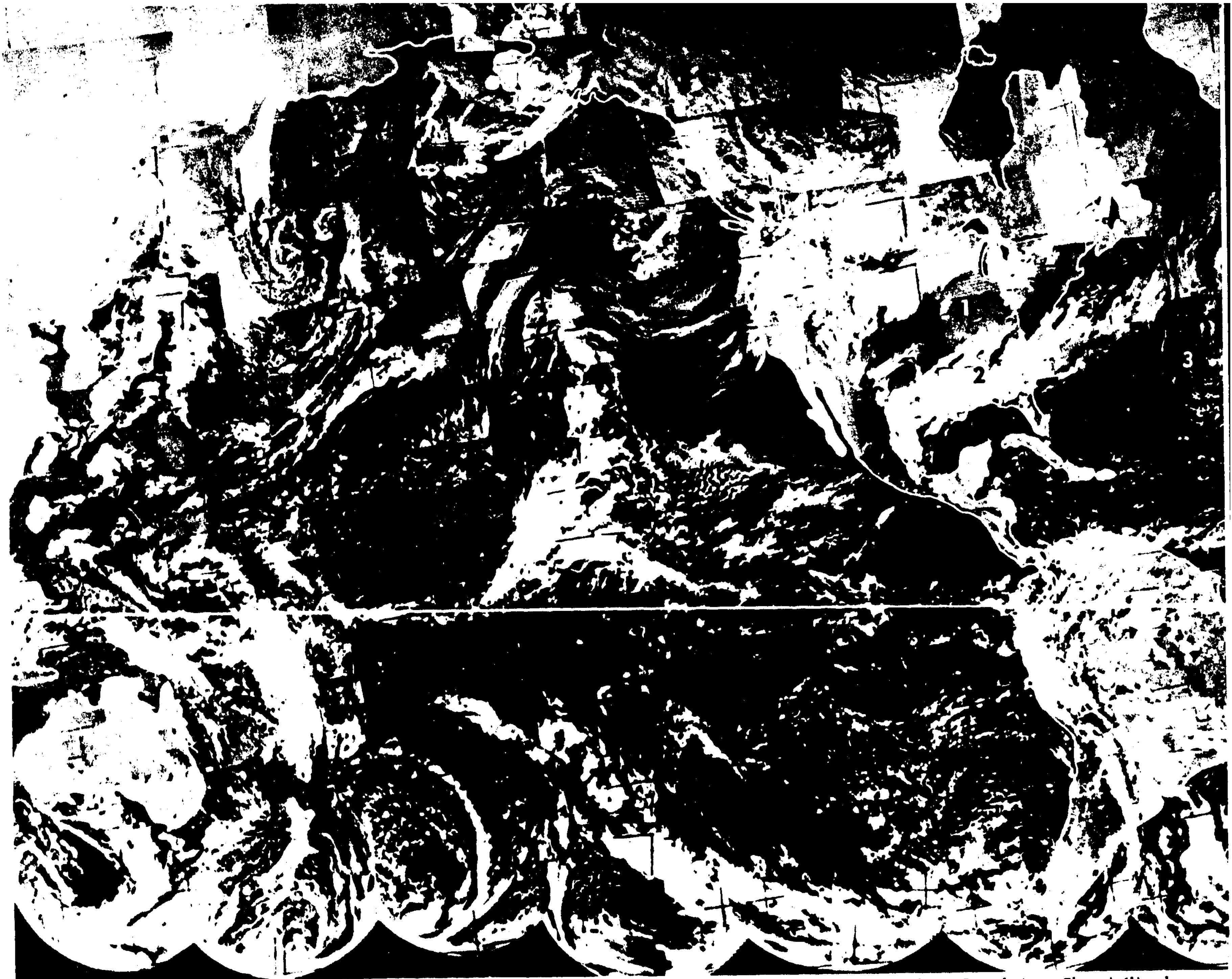
FORECAST FOR



The first complete view of the world's weather, Feb. 13, 1965. Land areas are outlined on a mosaic of satellite photos. Some features: Clear air (1) and a

In the long term, climate is cooling off—or is it warming up? As for tomorrow's weather, even the world's biggest computer can't say for sure what it will be.

By Alan Anderson Jr.

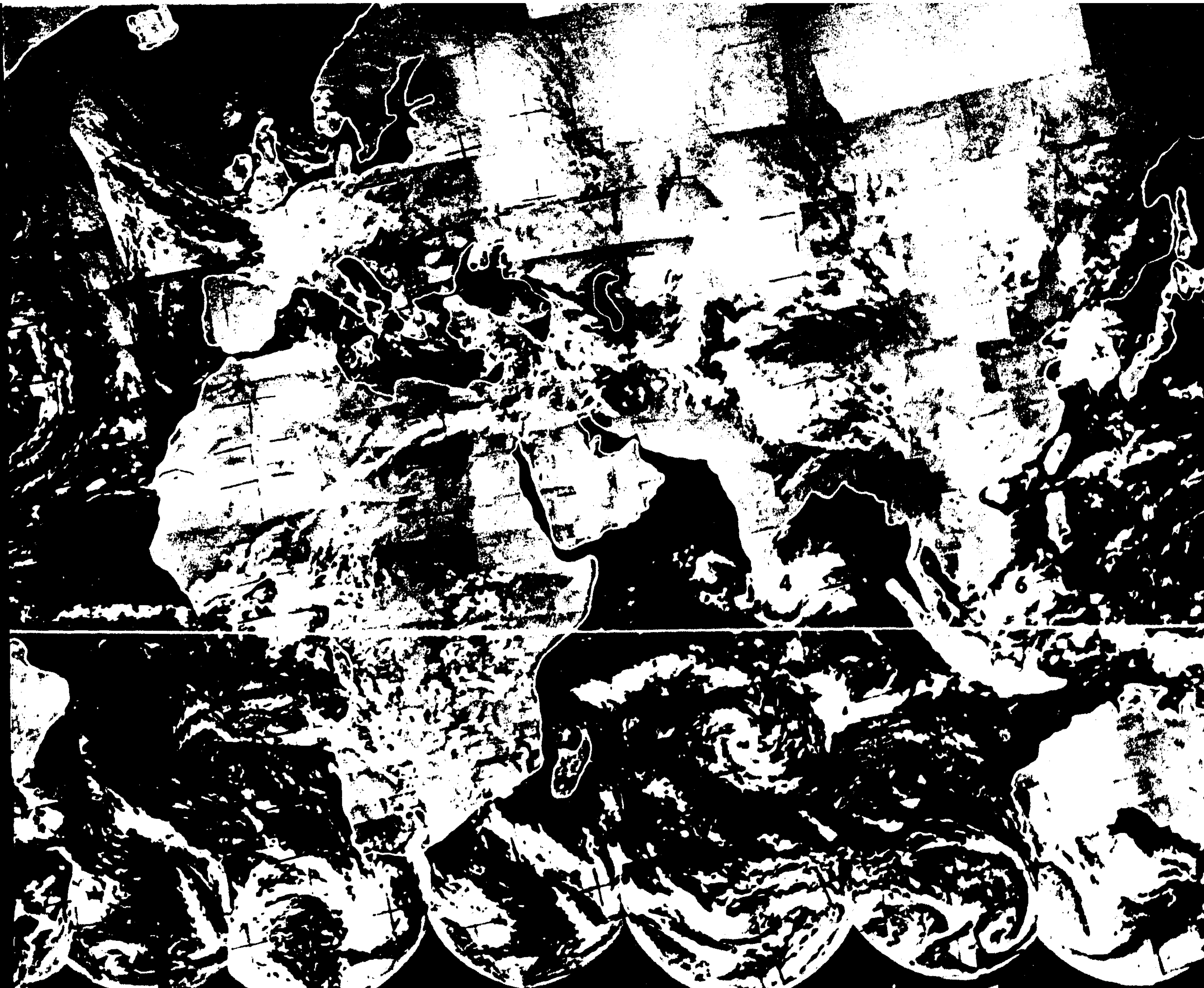
A number of climatologists, whose job it is to keep an eye on long-term weather changes, have lately been predicting deterioration of the benign climate to which we have grown accustomed. They point to signs both great (a steady global cooling trend since World War II) and quaint (the southward retreat from Nebraska of the warmth-loving armadillo) to support their claim that the coming years will feature colder, more erratic weather.

Alan Anderson Jr., a freelance science writer, refuses to make any predictions.

Some recent warnings, from reputable researchers in Japan, Europe and the U.S., have so worried policy-makers that last January certain scientists at a meeting of the National Academy of Sciences proposed the evacuation of some six million people from their parched homelands in the Sahel region of Africa.

At the same time, as anyone who watches the television weatherman knows, meteorologists are hard-pressed to predict the weather as much as five *days* in advance. A group of scientists, using the world's largest computer to simulate atmospheric behavior, still considers a two-week forecast only "an exciting possibility." How, then, can anyone propose a doomsday scenario spanning years and even decades?

FORECASTING: CLOUDY



rainy frontal zone (2) in the U.S.; a low pressure system in the Atlantic (3); tropical storms near India (4 and 5); a typhoon off Vietnam (6).

The discrepancy turns out to be more than a simple matter of scale. Climatologists, who study past climatic variations hundreds or even millions of years in duration, claim that they know a trend when they see one. Meteorologists, who are trying to understand the complex workings of the atmosphere on a minute-by-minute basis, protest that, without a better understanding of basic atmospheric physics, such long-range predictions are just unsubstantiated "hand-waving."

The dispute is of more than academic interest. Even slight climatic changes can force abrupt changes in agricultural patterns; the 1 degree centigrade drop in the annual average temperature worldwide has shortened the growing season in England, for example, by two weeks and caused permafrost to advance southward in Russia and Canada. Poorly understood shifts in high-altitude winds in 1972 are thought to have produced flooding along the eastern seaboard of the United States, irregular monsoon behavior in Asia, and drought in the Ukraine—all at once. During the same year, the mantle of polar ice increased by 12 per cent over previous years, and has not returned to its "normal" size. Sea temperatures in the North Atlantic have dropped, shipping lanes are cluttered with abnormal amounts of ice, and the Gulf Stream has retreated slightly southward.

Climatologists see this cooling as part of a trend—one that will surely lead to more erratic weather and so to food shortages. They do not fear the sudden advance of glaciers over our farms and cities; such an onslaught would take thousands of years to develop. They warn, rather, of long-lasting changes in rainfall and temperature around our croplands, and of heating or cooling of sea water in areas of high nutrient production. The huge grain surpluses of the nineteen-sixties have shrunk away almost overnight, so that crop failures in one of the world's crucial "breadbaskets," such as the wheat-growing region of the Ukraine, can produce high food prices and shortages worldwide.

This year, even the rich American Midwest took its lumps, just as farmers were hoping to make up for recent shortfalls. Even as grain growers sought to gain back losses of recent years, they were battered by spring flooding, midsummer drought and early frost. The har- *(Continued on Page 26)*

Forecasting

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vest of coarse grains (corn, oats, barley and rye) fell from 187 million tons in 1973 to 150 million tons in 1974. Food supplies can be increased only a little by expanding land and sea harvests. Most of the world's tillable land is already under cultivation, and fish and shellfish stocks are being hauled in at rates near the limit of replacement. "A major climatic change," reports a panel of the National Academy of Sciences, "would force economic and social adjustment on a worldwide scale."

Food shortages in themselves are not a complete surprise; some agricultural experts have been predicting them, largely on the basis of population growth, since the time of Malthus. But the idea that such shortages are being caused by deteriorating climate is relatively new—and far more fearsome. Perhaps the most outspoken and oft-quoted climatological doomsayer is Reid Bryson, director of the Institute for Environmental Studies at the University of Wisconsin. "It would appear," Bryson said recently, "that we are at the end of an era—the era of food surpluses and the era of benign climate." Bryson, a folksy, laconic man given to heavy irony, has been playing the role of climatological Jeremiah since the faint postwar cooling trend became discernible in the nineteen-sixties.

Most climatologists confine themselves to the search for patterns of past climatic changes. Bryson, more daring, is one of the few who are willing to make climatic predictions. Drawing largely upon the work of others (no single researcher could hope to carry out all the individual research projects from which a generalized theory must be assembled), Bryson warns that "the climate of the earth is changing and is changing in a direction that is not promising in terms of our ability to feed the world." Bryson argues that man, through industrial and agricultural activities, has been "stirring up the dust" at a sharply increasing rate since the nineteen-thirties. This dust, he says, is gradually reducing the amount of sunlight reaching the earth, especially in the northern hemisphere.

The effects of this solar screening might be slight, according to the theory, except for a key accomplice: a great skirt of whirling cold air known as the circumpolar vortex. This gigantic current of westerly winds, including the jet stream, rotates around the North Pole like a full skirt draped over much of the northern hemisphere. This "skirt" carries around its hem five to eight "folds" of alternating high and low pressure that reach into the mid-United States, northern Africa, southern Asia, and so on around the world.

Normally, the circumpolar vortex expands in winter and retracts in summer. Bryson and some of his colleagues contend that in recent years the thickening atmospheric dust has caused the vortex both to grow abnormally in the winter and to recede less in the summer. Because cold air is heavier than warm air, the cold polar vortex may block the normal warm-air storms such as the monsoons that bring life-giving rains northward each summer to the sub-Saharan Sahel region of Africa and to most of southern and eastern Asia. Bryson theorizes, for example, that in 1972, a year of wildly erratic weather, the high and low pressure "folds" of the polar vortex "skirt" were abnormally arranged in such a way as to cause, simultaneously, drought in Africa, floods in the eastern U.S. and drought in the mid-western U.S.

As long as man continues to put dust into the air, says Bryson, the circumpolar vortex will remain swollen, leading eventually ("sooner than you would think") to the deterioration of our climate. And he sees no way to avoid this fate. "You cannot turn off all industry, all mechanized agriculture, clean up every smokestack, tell all of the primitive farmers of the Congo and Southeast Asia to stop burning slash to clear new fields. I once saw a plume of smoke particles over Iceland that extended all the way from New York City. There is probably no way we can stop people from putting all this dust into the air. You tell people to stop doing things the way they have always done them, and they just look at you. I suppose I ought to stop worrying about whether people starve to death or not."

Bryson and a group of fellow climatologists met last summer in Bonn under the auspices of a group called the International Federation of Institutes for Advanced Study and issued a statement that startled many of their colleagues. It read, in part: "The facts of present climate change are such that the most optimistic experts would assign near certainty to major crop failures within a decade. If national and international policies do not take these near-certain failures into account, they will result in mass deaths by starvation and probably in anarchy and violence that could exact a still more terrible toll.... We are aware of differences among experts as to the cause-and-effect relationships of observed climatic facts and, consequently, as to the most likely prognosis. Professionally, the differences are important, but they do not—and should not be allowed to—obscure the larger consensus that the observed changes are neither trivial nor ephemeral." (Bryson's pessimism is not unconscious. "During the war, I used to be a forecaster at a combat airfield," he once told a colleague, "and it was my job to tell the pilots whether they could land when they got back. One day I predicted good weather and nine men were killed trying to land in heavy fog. I vowed I'd never make another optimistic forecast.")

The Bonn statement caused an uproar, and its strong wording was subsequently softened; a number of climatologists and meteorologists also took issue with the "consensus" it described. Professor Mikhail Budyko of the Soviet Hydrometeorological Service, for one, discounts the significance of the recent cooling trend and warns that over a longer term the climate has actually been getting *warmer* because of human activities, particularly the burning of fossil fuels, and that the sea level will

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soon rise dangerously as the Antarctic and other ice caps melt.

Researchers at the Geophysical Fluid Dynamics Laboratory in Princeton, N.J., one of the world's few groups testing sophisticated numerical models of the atmosphere, object that dire and sweeping forecasts are being made in the absence of any real understanding of what causes climatic change. One Princeton researcher, Syukuro Manabe, recently dismissed such predictions as "hand-waving"—lacking in supportive data. "If you speak out too loudly every time you suspect the cause of something, people won't listen to you after a while. We are talking about man's impact on climate, but nature has been causing trends such as ice ages all by herself for thousands of years." Joseph Smagorinsky, director of the laboratory, agrees: "There are all sorts of natural climatic cycles we don't understand yet. One man's trend is simply another man's periodicity—it just depends on whether you are using a telescope or a microscope. To go directly from a hand-waving hypothesis to contingency plans for moving six million people is a little frightening."

Another prominent dissenter is Jule Charney, professor of meteorology at M.I.T.: "I don't think we can predict climate now and I wouldn't trust anyone who said he could. The atmosphere is just too complex to take some of these vague statistics and try to use them to predict with. You can always find a single physical mechanism that will 'cause' one thing or another, but when you take them all together, it just gets too complicated. Worse yet are those 'weather forecasters' who say that they can predict the weather months in advance. Anyone who says he can tell you more than a few days ahead of time what the weather is going to be is practicing necromancy."

The skepticism of those who criticize Bryson's theory was reinforced last summer when, inexplicably, the six-year drought in the Sahel was broken. Smagorinsky, among others, mistrusts any theory that attempts to explain or predict drought on the basis of a single factor, such as increasing dust in the atmosphere. Manabe agrees, adding that drought is much too "tricky" a question: "If we had all the data from all the oceans and deserts around the drought area for those years, and we could compare them with a nondrought period, we could look for a significant difference. But we don't have the data."

At the most fundamental level, climate may be defined as the average of weather conditions—temperature, winds and precipitation—over a period of time. It is caused by the invisible motions of nitrogen and oxygen molecules, as well as those of less abundant materials such as water vapor and carbon dioxide, that make up our turbulent atmosphere. The heat energy to move the air molecules, and consequently, to cause weather, comes from the sun—a constant 23 trillion horsepower. About a third of this radiation is reflected back into space by clouds or light-colored patches of land; the rest is absorbed by the atmosphere or the ground and converted to heat.

The laws governing energy and motion—Boyle's law, Newton's laws of motion and the first law of thermodynamics—have been understood for over a century. Therefore, the movements are predictable—in theory. In practice, the molecules that do the work of weather are so numerous, and their activity so interrelated, that the equations governing their movements are extremely elaborate. As sunshine, wind and other conditions change in one region, the behavior of molecules in an adjacent region is altered, and meteorologists must continually update their calculations. In 1922, when English theoretician Lewis F. Richardson came up with the first numerical theory for global weather prediction, he labored for six weeks with a desk calculator to make a single (unsuccessful) 12-hour forecast. Richardson estimated that he would need a cast of 64,000 mathematicians punching away 24 hours a day to keep up with world weather.

At the same time, it is possible to understand the behavior of weather in a general way. More than half of the atmosphere's heat is generated in the tropics; because of the earth's spherical shape, sunlight strikes the equatorial regions more directly than the poles. The tropics have therefore been likened to the boiler that drives the planet's atmospheric engine. The "excess" tropical heat moves away from the equator toward the poles—about a third of it carried by warmed ocean currents and two-thirds by moisture-laden winds. From the temperate and polar regions this excess heat is reradiated into space; if it were not, the atmosphere would quickly heat up and the oceans would begin to boil.

If the earth were a smooth, motionless globe, the atmospheres of both the northern and southern hemispheres would behave as individual circulation cells, each resembling air in a room heated by a radiator along one wall. The air warmed by the radiator rises along the wall, moves along the ceiling toward the center of the room, sinking toward the floor as it cools, and then moves back toward the radiator along the floor. However, the earth is neither smooth nor motionless. The simple cell of air circulation actually takes the form of three linked cells. Mountains interrupt the flow of air, and the planet's eastward rotation skews the poleward movement of air so that it does not reach the poles fast enough to dissipate the excess energy. However, eddies form great storm systems, which are superefficient transporters of heat to the poles. Additional energy is released in other ways, such as precipitation. The raw material for rain, water vapor, is evaporated from the oceans by solar energy, mostly in the tropics. These molecules of gaseous water, which now carry latent energy, cool as they rise and move poleward. As they cool, the molecules tend to clump together in drops—releasing heat energy that was absorbed in the tropics during evaporation, and producing rain. (The formation of clouds and rain is still poorly understood, as is indicated by our continuing lack of rainmaking skills after decades of intensive research.) Additional energy is expended as wind in the form of hurricanes, fronts, cumulus convection, tornadoes, the jet stream and clear air turbulence. Processes such as these are responsible for about 75,000 thunderstorms a day around the world.

There is little hope of comprehending these processes without learning more about the tropical heat engine. The tropics are largely a meteorological blank spot, both because they are sparsely populated and because most equatorial countries are too poor to afford expensive weather programs.

Last summer, however, the first giant step was taken to learn something about equatorial weather. Meteorologists from 72 countries swarmed across the Atlantic for 100 days, bearing sensors in ships and aircraft for the first full-scale experiment of GARP, the Global Atmospheric Research Program, under the auspices of the United Nations. Adding their experimental information to the regular diet of data from 9,000 land stations, more than 6,000 daily reports from ships and 24-hour worldwide satellite surveillance, scientists sought to correlate oceanic and atmospheric conditions with observed weather. To the extent that they have increased understanding of the tropical heat engine, "the early results are amazing," says Dr. Charney. "They're beyond my expectations—and I suggested the experiment in the first place." Similar experiments are planned to study the Asian monsoon, the polar region, and, as a grand finale in 1978, the entire globe.

Since the nineteen-hundreds, weather scientists have known that all weather is part of a complex global fabric, and that conditions in one region are affected by those in neighboring regions. However, with inadequate knowledge of atmospheric physics and poor data-gathering facilities, global forecasting remained a dream until after World War II. The war sparked vigorous weather research, and meteorologists for the first time began building numerical models that bore some semblance to reality. More important, the first computers—originally used for ballistics ranging—became available for peacetime use. In 1946, famed computer pioneer John Von Neumann saw the value of high-speed computing for meteorology and began to assemble a group of brilliant young scientists at Princeton University. Using a machine known as the MANIAC (for Mathematical Analyzer, Numerical Integrator and Computer), Von Neumann's group in 1950 made a first—and wildly successful—computer run of their model. But later tests revealed inadequacies—according to one account, the computer once forecast a blizzard for Georgia in July.

Since then, computers and models alike have grown steadily more sophisticated: computer simulation remains an expensive and arcane specialty flourishing at only a handful of laboratories, including U.C.L.A., the Rand Corporation, the National Center for Atmospheric Research in Boulder, Colo., England's Meteorological Office and Princeton, where the descendants of the original group have continued Von Neumann's work. Now funded by the National Oceanic and Atmospheric Administration, the Princeton group is using the world's largest and fastest computer—an Advanced Scientific Computer made by Texas Instruments.

For purposes of numerical simulation, the earth's entire atmosphere is divided into boxes extending several hundred kilometers on a side and a kilometer or so in depth. A typical model may deal with 60,000 of these boxes. The computer is fed information about the boxes and about the basic laws of physics. It is then asked to compute on the basis of these laws, what will happen to the molecules in each of the boxes as temperature, humidity and wind speed change in neighboring boxes. In other words, it is asked to predict the weather all over the world, and to repeat this prediction every five minutes or so for as long as the model holds together.

The accuracy and range of the prediction obviously depend upon the reliability of the data and the model—and perhaps upon some intrinsic limits not yet understood. "We're now issuing five-day forecasts," says Donald Gilman, head of the long-range forecast division of the National Weather Service. "The consensus is that these models may let us see 10 to 14 days ahead for our daily predictions, although estimates range from one to four weeks. We are appreciably more accurate than we were 20 years ago, but it may be difficult to go on from here. That's one of the things the Global Atmospheric Research Program is designed to tell us: how much further we can expect to get. These models are very sensitive to little disturbances. If you give the model any sort of random kick, such as an error in wind speed, on day one the results you get three months later are very, very different from what you get without the kick. It will be very difficult to distinguish small but real atmospheric disturbances from random background 'noise.'"

> 'A really accurate three-day weather forecast would result in savings of $86-million a year just for growers of wheat in the state of Wisconsin.'

To predict climatic trends years or decades in advance, it is clearly impractical to recompute the world's weather every five minutes. Even with large "boxes," it takes tens of hours to run a model for a prediction of a week or two. With finer, more accurate grids, say 65 kilometers on a side, computation time becomes prohibitive.

Another apparent restraint upon long-range forecasting surfaced in the mid-nineteen sixties, when Edward Lorenz of M.I.T. demonstrated in what came to be known as the "butterfly theory" intrinsic limits on the predictability of individual storms or other bits of weather. Essentially, Lorenz showed that tiny, unpredictable random disturbances, such as the flap of a butterfly's wings, could change air currents and ultimately larger weather patterns in a way that no one can foresee. A multitude of such random "kicks" are enough to upset any model that attempts to be too specific.

Instead of aiming at specific predictions, therefore, numerical modelers seek to ignore the tiny kicks, and even eddies as large as hurricanes, in their search for the causes of climatic change. In fact, the theoreticians are looking beyond the atmosphere itself, exploring the oceans, the permanent ice cover and other elements of the earth's surface that change more slowly than the ephemeral atmosphere. The entire atmosphere may react to a change (such as a reduction of sunlight) in weeks, but the upper layer of the ocean may take months or years to react, the deeper ocean centuries, and the permanent ice cover (representing the bulk of the world's fresh water) hundreds to millions of years. Such slow-changing systems act as a kind of climatological "flywheel" on the atmosphere, damping most climatic oscillations before they become extreme. "There seems to be some kind of system with longer term fluctuations than the normal daily and seasonal weather we can observe," says Dr. Gilman. "It is probably not the sun—people have looked for a simple relationship there without any good results. The nature of this atmospheric flywheel is going to be the topic of lively debate in the next few years." Once numerical modelers can simulate the workings of the atmosphere-ocean-ice flywheel, they hope to be able to predict the results of specific changes, such as sudden, dust-producing volcanic eruptions or overgrazing of arid regions.

Both numerical modelers and climatologists agree that any attempts to alter climate would be foolhardy in the light of our rudimentary understanding of why climate changes. Russian scientists, for example, have proposed several scary schemes, such as diverting large Siberian rivers, melting Arctic ice, and damming the Bering Strait—all to gain irrigation water or warm the frigid fringes of the Soviet Union. "Suppose the Russians really believe they can halt the southward movement of permafrost," says Reid Bryson, "by spreading sunlight-absorbing carbon across the Arctic ice. Would this cause climatic dislocation that would ruin our own agriculture? I certainly hope they don't try it, because nobody knows."

A broad-based research program called CLIMAP, funded by the National Science Foundation, is seeking an understanding of such changes through a combination of both numerical modeling and classical climatology. "CLIMAP," says coordinator James Hays of Lamont-Doherty Geological Observatory, "is concentrating on climatic conditions that existed thousands of years ago. The goal is to generate air-sea models that will respond to such natural kicks as changes in solar input or dust levels. We can try tampering with the inputs and see how the model does in comparison to what really happened. We are looking for the trends, not the details, of weather. Ideally, climatologists should be able to look at previous changes and project them into the future—we hope on a scale as small as 100 years. We want to predict by past analogies."

National interest in long-range prediction has been spurred by recent crop failures and a shift toward practical applications of science. One good example is NASA's Goddard Institute for Space Studies in New York, a space-oriented think tank founded during the salad days of the moon program. "Roughly 80 per cent of our funding is channeled toward practical results now," says Goddard's director Robert Jastrow, an astrophysicist by training. "About half of this percentage is related to climate, and that fraction will grow steadily in the next few years. This makes sense because there is about $270-billion worth of weather-sensitive industry in this country. Dr. Vernon Suomi of the University of Wisconsin estimates that a really accurate three-day forecast would result in savings of $86-million a year just for growers of wheat in the state of Wisconsin. If we had a good 30-day forecast, we could predict droughts such as the Midwestern drought last summer. Such predictions would tamp down the gyrations of the commodities market and save millions of dollars. To get this kind of accuracy, we have to learn to ignore the little eddies of weather, just as quantum physicists had to learn to admit they could not pinpoint the exact location of an electron. The last thing we want to do in long-range forecasting is worry about where the eddies are. We must concern ourselves with the really important boundary conditions, such as the sun and the sea temperature. Without knowing the precise importance of these conditions, trying to predict weather now, in Jule Charney's words, is like trying to play pool with elliptical pool balls."

Climate researchers are haunted by the possibility that they will always have to play with elliptical pool balls —that climate varies so irregularly as to be inherently unpredictable. During moments of gloom, weather scientists compare themselves to economists, whose efforts at prediction have been notoriously unsuccessful. "Atmospheric instabilities," says Kikuro Miyakoda of Princeton, "seem very similar to economic instabilities in many ways. The economy of the entire world can be influenced by a few words from the president of one country. Fortunately, we think we are a little better off than this."

Joseph Smagorinsky prefers to believe that modeling may lead to good climatic prediction — eventually. "Climatic models won't use the same information as our short-term models. It isn't possible to follow all the details of weather. We shall be looking for the broad changes, trying to compute what will happen if we change the CO_2 content of the atmosphere or fly fleets of S.S.T.'s around the globe. The numerical model is the only fully consistent way to look at the myriad of processes that are operating. If you can't trust that approach, how can you trust hand-waving?" ■

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