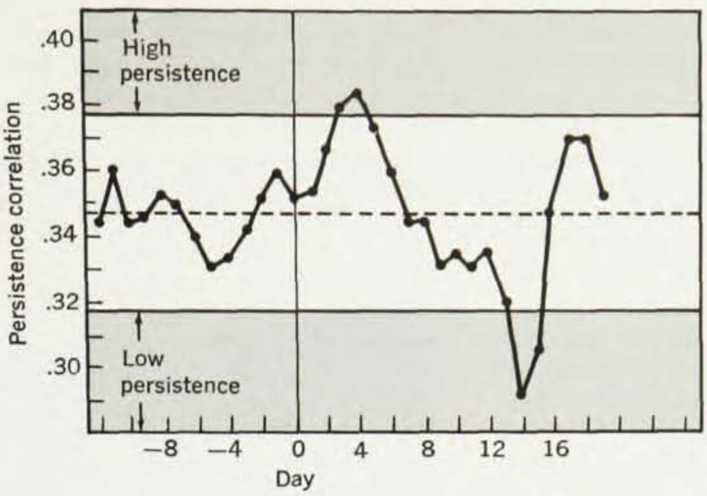
Although this intractable problem of finding the causes of climatic change may appear difficult, there are many clues and, I expect, real progress to come in the decade or two immediately before us.

Mysterious clues

A prime fact of large-scale atmospheric circulation that should lead to a physical clue is a striking regularity found in the tropical stratosphere. It is now known that every 26 months or so the circulation of westerly winds over the tropics goes through a cycle. The effect is seen in the winds that circulate in the high levels of the lower regions of the tropical stratosphere. During the cycle the westerly component decreases; then the cycle reverses, and after about 26 months the winds reach their maximal westerly velocity once again. This quasi-regular oscillation, which appears to be true for all tropical stations at all longitudes around the world, has recently become even more interesting because it seems to have dropped a half cycle.

Another clue is in hurricane formation. There are families of hurricanes that follow common paths, even though they seem to be quite independent in their initial formation. There are also clues in the tendency for weather to persist in certain patterns, temperatures and distributions, like the recent years of drought in the Northeast, now broken by persistent rain and snows. We also have clues to unravel in the evidence that even a force as nearly infinitesimal as the lunar tidal force in the atmosphere appears to have a significant influence on rainfall. This effect was reported in the work of Donald Bradley, Max Woodbury and Glenn Brier,[4] which is based on records of the most severe rainfalls. Severe rainfalls, for a given station, tend to cluster at certain phases of the moon. There is a greater frequency for record rainfall to show up a few days after the new moon or full moon. It is certainly important to explore the matter further.

Other fascinating effects occur when jet vapor trails grow in the sky; they, too, hold clues to the weather mystery. Figure 8 is a view from our laboratory in Boulder toward the mountains. In this photo cirrus clouds stretch across the sky, but a careful study shows that all the visible cirrus clouds developed by the gradual spreading of ice that first formed in a vapor trail behind a high-altitude jet airplane. When general cirrus cover like this develops, it tends to blanket the atmosphere and alters the radiative loss to space. This may have a significant influence on weather and climatic patterns. Here is certainly a large change in the earth's radiative balance, at least in the vicinity of commonly used jet airways, that occurs as a result of a small amount of energy released in the atmosphere by jet engines. In my view, the matter may have relevance to my efforts to find a cause-effect link for the apparent auroral influence on weather.



PERSISTENCE CORRELATION shows a theoretically unexplained change in weather patterns accompanying great auroras. —FIG. 7

CIRRUS CLOUDS develop when jet vapor trails grow in the sky. —FIG. 8

Global research program

At the present time, wind and weather systems are observed adequately and over a good range of heights for only about 10% of the earth. Although winds differ greatly from part to part of regions much smaller than the US, there are many areas of the earth as large as the US where there is but a single weather station systematically observing at a range of heights.

The objective of the Global Atmospheric Research Program is to bring the entire world under observation for a trial period sometime in the mid 1970's. The information will not necessarily be transmitted to research centers in "real time," but a set of data will ultimately be assembled covering a limited period of time, such as six months. We hope that for this period observations will be made over the entire earth at five or seven heights in the atmosphere, with approximately a 500-km spacing of stations. This is an enormous program, and there are many operational questions to be answered before we can assess its cost and overall feasibility. In fact, the feasibility of this program depends on the outcome of a number of preliminary programs now being planned.

One of the most interesting of these preprograms is the GHOST program of the National Center for Atmospheric Research. GHOST is an acronym for the Global HOrizontal Sounding Technique, by means of which we will gain weather data in vast unpopulous regions of the earth. For this program, Vincent E. Lally of our center has developed a new type of balloon that is simple in principle but new in realization. Lally's balloons are made of a rigid plastic; so when they reach full volume, they no longer expand. These balloons, some of which are about 5 meters in diameter, are partially inflated on the ground and released. The helium inside expands as they rise higher until they reach full volume. After this, the balloon rises a bit further, compressing the helium relative to the outside, until it reaches an equilibrium density level, where the balloon remains indefinitely. These balloons can carry appropriate weather-sensing and position-locating devices that pick up information to be radioed back to receiving stations or, in the future, to a satellite data-collecting system.

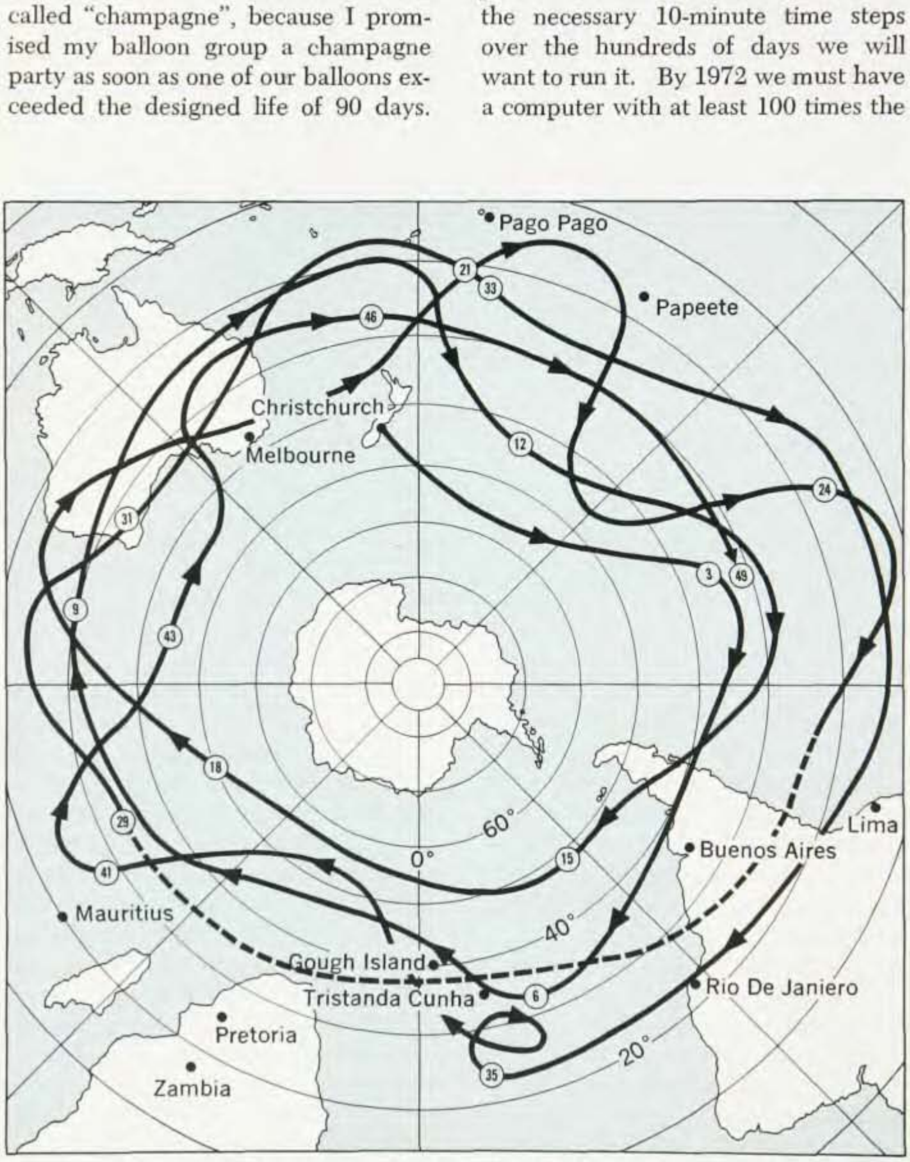
With the coöperation of the New Zealand government, NASA and the Weather Bureau, we have now completed a series of observations with GHOST balloons in the southern hemisphere. Figure 9 shows the trajectories of a GHOST balloon that was launched at Christchurch, New Zealand on 30 March 1966. The balloons we have so far launched have circled the southern hemisphere, oscillating between about 20 and 70 deg latitude and continuously transmitting their positions to a series of observing stations scattered about the southern hemisphere. This particular balloon is at an altitude of 40 000 feet and is called "champagne", because I promised my balloon group a champagne party as soon as one of our balloons exceeded the designed life of 90 days. The party was a great success. Several balloons have been up over 200 days and are still floating. During the Global Atmospheric Research Program in the mid 1970's, we hope to have 10 000 GHOST balloons flying continuously over the earth, transmitting their positions and other parameters of meteorological data to a communications satellite.

Another preliminary program involves the computer that we hope to have operational for pilot experiments well before 1975. It is obvious that the total body of information from the Global Atmospheric Research Program will be unmanageable unless an appropriate numerical model and supercomputer is available to integrate the complex nonlinear differential equations at the necessary 10-minute time steps over the hundreds of days we will want to run it. By 1972 we must have a computer with at least 100 times the speed and capacity of our present CDC 6600. This computer should also be adequately programed with appropriate models.

Before then we will need to know a number of things. For instance, we need to know whether a 500-km spacing between stations is sufficient for the tropics. To decide this, we must learn more about cloud and rainfall patterns and the way moisture is lifted to the upper troposphere, and the resulting effect upon the radiative balance, so that we can then parameterize these processes for use in a mathematical model of the global circulation.

By the mid 1970's, we will also need new kinds of weather sensors to fly in airplanes, new data systems for information communication, lasers to observe certain properties from ground stations, new types of radiosondes, launching platforms, new Doppler radars, and many other necessary tools.

Assuming that the computer, the GHOST balloon system and associated satellites and the many other tools of observation can merge by the mid 1970's, we will have the observations to test meteorological theory. By the end of the 1970's, we hope to have an operational world weather watch, which will transmit information on a real-time basis, spanning the world. This system will allow operational forecasting by a series of nations working on a worldwide coöperative network. The plans are already shaping up for the US under the leadership of the Environmental Science Services Administration (which includes the Weather Bureau). The 129 nations of the World Meteorological Organization are already coöperating in this venture, and three main points in the world system have been established in Melbourne, Washington and Moscow.



TRAJECTORY of a ghost balloon launched at Christchurch, New Zealand on 30 March 1966. These balloons transmit meteorological data. —FIG. 9

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