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The Extreme Weather Events of 1997 and 1998

By Kevin E. Trenberth

In late November of 1998, the Worldwatch Institute and Munich Re—the world's largest reinsurer—issued a report which assessed the total losses, worldwide, from storms, floods, droughts, and fires for the first eleven months of that unusual year. The staggering sum, at that time, was a record $89 billion: nearly 50 percent higher than the previous record of $60 billion in 1996. In addition to material losses, these weather-related events had taken an estimated 32,000 lives, while displacing 300 million people from their homes: more than the populations of Canada and the United States combined. Three months earlier, *LIFE* magazine had chosen "WEATHER" for its cover story, noting that in the preceding year and a half, an unusual run of weather-related disasters around the world had cost thousands of lives and tens of billions of dollars in damages. The extreme weather events that the magazine described were but a sampling of what was to become a staple of the daily news. And with ever mounting costs.

A Wild Ride

In early August, for example, major floods devastated parts of Korea, and in August and September 1998, extensive monsoon-related flooding struck heavily-populated eastern India and Bangladesh. Widespread heavy rains in China, at about the same time, released the mighty Yangtze River from its banks, with ensuing reports of more than 3,000 deaths, some 230 million people homeless, and over $30 billion in flood damage. In the summer of 1998 heat waves and air pollution episodes plagued many regions of the world, particularly in Egypt and other Mediterranean countries, and in southern Europe. In New Zealand, record floods in July and October 1998 were the worst in 100 years. But the costliest disaster of them all, in terms of human life, struck the Caribbean in late October. Hurricane Mitch caused the deaths of more than 11,000 people in Honduras, Nicaragua, Guatemala and El Salvador, primarily through the extensive flooding that followed prolonged and heavy rains.

Dr. Kevin E. Trenberth is an atmospheric scientist and Head of the Climate Analysis Section at the National Center for Atmospheric Research in Boulder, Colorado. He is a fellow of the American Meteorological Society and the American Association for the Advancement of Science, an honorary fellow of the Royal Society of New Zealand, and the Co-Chairman of the Scientific Steering Group for the World Climate Research Programme's Climate Variability and Predictability (CLIVAR) program. E-mail: trenbert@ucar.edu*

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A number of extreme-weather events with large human impacts fell in the same period in the United States, and most of them were explained, in news reports, as the expected impacts of the uncommonly strong El Niño of 1997-98. In the southeastern states, tornado outbreaks, and Florida floods (costing $1 billion in damage and taking at least 132 lives) were part of a pattern that led to the wettest winter on record there. Torrential rains in February 1998 in California brought flooding to many locales, with heavy mud slides and coastal erosion. A winter ice storm in early 1998 wreaked havoc in New England and southeastern Canada, leaving many communities without electric power for several weeks. At the same time, the northern tier of states experienced one of the mildest winters (1997-98) on record. Lake Erie failed to freeze for only the third time on record.

The spring of 1998 brought heavy flooding to Iowa, Indiana and other midwest states, and to some of New England, as part of generally wetter than normal conditions from Idaho to the U.S. Northeast. Ohio River flooding left 30,000 people without power.

Meanwhile drought enveloped the South. Extremely dry conditions from April through June 1998 led to wildfires which destroyed many structures, and in Florida alone, charred 485,000 acres—an area that is half the size of Rhode Island. In Texas the drought hung on through the summer months as well, bringing sweltering heat waves that devastated agriculture in much of the state.

The drought in Texas (the number one U.S. cotton producer) and the wetness in the winter and spring of 1998 in California (contributing to the spread of soil fungus in the second-ranked cotton producing state) resulted in a U.S. cotton crop that fell almost 25 percent below that of 1997. In October, another switch occurred in Texas—from too little to too much rain—leaving parts of Texas inundated, with twenty-two dead and reports of the worst flooding since the late 1920s. In early November heavy rains triggered floods in Kansas and Oklahoma.

These are but a sampling of the extreme weather events that have come our way in the past two or three years. Why so many, and what brought them on? Can these questions be answered at all with any certainty? How unusual were these extreme events, in the context of "normal" weather variability or within the limits of what meteorologists expect in El Niño years? Are we to anticipate more of the same in years ahead, and how much need we be concerned?

What Happened?

The authors of the Worldwatch Institute and Munich Re report felt certain that our own actions are in part responsible for the escalating costs of weather-related disasters, through (i) a combination of deforestation and land use change (which greatly affect water runoff during heavy rains); (ii) the effects of growing population pressures (which have led people to settle in flood plain and other regions vulnerable to flooding); and (iii) our energy-related impacts on climate itself. But can we tell whether human activities are really contributing?

The broadcasts and news stories that bring weather events to our attention as they happen are of necessity cursory and incomplete. With more extensive data and the benefit of hindsight we can hope to make more responsible assessments of what happened and why. A first step is to look for the telltale marks of probable causes, to help us sift out significant changes in global and regional weather from the chaff of more random variations.

Two probable causes

Two extremely likely suspects are potentially involved in what occurred, and neither can be much of a stranger to anyone who has watched or read or listened to the news: El Niño and global greenhouse warming. The first and more certainly involved is the 1997-98 El Niño and ensuing La Niña: a recurring, one-two punch to the global climate system that is driven by distinctive warming and later, cooling of surface waters in the tropical Pacific Ocean. El Niños—the better known of the two—are set in motion at irregular intervals, altering the course of weather and climate, around the world, for up to a year or so. The most recent were in 1982-83, 1986-87, 1990-95, and 1997-98.

We know from past occurrences that what might be called a "mini global warming" accompanies each El Niño, with the highest air temperatures typically occurring a few months after the peak in ocean surface warming. The record-breaking and long-lasting El Niño of 1997-98 began in April of the first year and persisted until May of the next. It almost certainly contributed in establishing 1998 as the world's warmest year on record.

But the exceptional nature of the 1997-98 El Niño—more intense in many ways than those well documented in the past—requires an explanation, and suggests that it was aided and abetted, somehow, by other climate forces. Most likely implicated is the warming of the Earth—quite independent of El Niño—that is expected from the accumulation of carbon dioxide and other greenhouse gases in the atmosphere. Did "global warming" also show its hand in the run of recent weather extremes, and did it amplify what might have been a more run-of-the-mill El Niño?

Trying to Explain Weather Events

In the early 1930s the U.S. experienced what is probably our best remembered period of extreme weather events, in what came to be known as the "Dust Bowl era." Extensive droughts, year after year, took a particularly heavy toll on farms and farm families in the bread basket of America, providing a backdrop for John Steinbeck's novel, *The Grapes of Wrath*, that tells the human impacts on displaced migratory farm workers. Some of the Dust Bowl years still stand today, in certain localities, as the warmest on record.

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Record-setting temperatures or precipitation amounts, and extreme events of all kinds are normal features of climate: they occur, somewhere, all the time, and always will. A year in which none was noted, anywhere, would indeed be noteworthy. But there seem to have been an uncommon number of such extremes in the late 1990s, particularly when we look at the world as a whole. Or could it be the result of more thorough reporting, or the existence of continuous TV news or weather channels that must find something of interest to broadcast, every hour of each day?

While we are indeed exposed to more and ever-wider coverage of the weather, the nature of some of the records being broken suggests a deeper explanation: that real changes are under way. In particular, global mean temperature records—based on the average of continual measurements taken at thousands of surface weather stations around the world—were broken month after month in 1998, and by margins never seen before.

The news media, reflecting valid public concerns, usually endeavor to include an explanation for dramatic weather events. Their queries are commonly answered by weather forecasters in terms of weather phenomena themselves: such as "the drought was caused by a big stationary anticyclone sitting over the region," or "the jet stream was displaced south of normal." But these are more descriptions of what happened, than explanations of why.

Why Does the Weather Change?

Such answers may be all that one can give, for often there is no identifiable "cause," given that weather has a wide range of natural variability, and is ever changing. *Weather systems* (such as the large-scale rotating wind patterns called *cyclones* and *anticyclones*) and *weather phenomena* (such as thunderstorms) arise primarily from *instabilities* within the atmosphere: where a small perturbation in the flow of air, for example, is rapidly amplified. The energy that drives these instabilities comes most often from the uneven way in which heat from the Sun is distributed over the surface of the Earth and with height above the ground.

An example is the cyclones and anticyclones and associated cold and warm fronts that arise from differences in the temperature of the air in the tropics (where the Sun is more directly overhead) and that at the poles of the Earth (where it is always lower in the sky). The pole-to-equator temperature difference is the result of the spherical shape of the planet, and the different angles at which the Sun's rays enter the atmosphere and reach the surface. The atmosphere responds to this unequal heating by continual attempts to reduce the pole-to-equator temperature gradients. It does this by generating, in the Northern Hemisphere, southerly winds to carry warm air polewards and cold northerly winds to carry the colder air to lower latitudes.

Another example of atmospheric instability is *convection*: the process through which near-surface air—warmed by solar heating—expands and rises, producing *thermals* which carry heat upward to give birth and shape to the clouds, and sometimes thunderstorms that bring rain.

When changes in solar radiation or any other component of the climate system (such as the land surface, oceans, or glaciers) influence the atmosphere in a systematic, as opposed to a random way, local weather patterns are likely to be affected, and will remain in an altered condition for seasons or years or longer. It is these more persistent changes in the prevailing weather at any place—which is to say, the *climate*—for which we can hope to find specific causes.

The most rudimentary of all climate changes is the annual cycle of the seasons, which results from the path of the Earth around the Sun, and the 23 1/2° angle at which the axis of rotation of the planet is inclined to the plane of that orbit. The next best understood—and the next most predictable climatic variation, thanks to quite recent research accomplishments—is El Niño, which occurs on an irregular schedule of a few years.

El Niños and La Niñas

In the early months of 1997, a familiar pattern of higher sea surface temperatures (SSTs) in the central and eastern tropical Pacific gave a clear signal that another El Niño was underway. It was also obvious, given the magnitude of the warming, that it could develop into a major event. For many months, peaking in December 1997, SSTs recorded in some of these tropical Pacific waters were more than 5° C (9° F) warmer than their average value. Over most of the ocean, by comparison, departures from average for even a single month rarely exceed 2° C. Over continental areas of similar size—where the solid surface of the ground is a less effective thermal buffer—departures of 5° from the normal can sometimes be found for shorter periods, but rarely for more than a month or two.

Records of past climate reveal that El Niños have been a recurring feature of the Earth's climate for thousands of years. But while we now know how their arrival is announced, and have set up monitoring systems in the oceans to warn of their coming, we don't know exactly when the next one, or the one after that, will first show its face: beyond the knowledge that they appear, on average, about every three to seven years.

El Niños are often preceded or followed by the opposite phase, dubbed La Niña, when surface temperatures in the tropical Pacific Ocean are systematically cooler than the long-term average. A corresponding modulation in the general circulation of the global atmosphere—called the *Southern Oscillation*—is also closely allied with these ocean changes. The name which is widely used by scientists to refer to the three together is the *El Niño-Southern Oscillation* phenomenon, or *ENSO*.

El Niño is the warm phase of ENSO, and La Niña the cold. Both involve the tropical oceans and the atmosphere, and the exchange of energy between the ocean surface and the air above it. The ocean and the atmosphere are linked together, interactively, and each affects the other. Atmospheric winds push the ocean currents and help determine the patterns of sea surface temperature. But SSTs at the same time help determine the force and direction of winds and atmospheric circulation, by adding heat or taking it away, chiefly by shifting the places where tropical thunderstorms preferentially occur.

The warmest large-scale pool of ocean water in the world is normally found in the vicinity of Indonesia—south of China and north of Australia. El Niño shifts the location of the warm water pool over 3200 km (2000 miles) eastward, to more open waters near the International Dateline or beyond. Meanwhile the normally dry zone over the eastern equatorial Pacific—from mid Pacific islands to the arid coasts of Chile and Peru and Ecuador—becomes much wetter.

When water vapor condenses and falls as rain, the heat that was stored when the water was originally evaporated is released into the air. Because of this, the major shift in the location of tropical Pacific rainfall that accompanies an El Niño alters the heating patterns of the whole atmosphere. Somewhat like a rock in a stream of water, the placement of a new source of heat sets up waves in the atmosphere that are as large as continents, and their effects reach beyond the tropics into mid-latitude regions. In the end, winds and storm tracks and the jet stream are all perturbed, in ways that affect, to some degree, almost everyone on Earth.

When La Niña takes control, the situation changes. Areas with drier than normal or even drought conditions during El Niño, such as Indonesia, the Philippines, Australia, Southeast Asia, Hawaii, and parts of Africa and Brazil, are apt to experience heavy rains during La Niña. Meanwhile, areas that have experienced El Niño floods, such as Peru, Ecuador, Uruguay and northern Argentina in South America, parts of Africa, and southern parts of the U.S. in winter, are apt to be drier than normal during the ensuing La Niña phase.

Impacts of the last El Niño

The most severe drought of the 1997-1998 El Niño struck Indonesia, with the result that many of the fires commonly set to clear land for agriculture raged out of control for weeks on end. So much ash was carried into the air that respiratory problems were reported as far as 1000 km (about 600 miles) away, and the loss of visibility was held responsible for the crash of a commercial airliner. El Niño-related drought and associated wildfires continued into 1998 in Brazil, Mexico, and Florida. As expected with El Niño, flooding hit Peru and Ecuador but also Chile, and coastal fisheries were disrupted.

Among the consequences of the 1997-98 El Niño was a persistent Northern Hemisphere jet stream that in winter blew with particular strength across the Pacific, over southern California, and then across the southern states to Florida. Atmospheric disturbances carried by these winds developed into major storms for the U.S., pummeling the West Coast and creating wet conditions from California to Florida. Storms generated by the jet stream as it crosses the North Pacific normally veer to the north and end up in the Gulf of Alaska, or enter the North American continent in the vicinity of British Columbia and the state of Washington. There they often link up with frigid Arctic and Canadian air masses and bring these down as recurring waves of individual cold fronts into the U.S.

When the jet stream instead veered south, the result in the U.S. was relatively mild winter conditions over the northern states that usually bear the brunt of these conditions, such that temperatures in February in the Great Lakes area averaged more than 10° C (18° F) above normal. The pattern was not confined to North America. The jet stream in the Southern Hemisphere was affected in a similar way, with similar effects on South America, where it was then late summer. One of the results was that the uncommonly warm February of 1998 set a record for the greatest departure from the average global temperature reading for any month on record.

A possibly unique development of 1997-98 El Niño conditions was a marked warming of surface waters in other tropical ocean basins. SSTs in the tropical Indian Ocean, for example, which are customarily about 27° C (80° F) exceeded 29° C (84° F); these waters were then warm enough to compete with the tropical Pacific in their effect on the atmosphere. As a result, strong thunderstorms developed over the western tropical Indian Ocean in October 1997, to spread over the Horn of Africa region and bring torrential rains to southern Somalia and Kenya for several months. Insect and disease outbreaks followed the resulting floods, leading to the proliferation of vector-borne diseases such as malaria, dengue fever, and Rift Valley fever. As is also often the case in the aftermath of severe storms, there and in other parts of the world, polluted local water supplies, degraded hygiene, and increased incidence of cholera occurred.

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In the spring of the year, the jet stream in the Northern Hemisphere normally migrates northwards, carrying much of the potential for stormy weather out of the reach of the central U.S. In 1998, however, as had happened on previous El Niño occasions, the jet stream continued to trace a course somewhat south of its normal position across the United States. As a result, a more southerly-than-normal storm track was established from Idaho to New England. This paved the way for a sequence of flooding events in Iowa, flooding in the Ohio Valley, and the wettest June on record in much of New England. It also diverted storms, and more normal rainfall, from the southern states. Regional weather patterns of this sort—wetter or colder in one area, dryer or hotter in another—persist longer than usual in El Niño years. By April 1998 conditions were rapidly drying out in the South, setting the stage for subsequent drought and wildfires.

Learning from the 1997-98 El Niño

Specific weather events—such as a major snowstorm in February in New England—cannot be attributed unequivocally to El Niño, or indeed to any other climatic cause. The weather will always vary, from day to day or week to week, and certainly from place to place and, as noted earlier, unusual swings, this way or that, can always be expected somewhere. What is definite is that El Niño, and La Niña, change the odds that certain kinds of weather will occur in a given place.

The most probable range of expected temperature, precipitation, and other meteorological conditions can be calculated for a given area, based on the unique perturbations that El Niño SSTs impose on the general circulation of the global atmosphere. This is done with the help of highly-detailed computer models of the climate system. The results will depend to some degree on what meteorological conditions were assumed to apply at the start of the calculation. But by repeating the modeled calculation for a representative range of these so-called "starting conditions," we can explore the scope of possible outcomes. These are then compared with what the same model projects in the absence of the El Niño perturbation.

The same models can be used to forecast the impacts of developing El Niños, provided that reasonably reliable projections can be made of sea surface temperatures. And indeed this can now be done, based on our improved understanding of how El Niño works and given the SST and sub-surface ocean observing system that is now in place in the tropical Pacific Ocean.

The new knowledge and observing capabilities were put to the test when the 1997-98 El Niño came into being, and the world profited, for climate simulations and forecasts throughout the event were more consistent and more skillful than had been the case before. What happened in these years to the circulation of the global atmosphere, for example—as seen in the changes in the jet stream and in storm tracks—was close to what was forecast by El Niño models several months in advance.

These successes can also help in identifying the cause of the extreme weather of 1997-98. The accurate forecast, based on El Niño, of many aspects of the winter weather patterns, is compelling evidence that El Niño was indeed a major contributor. Attributing the consequences—such as the proliferation of insects and other pests, or the outbreak of disease—requires similar tests of a longer chain of events, and is hence less certain. Nevertheless, the sorts of El Niño impact chains that now seem likely include the warmer and wetter conditions which favor the reproduction of malaria-carrying mosquitoes, with consequences for public health; and the lack of more normal freezing temperatures that would ordinarily kill off or delimit populations of pests or fungi, with possible impacts across the spectrum of animal life.

The severe weather events that were attributed at the time to the 1997-98 El Niño dealt heavy blows to many geographic areas and commercial sectors, while actually helping others. For instance, while it may be possible to attribute the tornadoes in Florida to a more active and southward-deflected storm track, it is possible that without the interference from El Niño, equivalent tornado damage could have been inflicted elsewhere, such as in neighboring Georgia, with equivalent loss of life and property. A similar instance of deflected misery can be found in the shift in 1997-98 hurricane activity from the Atlantic basin to the Pacific.

One of many examples of a different kind was the mixed benefit of the warmer winter of 1997-98: a boon to consumers but not for the natural gas and heating oil industries. These all highlight the need to identify what was clearly attributable to the 1997-98 El Niño and what was not. In doing this we need to consider both the positive and negative impacts, in terms of human values as well as economic terms.

The Role of Long-Term Global Warming

The terms "global warming" or "enhanced greenhouse warming" are commonly used to describe the human-induced change in global climate that is projected to occur in the course of the next century or two. Behind the projection is a continuing and well-documented increase in the concentration of the atmospheric greenhouse gases in the atmosphere. The most notable among them is carbon dioxide, which accumulates in the air when fossil fuels—such as coal or natural gas or gasoline—are burned, or when forests are cleared. As a result of these human activities, the amount of CO_2 that has accumulated in the air today is 30 percent greater than the stable levels of pre-Industrial times. Most of this increase, moreover, has come about since 1950.

Since these gases are the principal thermostat for the planet, the question is not whether the global temperature will respond to their increasing concentrations, but when, and by how much, and whether other climate factors—such as clouds or ocean circulation—might possibly compensate, and soften the blow.

There are many signs, including but not limited to meteorological data, that the expected global warming may already be upon us. The average surface temperature of the Earth has been gradually rising for the last 100 years, and more steeply in the past two decades (Figure 1). The last ten years are the warmest decade on record. 1998 is far and away the warmest year on record, and 1997 the second warmest.

The oft-cited value for the amount that the average surface temperature of the Earth has warmed during the present century is about 0.5° C (or 1° F.) These numbers, however, were derived for the period through 1995. As a result of a record-warm 1997, and an even hotter 1998, the overall warming relative to last century is now closer to 0.8° C (1.5° F). The melting of glaciers over most of the world, diminishing sea-ice in polar waters, and rising sea level are among the growing number of signs that seem to confirm the reality of the increase in global temperature.

Nature responds to weather in ways that enable those who study tree-rings and ice cores and other *paleodata* to extend our knowledge of climate history far back into the past. A recent analysis of the most extensive of such records produced a year-by-year temperature history for much of the Earth for the last 1000 years: adding over eight centuries to what we can glean from available thermometer readings. In no year—or decade—of that long span was the average temperature of the Earth as warm as it is now.

Hotter air temperatures are but one of many consequences when extra heat is added to the lower atmosphere, as will happen with enhanced global greenhouse warming. Another result is increased evaporation of surface moisture. Hotter air can hold more water and, together with enhanced evaporation, the inevitable result is a marked increase in atmospheric moisture. In the U.S., for example, the average amount of moisture in the atmosphere increased by 5 percent per decade in the years from 1973 to 1993. This remarkable trend toward wetter and wetter air is more than can be accounted for by global warming alone, however, highlighting the need to account for El Niño-related and other changes.

When the hydrologic cycle is predisposed in this way by global warming, naturally-occurring droughts—such as those brought on by El Niño—will set in quicker, plants will wilt sooner, and the droughts will likely become more extensive and longer lasting. Moreover, when there is little or no moisture in the soil to evaporate, all the incident solar radiation goes into raising temperature, bringing on sweltering heat waves of the sort that plagued Texas in 1998.

Further, over the Earth as a whole, any enhanced evaporation must be balanced, somewhere, sometime, by an equivalent increase in precipitation, for the global atmosphere can hold but so much water. Outside the tropics, moreover, roughly 75 percent of the water that falls as rain or snow comes from moisture that was stored in the atmosphere when the storm began. Thus with more moisture in the atmosphere, we can expect an enhancement of rainfall or snowfall in precipitating weather systems, be they thunderstorms, or extra-tropical rain or snow storms. Over the U.S., as in many other parts of the world, the number of heavy rainfall events has been increasing throughout the current century, adding to the potential for floods. The amount of annual precipitation has also increased by about 10 percent in the last 100 years. Thus, observations show that when it rains it pours, harder than it would have under similar circumstances just a couple of decades ago!

We should note that heavy rainfall is but one of several factors that determine whether or not a flood occurs. The spatial extent of the storm, the total amount of rain, and the rainfall rate are also important, as are the nature and condition of the terrain on which it falls. Important factors regarding the land include whether melting snow is present; the precondition of natural drains, streams and rivers; whether ice dams exist; and the degree of soil wetness. Geophysical, topographical, and vegetation conditions are all involved. Every bit as important, however, is whether human land use and structures, such as ditches, dams, levees, and reservoirs, allow the runoff to be channeled and ultimately managed. Because of these factors, flood records in themselves are unreliable indicators of changes in rainfall.

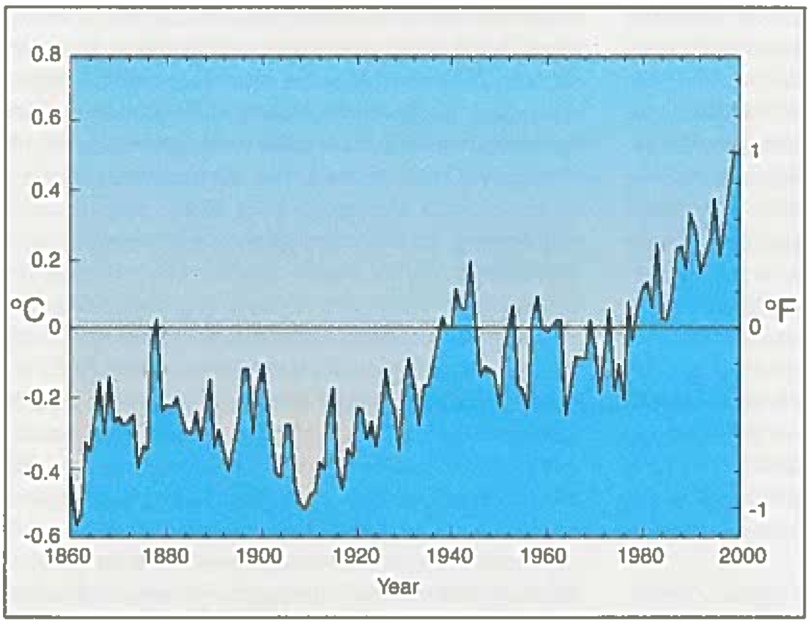

Figure 1 Global annual mean temperatures from 1860 to 1998. Shown (in terms of degrees C or F, at left and right) is the difference (or "temperature anomaly") between each annual mean temperature and the average for the 30-year period from 1961 to 1990. (Courtesy James Hurrell; adapted from data provided by the Hadley Center, United Kingdom Meteorological Office, and the Climate Research Unit, University of East Anglia, Norwich, England).

What climate models say

How much might the Earth warm with added greenhouse gases, and what can we expect in years ahead in terms of altered weather? Many projections have been made, in scientific laboratories around the world, using the best available climate models. Most commonly they endeavor to foretell conditions through the next century or so, to about the year 2100. But the models used, by necessity, include assumptions that can have a major influence on what they project.

By far the most uncertain of these are the "what if" assumptions regarding the often personal choices that people and governments will make, around the world, in years to come. For example, the projections of global warming models depend heavily on what each assumes about future rates of energy production and fossil fuel consumption. The projected rate of temperature increase will depend, in addition, on how faithfully the model simulates natural processes, including how clouds are depicted, or how vegetation responds. A climate model's answer to questions asked of it is almost never the single, simple answer that policymakers want.

When the character of El Niño changes so dramatically, and for so many years, we suspect that something else— most likely global greenhouse warming— is also involved.

In spite of all the caveats and uncertainties, an ever-present feature of every climate model is a projected increase in global mean temperatures in coming decades and centuries. The consensus projection for the so-called "mid-range" emissions scenario—in which the CO_2 content of the atmosphere increases to twice the 1990 value by the year 2100—is an increase in the mean temperature of 1.3° C to 2.9° C above that of 1990, with a "best estimate" of about 2° C (4° F). In addition, we need remember that other significant changes will accompany the projected surface warming, including the more prevalent extremes in rainfall that were noted above. Another major concern is the rate at which the world's climate is expected to change in response to enhanced greenhouse warming: more rapid than any natural variation in the past 10,000 years.

Based on the close agreement between observed climate indicators and what is predicted in global warming models, the Intergovernmental Panel on Climate Change (IPCC) concluded in 1995 that "the balance of evidence suggests that there is a discernible human influence on global climate."

El Niño and Global Warming: A Potent Combination

The El Niño of 1997-98 was in many ways the largest yet recorded. Was this by chance, or was it lifted to record levels by the help of other hands? In attempting to answer that question we should first note that El Niños seem to have marched to a different drummer in the course of the last twenty years. Since 1976, there have been more El Niños (7) and fewer La Niñas (4), when compared with the historical record of the previous hundred years—in which the two have occurred in more equal numbers. In the past two decades, moreover, we have seen the two biggest El Niños on record—the most recent, and the previous record holder, 1982-83—as well as the longest on record. The latter persisted for half a decade, from roughly 1990 to mid-1995, as three modest El Niños were blurred into one, when sea surface temperatures in the equatorial Pacific failed to fall below average conditions in between.

When the character of El Niño changes so dramatically, and for so many years, we suspect that something else—most likely global greenhouse warming—is also involved.

Before we make that claim, however, we need a plausible explanation of how a long-term, global warming trend could have so marked an effect on a recurring feature of shorter-term climate change; how it might favor and accentuate El Niños, at the expense of the opposite, La Niña phase; and what the combined effect should be, in terms of our day-to-day weather.

Charging and discharging the Warm Water Pool

How might El Niño be affected by global warming? The amount of warm water in the tropics builds up prior to—and is then depleted during—each El Niño. During the years of the cold La Niña phase, clearer skies are more prevalent across the wide Pacific, allowing radiation from the Sun to gradually warm the surface waters of the tropical Pacific Ocean. The added heat is stirred and redistributed by ocean currents, with most of it carried westward, where it accumulates in the deep Warm Pool in the equatorial western Pacific.

At the start of an El Niño, warm water from this Pacific reservoir is carried eastwards towards South America, to initiate the chain of events on the world's weather that are now well known. After their long eastward sweep along the equator, the warmer surface waters are deflected north or south toward higher latitude by altered ocean currents. Some of the heat that they have carried escapes to the air, mainly by increased evaporation, which further cools the ocean surface. When this added moisture falls out as rain—usually hundreds or thousands of miles away—it contributes to a general rise in surface temperature around the world that peaks a few months after the start of a strong El Niño event.

It was not by chance that the record-breaking temperatures of the first half of 1998 came just after the December 1997 peak of the 1997-98 El Niño, during the time when the Pacific Ocean was rapidly dumping its excess heat. This suggests that ENSO events are most simply an alternating sequence of storing up and then releasing thermal energy—like repeatedly filling a bucket, then pouring most of it out. The spacing of ENSO events would then be determined by the time spent in recharging the system—that is, in accumulating a sufficient volume of warm water in the tropics—plus the time for the ensuing El Niño to run its course. An endless cycle of charging and then discharging would also explain why El Niños are preceded and followed by La Niñas.

The effects of global warming

If ENSO is fundamentally a process that redistributes heat within the climate system, then tampering with the global thermostat—by injecting more greenhouse gases into the air—will likely interfere. Some possible explanations for the changed behavior of El Niños in the past twenty years are that the Warm Pool in the tropical western Pacific is expanding; and/or the recharge phase of El Niño has speeded up; and/or the heat loss phase is less efficient. Any of these could follow from warming and result in more frequent El Niño events. With global greenhouse warming we should expect higher temperatures in the upper layers of the ocean, and a steeper drop in temperature beneath the surface, which would increase the magnitude of swings between La Niña and El Niño.

One of the projected effects of global warming in climate models are changes in ENSO patterns and frequency, but as yet, none of the models simulates ENSO with sufficient fidelity to give confidence to the results. Also, how clouds might change, and especially the brightness of the ever-present convective clouds at equatorial latitudes, is particularly uncertain and can influence the outcome. Similar questions apply to the ocean, where changes that might alter the slow stirring of water beneath the surface could act in ways that are quite uncertain. Thus the question of how El Niño will change with global warming is not yet answered.

This also highlights the need for more comprehensive climate models, and particularly those that deal not only with El Niño and SSTs, but changes in the composition of the atmosphere, as well, including the greenhouse gases and solid pollutants that we add, and debris from volcanic eruptions. The impacts of the El Chichon volcanic eruption in Mexico in April 1982—at the time of onset of the 1982-83 El Niño—have yet to be combed from the snarled climatic record of these two overlapping events. Could this chance eruption explain some of the differences between the 1982-83 and 1997-98 El Niños?

When someday we make reliable climate projections months or years in advance, as now is done for the daily weather, the models employed will of necessity include these and all other likely climate forcings. They will also recognize that interannual variations, like ENSO events, take place in a setting of decadal changes, and these, in turn, against a back-drop of even longer-term variations, which may be controlled by the world's oceans, and perhaps the Sun.

Changes in atmospheric circulation and temperature

Although the average temperature of the Earth has been generally rising (Figure 1), the change, from place to place, is not at all the same. What we know of the atmosphere—and particularly the nature of atmospheric waves—would seem to guarantee a global inequality: some areas with greater-than-average warming, others with less, and a few where the average temperature has even dropped. The status of recent warming over the Earth, shown in Figure 2 (page 12), reveals that warming has been largest over most of the northern continents, much less in the eastern half of the United States, and absent altogether in the North and South Pacific and North Atlantic, where ocean surface temperatures have cooled somewhat.

It has also been demonstrated that the pattern of warmer winter temperatures in the Northern Hemisphere arises in large part from changes in atmospheric circulation. Some of these changes in flow are linked to El Niño, whereby warming in the tropical Pacific is spread along the coast of North America and throughout much of Canada and Alaska. The cooling in the North and South Pacific can also be attributed to the increase in El Niños.

Other changes were a wintertime increase in westerly winds in the Atlantic ocean area, that contributed to warmer temperatures throughout Europe and Asia and cooler ones over the western North Atlantic and Greenland. Overall, the land has warmed more than the ocean, in large part because of the way the atmospheric winds have changed.

It is not at all clear how the atmospheric circulation will respond to further increases in greenhouse warming. Nor can we anticipate, given these uncertainties, the meteorological consequences that could follow alterations in so fundamental a feature of the atmosphere. We should expect, however, that global warming will be manifested through changes in natural modes of behavior of the climate system, such as ENSO, by way of changes in the relative frequency and strengths of El Niño and La Niña events. Moreover, the ENSO-caused floods and droughts will be exacerbated by global warming.

One of the major impacts of El Niño involves the distribution and intensity of hurricanes. In El Niño years, there is more vigorous activity in the Pacific—especially the central and eastern portions—and fewer and less energetic hurricanes in the Atlantic and Caribbean. When the opposite, La Niña conditions prevail, as in 1995 and the latter half of 1998, the Atlantic is again more prone to an active hurricane season. What is not so clear is how global warming will influence hurricanes. While hotter SSTs can fuel more vigorous storms, with global warming the increase in air temperature will exceed that of the sea, which should stabilize the atmosphere and decrease the potential for tropical storms.

Why Extremes are Important

El Niño brings on floods and droughts in different parts of the world, and global warming will likely exacerbate the extremes of flooding and drought, no matter what their origin. Moreover, any change in the average rainfall or temperature or other meteorological variable will be accompanied by a disproportionate shift in the expected extremes.

What happens to the expected range of temperature readings—and particularly the extremes—when the mean surface temperature warms but a small amount can be seen in Figure 3, for the simple case of a 5° increase in a mean temperature of 50° F. The resulting change in the probable occurrence of any temperature reading that is close to the mean value—which might be called the silent majority—is very small. In contrast, at the two ends of the bell-shaped curve of expected temperatures, corresponding to the expected extreme readings, the impact is enormous. Temperature readings in excess of 75° F, for example, are more than twice as likely when the mean temperature rises from 50° to only 55° F and the variability remains constant. And the same is true for temperature readings below 25° F, at the other end of the expected spread.

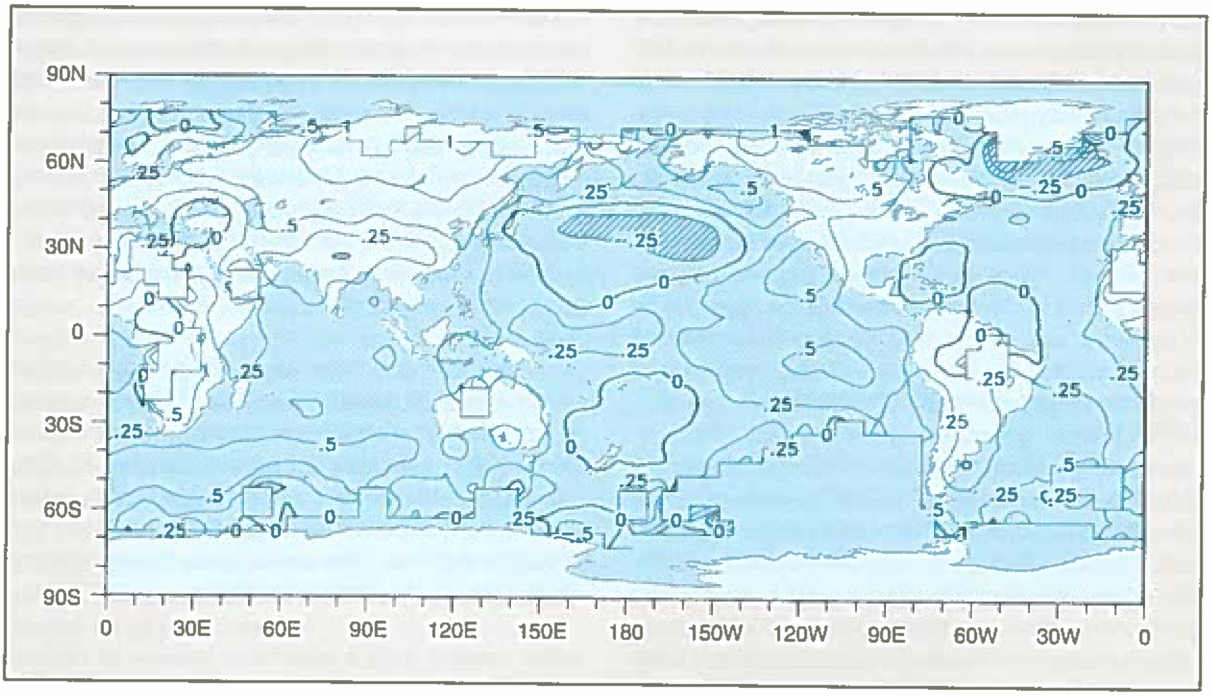

Figure 2 How much, and in what sense regional temperatures have systematically changed, around the world, in the last fifty years. The contours express the temperature change in degrees C: in this case, the difference between the mean temperature for 1981-1997 and that for 1951-1980. The mean temperature increase in this time, averaged over the globe, was about 0.4° C. The greatest changes, as expected, were generally at higher latitudes, although surface readings over isolated portions of the North Atlantic and North Pacific Oceans have cooled by about as much. (As in Figure 1, courtesy of J. Hurrell; adapted from data provided by the Hadley Center, UKMO, and CRU, University of East Anglia).

Because of the natural variability of the weather—where day-to-day swings of 20° F or more are not uncommon—most of us would never notice incremental changes in the mean temperature, were it not for their effect on the resulting temperature extremes.

Extremes in temperature or other meteorological indicators are exceedingly important to both natural systems and to human systems and infrastructure, in that they, and we, are designed to tolerate a limited range of natural weather conditions. We readily adapt and adjust to the variability and frequency of extremes that accompany that span. But when extremes are reached that exceed the accustomed spread, or when they are encountered more often, the limits of adaptation or of linear response can easily be exceeded: as with the "straw that breaks the camel's back."

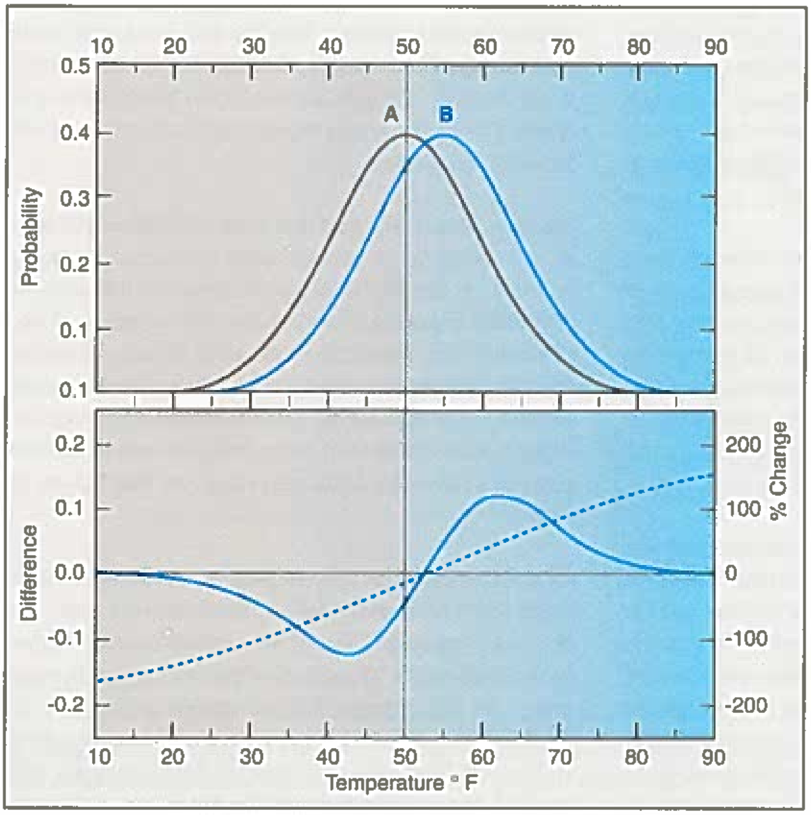

Figure 3 An illustration of how a small change in the mean or average value of a meteorological variable can have a large effect on the expected number of extreme readings. UPPER FIGURE (black curve, A): the probability of different temperature readings when the mean temperature is 50° F. UPPER FIGURE (blue curve, B):the same, when the mean temperature rises 5°, to 55° F. The shape or spread of the bell-shaped pattern by which expected values are distributed on either side of the mean is the same in both cases. LOWER FIGURE: the corresponding changes in the probability of the temperature readings shown on the bottom scale. The solid blue curve (with scale at left) is the difference in probability of the readings shown on the bottom scale. The greatest difference is for temperatures about 10° above and below the mean value of 55°. The dashed blue curve (scale at right) is the percentage change in probability. Readings of 60 to 70°, for example, are expected roughly twice as often as before.

Flooding is an example. With global warming, the 100-year floods that are routinely considered in building and land-use practices—expected, on average, but once each century—may now become 50- or 30-year floods. The change could be seen in floods that flow over dams or break levees, inundating the surrounding countryside and urban areas, resulting in drownings, water damage, and more subtle impacts that include polluted drinking water.

The late-1998 flooding of the Yangtze River is a recent case, but the same has also happened in the United States: in California in early 1997, in the Red River valley in the Dakotas in spring 1997, and in the Upper Mississippi Basin in 1993, to cite but three examples. Insect and disease outbreaks often follow, especially in tropical countries, where, as in some areas of Africa and South America, cholera outbreaks and mosquito-borne diseases such as malaria, dengue fever, and Rift Valley fever are often associated with flooding.

Global Warming Analogs

Short-term climate anomalies, such as were experienced with El Niño, can serve as useful proxies, or *analogs,* for what might happen, more often, in the course of future global greenhouse warming. They can also teach us what we can do by way of mitigation, and of particular importance in this regard are the forecasts that were made of the 1997-98 event. Some of the relevant impacts of the 1997-98 El Niño are listed below.

- A rise of about six inches (fifteen cm) in sea-level along the coast of California, which combined with storms to produce particularly damaging coastal erosion. Sea level is expected to rise around the world with global warming.

- Substantially higher than normal temperatures over land, particularly in some areas in the winter of 1997-98, that mirrored the kinds of changes that have been projected for global warming. Among the economic impacts were major changes in the demand for heating fuels.

• Changes in precipitation patterns, leading to flooding in some areas (such as Chile, Peru, California, and the southeastern U.S.), and to drought in others (as in Indonesia and Central America) that resulted in out-of-control fires, often arising from slash and burn agriculture, in spite of ample warnings. While changes in precipitation with global warming would differ from those of the El Niño, the effects on agriculture, water resources, and fires, for example, and how communities dealt with them, could be much the same.

• The expected emergence of a number of significant, secondary impacts. The fires in Indonesia, for example, brought respiratory problems to areas that were 600 miles away. Some of the results of California floods were an abundance of insects, rodents, and snakes, an increase in soil fungus, and contamination of domestic water supplies with consequences for human health. Uncommon winter rains in the U.S. Southwest resulted in swarms of grasshoppers in Arizona, and a surge in the population of hantavirus-carrying rodents in New Mexico. Outbreaks of disease occurred, such as Rift Valley fever in Kenya, cholera in Peru and Tanzania, and malaria in Africa, which could have been anticipated (and to some extent were.) All of these can provide lessons for other climatic changes.

• Because prediction was possible and warnings were made, individuals and institutions could respond in ways that lessened the negative impacts. Some were unable to act; others chose not to. Projections of impending climate change associated with global warming are also now available, in large part through the continuing efforts of the IPCC, and are being taken notice of by some communities and countries more than others.

These and other examples demonstrate the potential benefit of enlightened mitigation. For example, in some areas, including Australia, the removal of litter and debris reduced the risk of drought-associated fires. In some flood prone areas, drains and ditches were cleared, roofs repaired, and dikes strengthened in anticipation of the forecast heavy rains. Advanced plans were made for medical supplies, or for meeting anticipated shortages in food and other commodities. In retrospect, far more could have been done, given the overall accuracy of what was forecast.

The modeled projections were not wholly on the mark, for in some areas (and notably in Asia) the forecasts did not match what happened. As a result, efforts to prepare were misdirected, and we can assume, public faith in future projections of this kind was probably eroded. In these experiences, good and bad, we have for future study a natural experiment in how people, institutions, and governments can cope, particularly in making decisions under uncertainty, and lessons for longer-term climate change, whatever its cause.

A Personal Perspective on Recent Weather Events

To explain the weather disruptions over the past year or so, or weigh the influences of El Niño or possible global warming, it is important to have (1) a picture of what happened over the whole Earth, as opposed to a single country, or region, or hemisphere; (2) weather data from at least several months, to allow temporal and geographic patterns to be discerned; and (3) a perspective that encompasses all aspects of the weather.

In particular, it is misleading to think only in terms of temperatures when considering the effects of global warming. The "air conditioning" effects of moisture are extremely important in making meaningful projections of climatic change, as are regional differences in where weather systems develop and persistent conditions apply. For example, through the winter of 1997-98 in the U.S., the <u>wet</u> regions in the South were quite distinct from the <u>warm</u> regions in the North, and vice versa in the spring.

The floods and droughts that future El Niños will usher in are likely to be exacerbated by global warming, whether or not El Niños are themselves affected—in that these transient disturbances will be imposed on a climate system that is in some ways already disturbed. But the El Niño phenomenon could also be itself transformed as the underlying climate warms, evolving, perhaps, in the direction of more frequent and more energetic appearances, or in ways that we can not as yet foresee.

Unquestionably, for fifteen consecutive months—from April 1997 until about July of the following year—the last and greatest El Niño of this century exerted a dominant influence on all aspects of prevailing weather patterns. Its heavy hand shifted weather patterns on the global map, and held them there, relentlessly. Similarly, after June 1998, the rapidly developing La Niña exerted major influence: on the hurricane season and especially Asian flooding.

It is likely that global warming also contributed. Since the time of the 1995 IPCC assessment, observational evidence has continued to mount for a significant human influence on global climate. The best assessment of the contribution of enhanced greenhouse warming to the climate of today is that it is still small, but it is there. The expected signals seem now to be emerging from the noise of background variability, most clearly, perhaps, in the nature of weather extremes. And while some changes arising from global warming could prove benign or even beneficial, the economic costs of the impacts of more extreme weather are substantial and clearly warrant further attention in policy debates.

It may prove significant that the emergence of clear signs of global surface warming, beginning in the late 1970s, is coincident in time with the more frequent appearance of El Niños. A possible explanation is that although present, the global warming influence was until that time insufficient to perturb the normal working of the climate system: that its capacity to affect the overall behavior of the climate system was reached only after a certain threshold had been passed. Were this what really happened, it would identify global greenhouse warming as an abrupt, as opposed to a gradual, and thus more easily accommodated climate change. It may take several years to determine whether this perspective is the right one.

For Further Reading

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A list of more technical references that pertain to this article may be found on the *World Wide Web* version of this issue, at http://www.gcrio.org/CONSEQUENCES/introCON.html

Reviewers

***Dr. Phillip Arkin** is the Deputy Director of the recently-established International Research Institute for Climate Prediction located at the Lamont-Doherty Geological Observatory in Palisades, New York. Before taking this assignment he served on the staff of the Office of Global Programs of the National Oceanic and Atmospheric Administration in Rockville, Maryland.*

***Dr. Kenneth Kunkel** is a climatologist at the Illinois State Water Survey in Champaign, Illinois, with particular interests in precipitation, drought, and soil moisture.*

***Prof. Otis Brown** is a physical oceanographer who studies upper ocean phenomena using satellite remote sensing techniques. He is currently Dean of the Rosenstiel School of Marine and Atmospheric Science at the University of Miami and the developer of methods to derive sea-surface temperatures from radiation measurements made on the NASA Earth Observing System.*

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