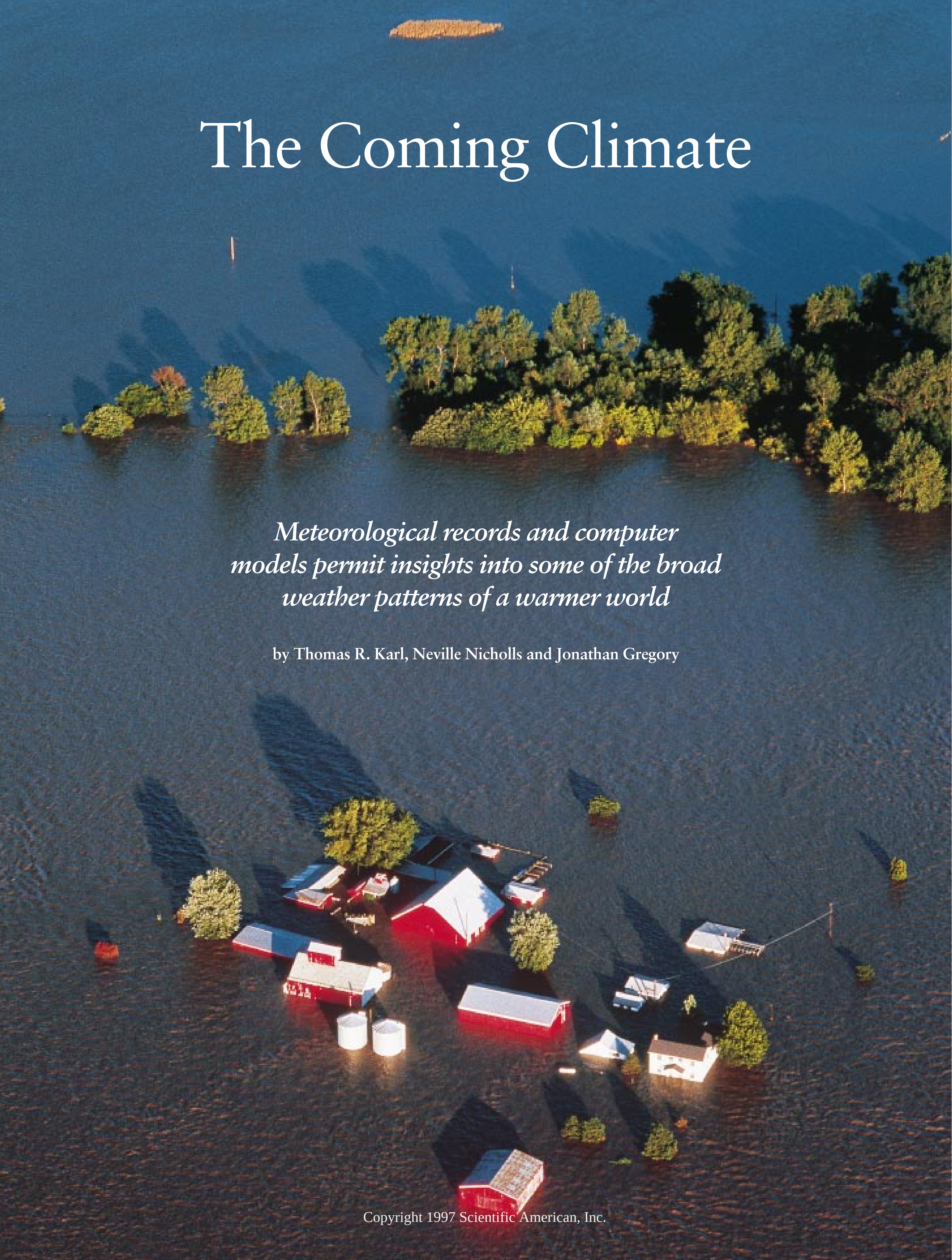

The Coming Climate

Meteorological records and computer models permit insights into some of the broad weather patterns of a warmer world

by Thomas R. Karl, Neville Nicholls and Jonathan Gregory

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Human beings have in recent years discovered that they may have succeeded in achieving a momentous but rather unwanted accomplishment. Because of our numbers and our technology, it now seems likely that we have begun altering the climate of our planet.

Climatologists are confident that over the past century, the global average temperature has increased by about half a degree Celsius. This warming is thought to be at least partly the result of human activity, such as the burning of fossil fuels in electric power plants and automobiles. Moreover, because populations, national economies and the use of technology are all growing, the global average temperature is expected to continue increasing, by an additional 1.0 to 3.5 degrees C by the year 2100.

Such warming is just one of many consequences that climate change can have. Nevertheless, the ways that warming might affect the planet's environment—and, therefore, its life—are among the most compelling issues in earth science. Unfortunately, they are also among the most difficult to predict. The effects will be complex and vary considerably from place to place. Of particular interest are the changes in regional climate and local weather and especially extreme events—record temperatures, heat waves, very heavy rainfall, or drought, for example—which could very well have staggering effects on societies, agriculture and ecosystems.

Based on studies of how the earth's weather has changed over the past century as global temperatures edged upward, as well as on sophisticated computer models of climate, it now seems probable that warming will accompany changes in regional weather. For example, longer and more intense heat waves—a likely consequence of an increase in either the mean temperature or in the variability of daily temperatures—would result in public health threats and even unprecedented levels of mortality, as well as in such costly inconveniences as road buckling and high cooling loads, the latter possibly leading to electrical brownouts or blackouts.

CAMERON DAVIDSON *Tony Stone Images*

FLOODED FARM near the Mississippi River in 1996 illustrates one likely consequence of warming trends. Rainfall will not only increase overall, but individual events will become more intense.

Climate change would also affect the patterns of rainfall and other precipitation, with some areas getting more and others less, changing global patterns and occurrences of droughts and floods. Similarly, increased variability and extremes in precipitation can exacerbate existing problems in water quality and sewage treatment and in erosion and urban storm-water routing, among others. Such possibilities underscore the need to understand the consequences of humankind's effect on global climate.

Two Prongs

Researchers have two main—and complementary—methods of investigating these climate changes. Detailed meteorological records go back about a century, which coincides with the period during which the global average temperature increased by half a degree. By examining these measurements and records, climatologists are beginning to get a picture of how and where extremes of weather and climate have occurred.

It is the relation between these extremes and the overall temperature increase that really interests scientists. This is where another critical research tool—global ocean-atmosphere climate models—comes in. These high-performance computer programs simulate the important processes of the atmosphere and oceans, giving researchers insights into the links between human activities and major weather and climate events.

The combustion of fossil fuels, for example, increases the concentration in the atmosphere of certain greenhouse gases, the fundamental agents of the global warming that may be attributable to humans. These gases, which include carbon dioxide, methane, ozone, halocarbons and nitrous oxide, let in sunlight but tend to insulate the planet against the loss of heat, not unlike the glass of a greenhouse. Thus, a higher concentration means a warmer climate.

Of all the human-caused (anthropogenic) greenhouse gases, carbon dioxide has by far the greatest impact on the global heat budget (calculated as the amount of heat absorbed by the planet less the amount radiated back into space). Contributing to carbon dioxide's greenhouse potency is its persistence: as much as 40 percent of it tends to remain in the atmosphere for centuries. Accumulation of atmospheric carbon dioxide is promoted not only by combustion but also by tropical deforestation.

The second most influential human-caused effect on the earth's radiation budget is probably that of aerosols, which are minute solid particles, sometimes covered by a liquid film, finely dispersed in the atmosphere. They, too, are produced by combustion, but they also come from natural sources, primarily volcanoes. By blocking or reflecting light, aerosols tend to mitigate global warming on regional and global scales. In contrast to carbon dioxide, aerosols have short atmospheric residence times (less than a week) and consequently are concentrated near their sources. At present, scientists are less certain about the radiative effects of aerosols than those of greenhouse gases.

By taking increases in greenhouse gases into account, global ocean-atmosphere climate models can provide some general indications of what we might anticipate regarding changes in weather events and extremes. Unfortunately, however, the capabilities of even the fastest computers and our limited understanding of the linkages among various atmospheric, climatic, terrestrial and oceanic phenomena limit our ability to model important details on the scales at which they occur. For example, clouds are of great significance in the atmospheric heat budget, but the physical processes that form clouds and determine their characteristics operate on scales too small to be accounted for directly in global-scale simulations.

How Hot, and How Often?

The deficiencies in computer models become rather apparent in efforts to reproduce or predict the frequency of climate and weather extremes of all kinds. Of these extremes, temperature is one of the most closely studied, because of its effect on humanity, through health and mortality, as well as cooling loads and other factors. Fortunately, researchers have been able to garner some insights about these extremes by analyzing decades of weather data. For statistical reasons, even slight increases in the average temperature can result in big jumps in the number of very warm days [*see top illustration on next page*].

One of the reasons temperature extremes are so difficult to model is that they are particularly sensitive to unusual circulation patterns and air masses, which can occasionally cause them to

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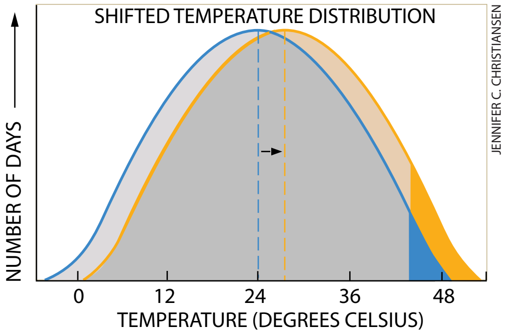


JENNIFER C. CHRISTIANSEN

SMALL SHIFTS in the most common daily temperature cause disproportionate increases in the number of extremely hot days. The reason is that temperature distributions are roughly Gaussian. So when the highest point in the Gaussian "bell" curve moves to the right (*above*), the result is a relatively large increase (*yellow area*) in the probability of exceeding extremely high temperature thresholds. A greater probability of high temperature increases the likelihood of heat waves (*right*).

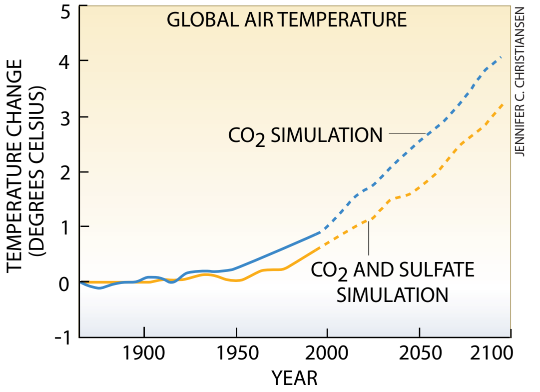
follow a trend in the direction opposite that of the mean temperature. For example, in the former Soviet Union, the annual extreme minimum temperature has increased by a degree and a half, whereas the annual extreme maximum showed no change.

The National Climatic Data Center, which is part of the U.S. National Oceanic and Atmospheric Administration (NOAA), has developed a statistical model that simulates the daily maximum and minimum temperatures from three properties of a plot of temperature against time. These three properties are the mean, its daily variance and its day-to-day correlation (the correlation is an indication of how temperatures persist—for example, how often a hot day is followed by another hot day). Given new values of mean, variance and persistence, the model will project the duration and severity of extremes of temperature.

Some of its predictions are surprising. For example, Chicago exhibits considerable variability of temperature from week to week. Even if the mean January temperature went up by four degrees C (an occurrence that may actually take place late in the next century) while the other two properties remained constant, days with minimum temperatures less than –17.8 degrees C (zero degrees Fahrenheit) would still occur. They might even persist for several days in a row. There should also be a significant reduction in the number of early- and late-season freezes. And, not surprisingly, during the summer, uncomfortably hot spells, including so-called killer heat waves, would become more frequent. With just a three degree C increase in the average July temperature, the probability that the heat index (a measure that includes humidity and measures overall discomfort) will exceed 49 degrees C (120 degrees F) sometime during the month increases from one in 20 to one in four.

Because of their effects on agriculture, increases in the minimum are quite significant. Observations over land areas during the latter half of this century indicate that the minimum temperature has increased at a rate more than 50 percent greater than that of the maximum. This increase has lengthened the frost-free season in many parts of the U.S.; in the Northeast, for example, the frost-free season now begins an average of 11 days earlier than it did during the 1950s. A longer frost-free season can be beneficial for many crops grown in places where frost is not very common, but it also affects the growth and development of perennial plants and pests.

The reasons minimum temperatures are going up so much more rapidly than maximums remain somewhat elusive. One possible explanation revolves around cloud cover and evaporative cooling, which have increased in many areas. Clouds tend to keep the days



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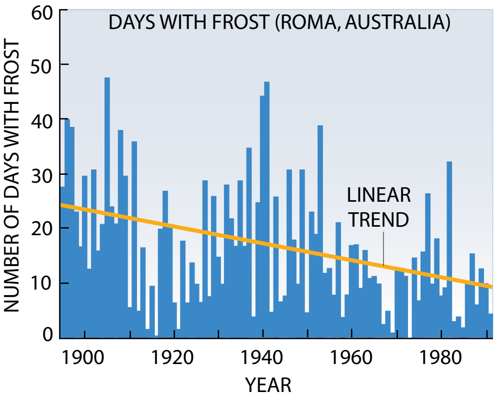

GLOBAL AIR TEMPERATURE rise was simulated (*above, left*) by a climate model at the U.K. Meteorological Office's Hadley Center. The blue line is from a simulation based on carbon dioxide only; the yellow line also takes into account sulfate. As the global temperature has increased, the number of days with minimums below zero degrees Celsius has gone down. This example (*left*) shows the annual number of days with frost in Roma, Queensland, in Australia.

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WARREN MARR *Panoramic Images*

cooler by reflecting sunlight and the nights warmer by inhibiting loss of heat from the surface. Greater amounts of moisture in the soil from additional precipitation and cloudiness inhibit daytime temperature increases because part of the solar energy goes into evaporating this moisture. More conclusive answers, as well as a prediction about whether the asymmetry in daytime and nighttime warming will continue, await better computer models.

Projections of the day-to-day changes in temperature are less certain than those of the mean, but observations have suggested that this variability in much of the Northern Hemisphere's midlatitudes has decreased as the climate has become warmer. Some computer models also project decreases in variability. The variability depends on season and location and is also tied to surface characteristics, such as snow on the ground or moisture in the soil. In midlatitudes, changes in the daily variability of temperature have also been linked to changes in the frequency and intensity of storms and in the location of the paths commonly taken by storms. These storm tracks are, in effect, a succession of eastward-moving midlatitude depressions whose passage dominates the weather.

The relation between these storms and temperature is complex. In a warmer world, the difference of temperature between the tropics and the poles would most likely cover a smaller range, because greater warming is expected near the poles. This factor would tend to weaken storms. On the other hand, high in the atmosphere this difference would be reversed, having the opposite influence. Changes in storms could also happen if anthropogenic aerosols continue to cool the surface regionally, altering the horizontal temperature contrasts that control the location of the storm tracks.

More Precipitation

The relation between storms and temperature patterns is one of the reasons it is so difficult to simulate climate changes. The major aspects of climate—temperature, precipitation and storms—are so interrelated that it is impossible to understand one independently of the others. In the global climate system, for example, the familiar cycle of evaporation and precipitation transfers not only water from one place to another but also heat. The heat used at the surface by evaporation of the water is released high in the atmosphere when the water condenses again into clouds and precipitation, warming the surrounding air. The atmosphere then loses this heat by radiating it out into space.

With or without additional greenhouse gases, the earth takes in the same amount of solar energy and radiates the same amount back out into space. With a greater concentration of greenhouse gases, however, the surface is better insulated and can radiate less heat *directly* from the ground to space. The efficiency with which the planet radiates heat to space goes down, which means that the temperature must go up in order for the same amount of heat to be radiated. And as the temperature increases, more evaporation takes place, leading to more precipitation, averaged across the globe.

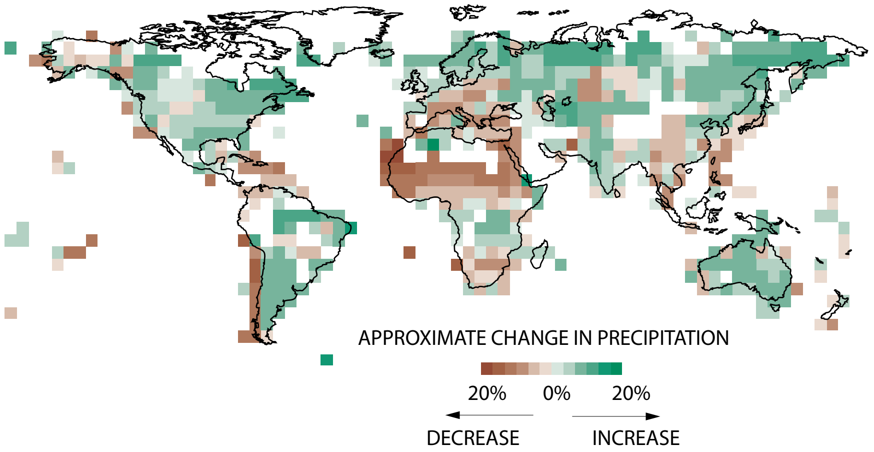
Precipitation will not increase everywhere and throughout the year, however. (In contrast, all areas of the globe should have warmer temperatures by the end of the next century.) The distribution of precipitation is determined not only by local processes but also by the rates of evaporation and the atmospheric circulations that transport moisture.

For instance, most models predict reduced precipitation in southern Europe in summer as a result of increased greenhouse gases. A significant part of the rainfall in this region comes from local evaporation, with the water not precipitated locally being exported to other areas. Thus, in a warmer climate, increased evaporation in the spring would dry out the soil and lead to less water being available for evaporation and rainfall in the summer.

On a larger scale, most models predict an increase in average precipitation in winter at high latitudes because of greater poleward transport of moisture derived from increased evaporation at low latitudes. Since the turn of the century, precipitation has indeed increased in the high latitudes of the Northern Hemisphere, primarily during the cold season, as temperatures have increased. But for tropical and subtropical land areas, precipitation has actually decreased over the past few decades. This is especially apparent over the Sahel and eastward to Indonesia.

In northernmost North America (north of 55 degrees) and Eurasia, where conditions are normally far below freezing for much of the year, the amount of

PRECIPITATION TRENDS between 1900 and 1994 reveal a general tendency toward more precipitation at higher latitudes and less precipitation at lower ones. Green indicates more rain; brown less.



LAURIE GRACE

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snowfall has increased over the past several decades. Further increases in snowfall are likely in these areas. Farther south, in southern Canada and the northern U.S., the ratio of snow to rain has decreased, but because of the increase in total precipitation there has been little overall change in the amount of snowfall. In the snow transition belts, where snow is intermittent throughout the cold season, the average snowfall will tend to diminish as the climate warms, before vanishing altogether in some places. Interestingly, areal snow cover during spring and summer abruptly diminished by nearly 10 percent after 1986. This decrease in snow cover has contributed to the rise of spring temperatures in the middle and high latitudes.

Besides the overall amounts of precipitation, scientists are particularly interested in the frequency of heavy downpours or rapid accumulations because of the major practical implications. Intense precipitation can result in flooding, soil erosion and even loss of life. What change do we expect in this frequency?

Whether precipitation occurs is largely determined by the relative humidity, which is the ratio of the concentration of water vapor to its maximum saturation value. When the relative humidity reaches 100 percent, water condenses into clouds, making precipitation possible. Computer models suggest that the distribution of relative humidity will not change much as the climate changes.

The concentration of water vapor needed to reach saturation in the air rises rapidly with temperature, however, at about 6 percent per degree Celsius. So in a warmer climate, the frequency of precipitation (which is related to how often the relative humidity reaches 100 percent) will change less than the amount of precipitation (related to how much water vapor there is in the air). In addition, not only will a warmer world be likely to have more precipitation, but the average precipitation event is likely to be heavier.

Various analyses already support the notion of increased intensity. In the U.S., for example, an average of about 10 percent of the total annual precipitation that falls does so during very heavy downpours in which at least 50 millimeters falls in a single day. This proportion was less than 8 percent at the beginning of this century.

HURRICANES, a kind of tropical cyclone, will probably occur in different global patterns as a result of warming; their overall incidence, however, may not change. Hurricane Andrew, shown raging here in Miami, struck the southeast coastal U.S. in 1992, causing $30-billion worth of damage.

WARREN E. FAIDLEY *Weatherstock*

As incredible as it may seem with all this precipitation, the soil in North America, southern Europe and in several other places is actually expected to become drier in the coming decades. Dry soil is of particular concern because of its far-reaching effects, for instance, on crop yields, groundwater resources, lake and river ecosystems and even on down to the foundations of buildings. Higher temperatures dry the soil by boosting the rates of evaporation and transpiration through plants. Several models now project significant increases in the severity of drought. Tempering these predictions, however, are studies of drought frequency and intensity during this century, which suggest that at least during the early stages of global warming other factors have overwhelmed the drying effects of warmer weather. For example, in the U.S. and the former U.S.S.R., increases in cloud cover during the past several decades have led to reduced evaporation. In western Russia, in fact, soil moisture has increased.

Stormy Weather

Great as they are, the costs of droughts and heat waves are less obvious than those of another kind of weather extreme: tropical cyclones. These storms, known as hurricanes in the Atlantic and as typhoons in the western North Pacific, can do enormous damage to coastal areas and tropical islands. As the climate warms, scientists anticipate changes in tropical cyclone activity that would vary by region. Not all the consequences would be negative; in some rather arid regions the contribution of tropical cyclones to rainfall is crucial. In northwest Australia, for example, 20 to 50 percent of the annual rainfall is associated with tropical cyclones. Yet the damage done by a single powerful cyclone can be truly spectacular. In August 1992 Hurricane Andrew killed 54 people, left 250,000 homeless and caused $30-billion worth of damage in the Caribbean and in the southeast coastal U.S.

Early discussions of the possible impacts of an enhanced greenhouse effect often suggested more frequent and more intense tropical cyclones. Because these storms depend on a warm surface with unlimited moisture supply, they form only over oceans with a surface temperature of at least 26 degrees C. Therefore, the reasoning goes, global warming will lead to increased ocean temperatures and, presumably, more tropical cyclones.

Yet recent work with climate models and historical data suggests that this scenario is overly simplistic. Other factors, such as atmospheric buoyancy, instabilities in the wind flow, and the differences in wind speed at various heights (vertical wind shear), also play a role in the storms' development. Beyond enabling this rather broad insight, though, climate models have proved of limited use in predicting changes in cyclone activity. Part of the problem is that the simulations are not yet detailed enough to model the very intense inner core of a cyclone.

The historical data are only slightly more useful because they, too, are im-

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perfect. It has been impossible to establish a reliable global record of variability of tropical cyclones through the 20th century because of changes in observing systems (such as the introduction of satellites in the late 1960s) and population changes in tropical areas. Nevertheless, there are good records of cyclone activity in the North Atlantic, where weather aircraft have reconnoitered since the 1940s. Christopher W. Landsea of the NOAA Atlantic Oceanographic and Meteorological Laboratory has documented a decrease in the intensity of hurricanes, and the total number of hurricanes has also followed suit. The years 1991 through 1994 were extremely quiet in terms of the frequency of storms, hurricanes and strong hurricanes; even the unusually intense 1995 season was not enough to reverse this downward trend. It should be noted, too, that the number of typhoons in the northwestern Pacific appears to have gone up.

Overall, it seems unlikely that tropical cyclones will increase significantly on a global scale. In some regions, activity may escalate; in others, it will lessen. And these changes will take place against a backdrop of large, natural variations from year to year and decade to decade.

Midlatitude cyclones accompanied by heavy rainfall, known as extratropical storms, generally extend over a larger area than tropical cyclones and so are more readily modeled. A few studies have been done. A recent one by Ruth Carnell and her colleagues at the Hadley Center of the U.K. Meteorological Office found fewer but more intense storms in the North Atlantic under enhanced greenhouse conditions. But the models do not all agree.

Analyses of historical data also do not give a clear conclusion. Some studies suggest that since the late 1980s, North Atlantic winter storm activity has been more extreme than it ever was in the previous century. Over the past few decades, there has also been a trend toward increasing winds and wave heights in the northern half of the North Atlantic Ocean. Other analyses by Hans von Storch and his colleagues at the Max Planck Institute for Meteorology in Hamburg, Germany, found no evidence of changes in storm numbers in the North Sea. In general, as with the tropical cyclones, the available information suggests that there is little cause to anticipate global increases in extratropical storms but that regional changes cannot be ruled out.

The Future

Although these kinds of gaps mean that our understanding of the climate system is incomplete, the balance of evidence suggests that human activities have already had a discernible influence on global climate. In the future, to reduce the uncertainty regarding anthropogenic climate change, especially on the small scales, it will be necessary to improve our computer modeling capabilities, while continuing to make detailed climatic observations.

New initiatives, such as the Global Climate Observing System, and detailed studies of various important climatic processes will help, as will increasingly powerful supercomputers. But the climate system is complex, and the chance always remains that surprises will come about. North Atlantic currents could suddenly change, for example, causing fairly rapid climate change in Europe and eastern North America.

Among the factors affecting our predictions of anthropogenic climate change, and one of our greatest uncertainties, is the amount of future global emissions of greenhouse gases, aerosols and other relevant agents. Determining these emissions is much more than a task for scientists: it is a matter of choice for humankind.

The Authors

THOMAS R. KARL, NEVILLE NICHOLLS and JONATHAN GREGORY were all members of the Intergovernmental Panel on Climate Change, which assessed and reported on the human impact on global climate. Karl is a senior scientist at the National Oceanic and Atmospheric Administration's National Climatic Data Center. Nicholls is a senior principal research scientist at the Australian Bureau of Meteorology Research Center. Gregory is a climate modeler at the Hadley Center of the U.K. Meteorological Office.

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