



FUTURE HURRICANES could be more severe thanks to global warming.

WARMER OCEANS, STRONGER HURRICANES

Evidence is mounting that global warming enhances a cyclone's damaging winds and flooding rains *By Kevin E. Trenberth*

The summer of 2004 seemed like a major wake-up call: an unprecedented four hurricanes hit Florida, and 10 typhoons made landfall in Japan—four more than the previous record in that region. Daunted, scientists offered conflicting explanations for the increase in these tropical cyclones and were especially divided about the role of global warming in the upsurge. Then Mother Nature unleashed a record-breaking 2005 season in the North Atlantic, capped by the devastating hurricanes Katrina and Rita. But in 2006, as insurance rates in the southeastern U.S. soared, the number of North Atlantic storms dropped well below predictions. If global warming was playing a role, why was the season so quiet?

Careful analyses of weather patterns are yielding a consensus explanation for both the dramatic rises in 2004 and 2005, as well as the strangely tame 2006 season. Unfortunately, that explanation forebodes meteorological trouble over the long term.

A hurricane begins as a tropical atmospheric disturbance that may develop into an organized

system of thunderstorms. If the system begins to rotate and winds exceed 39 miles an hour, meteorologists give it a name. When the maximum wind speed exceeds 74 mph, the system is called a tropical cyclone. The synonym “hurricane” is used for such storms in the Atlantic and northeastern Pacific, “typhoon” in the northwestern Pacific, and simply “cyclone” in the Indian Ocean. In this article, I will use the terms interchangeably.

To determine whether global warming is affecting the number, size or intensity (wind speed) of hurricanes, scientists first need to understand the recipe for cooking up such storms. Over the years they have devised ever more detailed models of how hurricanes form. Hurricanes require warm water, and most take shape in the tropics where the sun beats down from almost vertically overhead. The ocean absorbs most of the incoming energy and then expels the excess heat mainly through evaporation; when the rising moisture condenses into rain, it releases latent energy, heating the atmosphere. In winter, winds carry this heat to higher latitudes

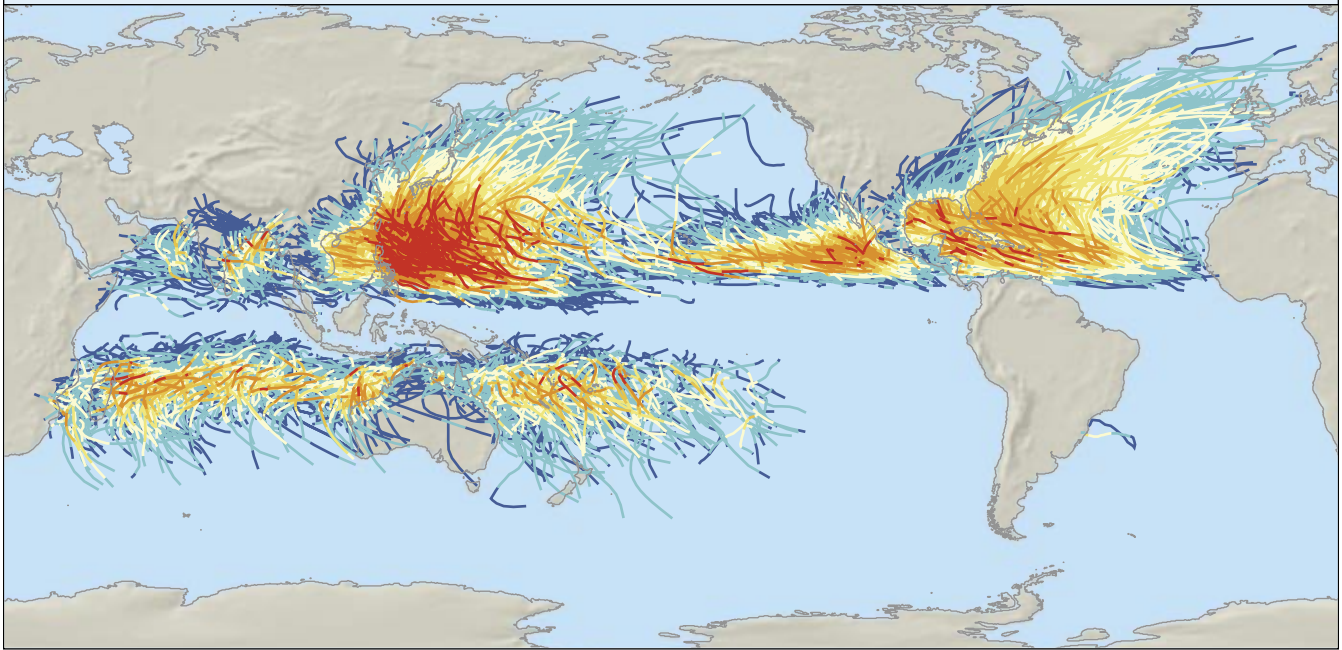
KEY CONCEPTS

- Global warming caused by human activity is raising the temperature of the world's oceans as well as increasing their evaporation. These two factors are exacerbating the strength of hurricanes.
- Even a small increase in the ocean's warmth can turn more tropical disturbances into hurricanes or pump up an existing storm's power and add to its rainfall.
- Nevertheless, the number of hurricanes in any given year is strongly influenced by the seasonal ocean patterns known as El Niño and La Niña—which calmed Atlantic cyclone activity in 2006. —*The Editors*

WHERE CYCLONES ROAM

Tracks and wind speed of all tropical storms recorded through September 2006 show the regions at highest risk.

STORM SEVERITY: Tropical depression Tropical storm Category 1 Category 2 Category 3 Category 4 Category 5



RATING STORMS BY WIND SPEED

HURRICANE CATEGORIES
(Saffir-Simpson scale)

- 5 ■ 156+ mph
- 4 ■ 131 to 155 mph
- 3 ■ 111 to 130 mph
- 2 ■ 96 to 110 mph
- 1 ■ 74 to 95 mph

TROPICAL STORM

■ 39 to 73 mph

TROPICAL DEPRESSION

■ 38 mph or less

A TROPICAL CYCLONE IS CALLED A ...

Hurricane in the Atlantic and northeastern and southern Pacific

Typhoon in the northwestern Pacific

Cyclone in the Indian Ocean and Australian region

where it can radiate to space. But in summer, the energy primarily rises through convection to higher altitudes within the tropics, creating various phenomena, from cumulus clouds to thunderstorms. Under the right circumstances, a collection of thunderstorms can organize into a vortex—a hurricane—that pumps large amounts of heat out of the ocean.

A preexisting atmospheric disturbance is needed to initiate vortex formation; in the North Atlantic, such disturbances typically slip off the west coast of central Africa, where they are often set up by temperature contrast between inland desert and forested coastal mountain regions. Other favorable conditions are also needed, including a sea-surface temperature (SST) greater than about 26 degrees Celsius (80 degrees Fahrenheit), plentiful water vapor, low pressure at the ocean surface, and weak wind shear between low and high altitudes (strong wind shear tends to tear a nascent vortex apart).

Given that sea-surface temperature is a key driver of hurricane formation, scientists wondering about the recent patterns wanted to know how SSTs may have changed over the past decades and whether the number, size and intensity of hurricanes have changed with them. If so, was global warming, now known to be caused by human activities, a major contributor? And

what was unique about conditions in 2004 and 2005 that made them record years? Scientists have long understood that mounting greenhouse gases (such as carbon dioxide from burning fossil fuels) warm the planet and can raise SSTs, as well as the production of water vapor, thereby elevating the potential for the convective activity that forms hurricanes. The question after 2005 was, Had SSTs in fact risen already and to what extent was global warming responsible?

Hotter Spawning Ground

Climatologists are not certain about the number of hurricanes that occurred worldwide before 1970, when satellite observations became routine. But they consider the record in the tropical North Atlantic quite reliable from 1944 on, when aircraft surveillance of tropical storms began. A look at that history indicated that the number of named storms and hurricanes in the North Atlantic had risen since 1994—and that, notably, the rise coincided with an increase in SSTs in a latitudinal region from about 10 to 20 degrees north. This band of tropical water just north of the equator, stretching from Africa to Central America, is the critical zone of hurricane formation.

Some scientists claim that the rise in North Atlantic SSTs since 1994 simply reflects the so-

HOW HURRICANES FORM

4 CYCLONE

Rising air dries as it loses moisture and gains energy. Some of the air dives back into the eye and into bands between adjacent thunderstorms; the rest spirals out and descends many kilometers away. Cyclones can increase ocean evaporation, and thus cooling, by an order of magnitude as compared with normal trade winds and mix the top layers of the water, producing a net cooling of sea-surface temperatures by as much as five degrees Celsius (nine degrees Fahrenheit).

3 THUNDERSTORM

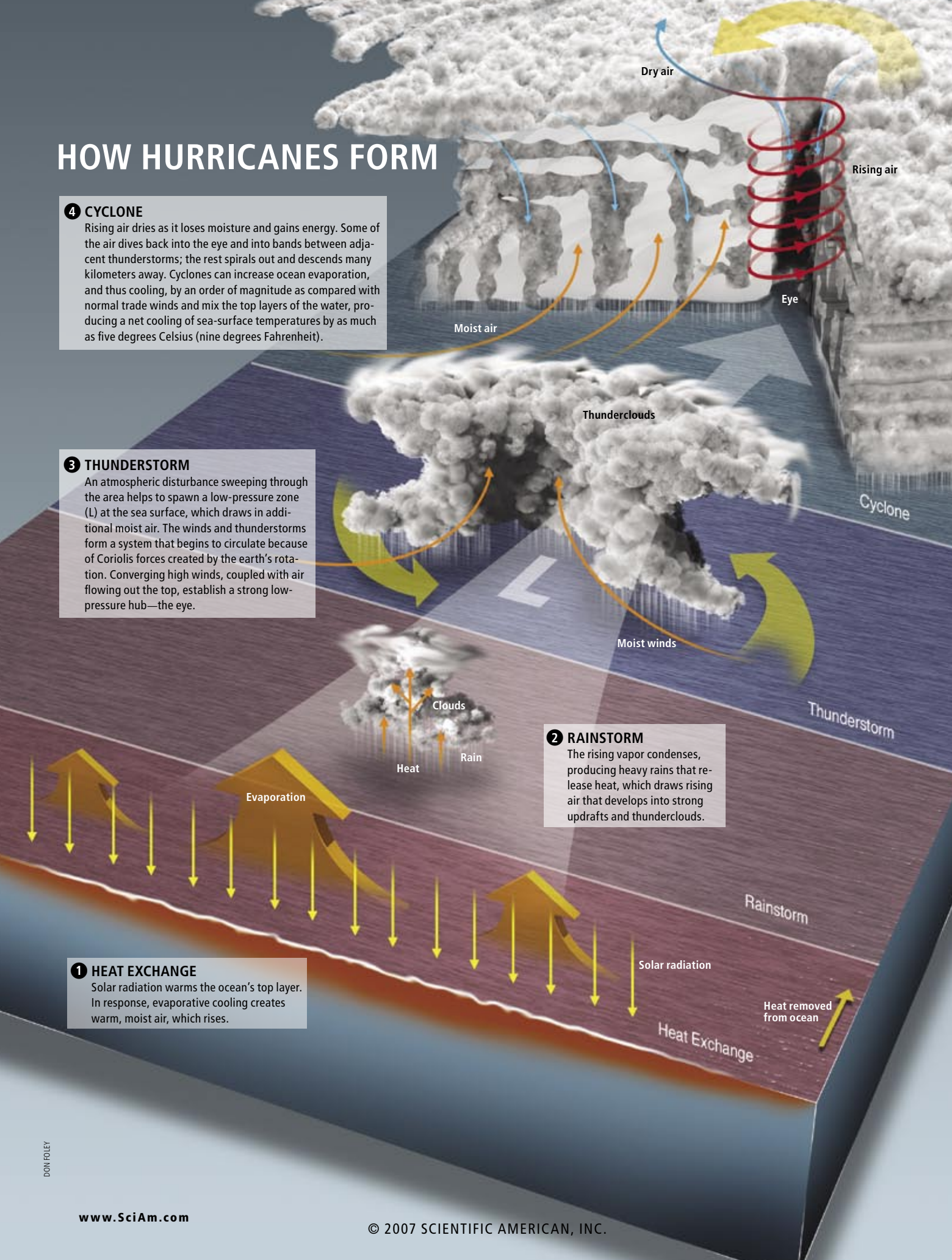
An atmospheric disturbance sweeping through the area helps to spawn a low-pressure zone (L) at the sea surface, which draws in additional moist air. The winds and thunderstorms form a system that begins to circulate because of Coriolis forces created by the earth's rotation. Converging high winds, coupled with air flowing out the top, establish a strong low-pressure hub—the eye.

2 RAINSTORM

The rising vapor condenses, producing heavy rains that release heat, which draws rising air that develops into strong updrafts and thunderclouds.

1 HEAT EXCHANGE

Solar radiation warms the ocean's top layer. In response, evaporative cooling creates warm, moist air, which rises.



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It does not take much of a change in ocean temperature to significantly affect a storm's power.

called Atlantic multidecadal oscillation (AMO). This phenomenon is a natural cycle in which North Atlantic sea temperatures remain relatively low for several decades, rise to a warmer phase for decades after that, then drift downward again (the maximum temperature difference is on the order of 0.5 degree C). Experts think the pattern results from a change in ocean currents—such as those caused by the Gulf Stream that runs across the Atlantic—and deeper return flows. From the 1970s to early 1990s, North Atlantic SSTs were low. Since then, the AMO has returned to warmer conditions, and more hurricanes have formed than arose during the cooler phase. Yet computer models indicate that the AMO cycle cannot solely explain the heightened trend since 1995 or what happened in 2005 and 2006.

Although humanity is performing a giant, uncontrolled experiment by significantly adding

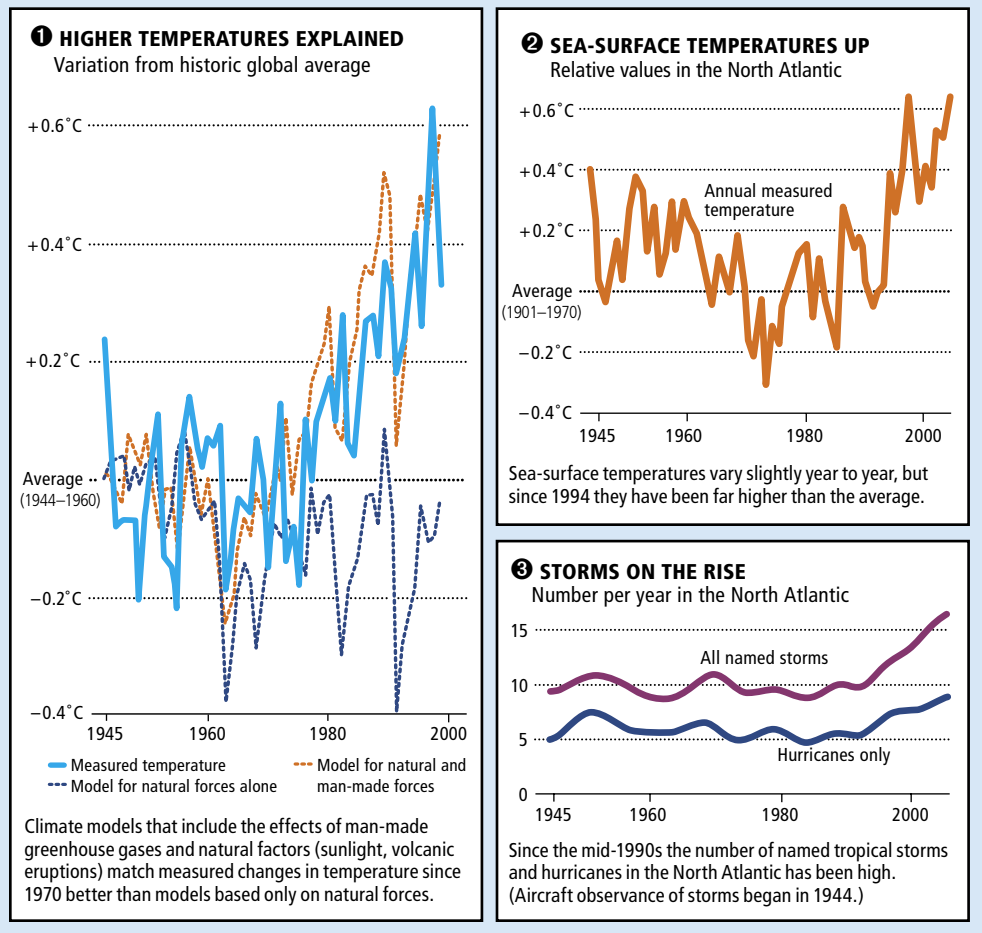
greenhouse gases to the atmosphere, climate scientists have no way to run experiments that alter the real earth. Instead climate models are needed to tease out the various factors influencing SSTs and hurricanes. These models attempt to replicate all the important physical, chemical and biological processes that affect climate. After many years of work, scientists at the National Center for Atmospheric Research (NCAR) in Boulder, Colo., and elsewhere have devised global climate models that replicate reasonably well the actual air and sea-surface temperatures recorded worldwide over the past century. The simulations take into account changes in the atmosphere's chemical composition, the sun's energy output, and conditions such as large volcanic eruptions that can block solar radiation enough to cool the planet for a year or two.

Using the models, we can isolate changes imposed by humans, such as dumping smoke and

[CAUSE AND EFFECT]

Global Warming Exacerbates Storms

As human activities raise the earth's temperature ❶, sea-surface temperatures increase ❷, leading to more hurricanes in the North Atlantic ❸.



CARLYE CALVIN/UCAR (Trenberth); JEN CHRISTIANSEN; SOURCES: KEVIN E. TRENBERTH AND GERALD MEEHL/NCAR (graphs)

pollution into the atmosphere, and assess their impact. Doing so clearly shows that warming of the Atlantic, beyond anything attributable to the AMO, has occurred and is related to atmospheric heating caused by human actions. A recent study published by climate scientist Ben Santer of Lawrence Livermore National Laboratory and his colleagues goes further, concluding that warming in both the tropical Atlantic and Pacific is attributable to increases in greenhouse gases generated by humans. Leading estimates indicate that global SSTs have risen about 0.6 degree C (one degree F) from global warming, mainly since about 1970. Although this number may sound small, it does not take much of a change to significantly affect a storm's power; as Hurricane Katrina traveled across the Gulf of Mexico, a rise or fall in SST of a mere one degree was enough to change the storm's intensity by an entire category (such as from Category 2 to 3).

Because tropical cyclone activity depends greatly on SSTs, we can conclude that global warming has led to more intense storms. I published a detailed rationale for this link in the June 2005 *Science*, and Kerry Emanuel of the Massachusetts Institute of Technology independently published direct observational evidence in *Nature* only two months later. He showed that significant increases in cyclone intensity and duration around the world since 1970 have been strongly related to rising SSTs. Challenges from other experts have led to modest revisions in the specific correlations but do not alter the overall conclusion. In September 2005 Peter Webster of the Georgia Institute of Technology and his colleagues published an article in *Science* that explicitly showed a substantial rise in the number of Category 4 and 5 hurricanes since 1970 and in the percent of total hurricanes that fit that description. They concluded that the rise was to be expected, given the observed increase in SSTs.

Why the Lull?

The record number of hurricanes in 2004 and 2005 was also in line with these conclusions. But if that is the case, why was the 2006 hurricane season so quiet? During the summer of 2005, SSTs in the tropical North Atlantic (the 10 to 20 degree north band) were at record highs. They were 0.92 degree C above the 1901 to 1970 norm, which is more than even the AMO fluctuation plus global warming can account for. What was at fault, then? The main added factor



GRETTNA, LA., just outside New Orleans, is hit by Hurricane Katrina.

was a force that operated during the preceding winter and spring: El Niño. This phenomenon is a warming of the tropical Pacific Ocean that arises when a coupling occurs between oceanic and atmospheric flows.

In the Northern Hemisphere winter of 2004 to 2005, a weak to moderate El Niño was under way. It led to sunny skies and weak winds in the tropical Atlantic, which meant less evaporative cooling, allowing the ocean to warm by an estimated additional 0.2 degree C. But the El Niño petered out by summer, minimizing wind shear in the Atlantic, which created another favorable condition for hurricane formation. The end result for 2005 was that El Niño—on top of the AMO and global warming factors—allowed a record number of hurricanes to spawn as well as grow large.

In contrast, a La Niña—marked by cooling of the tropical Pacific—took hold during the 2005 to 2006 winter, leading to much stronger than normal North Atlantic trade winds that pulled heat out of the ocean. That left SSTs slightly below or near normal levels for the 2006 hurricane season. Moreover, during the 2006 summer an El Niño began to form, contributing to greater wind shear in the Atlantic. The lower SSTs and unfavorable wind shear fundamentally changed the tropical Atlantic conditions from those of a record-breaking 2005 hurricane season to a quiet 2006 season. Although a new background of higher SSTs now exists overall, annual variabilities are superposed on that and can dominate in any given year.

WORST CYCLONES

Costliest:
Katrina, Gulf Coast, in 2005;
more than \$100 billion in damage

Deadliest:
Bhola, Ganges Delta, in 1970;
killed more than 300,000

Most Intense on Landfall:
Camille, Gulf Coast, in 1969;
maximum sustained wind speed
of 190 mph

Longest-Lasting:
John, Pacific Ocean, in 1994;
duration of 31 days

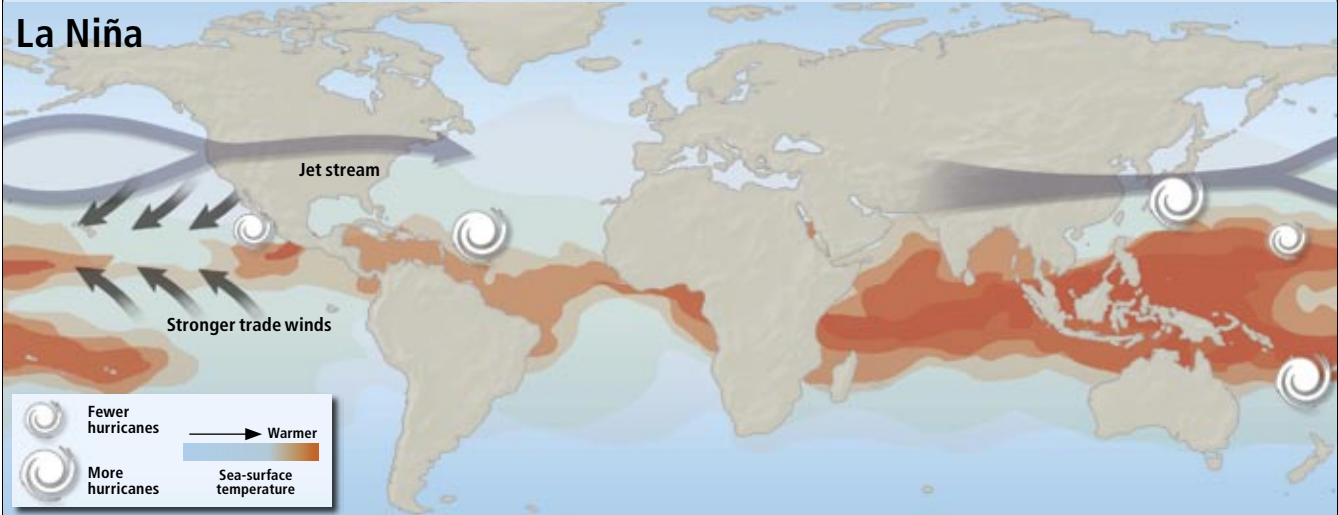
Widest:
Tip, Pacific Ocean, in 1979;
2,200 km (1,350 miles) across

THE 2006 LULL EXPLAINED

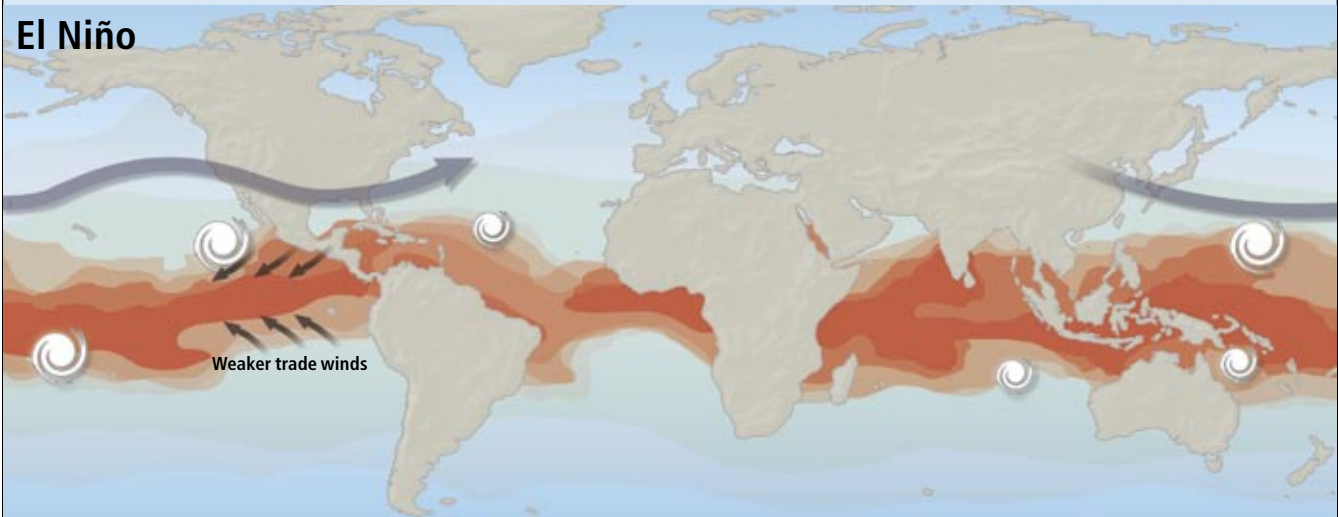
Despite warmer oceans, transient couplings between atmosphere and ocean can influence how many hurricanes form in a given year. If a La Niña (cooling of the Pacific) occurs during a Northern Hemisphere winter and spring, stronger than normal eastern Pacific trade winds pull heat from the ocean, lessening the potential energy for storms there. But the phenomenon splits the Pacific jet stream and holds the Atlantic portion to the north,

allowing hurricanes that form off of Africa to advance west toward the Caribbean. That tendency is part of what led to a record year there in 2005. If an El Niño (warming of the Pacific) grows during spring and summer, the jet stream dips south over North America, creating greater wind shear that will tear apart nascent storms that try to organize in the Atlantic. These conditions led to fewer hurricanes there in 2006.

La Niña



El Niño



More Flooding, Too

These conclusions, of course, are only as trustworthy as the observations and models that produce them. In simulating and forecasting hurricanes, at NCAR we use the so-called Weather Research and Forecasting model, which segments real-world climate data into a grid with nodes four kilometers apart—high resolution by most standards. Global simulations run by the National Weather Service have 35-kilometer resolution, and their regional models have 12- to eight-kilometer resolution. Calculating at

four-kilometer resolution requires massive computer power and long run times; weather forecasters must limit themselves to an eight-kilometer grid to make their predictions timely. Our models calculate convection effects directly.

We also have faith in our models because they have replicated features of actual storms very well when real data are fed into them, notably the storm tracks of hurricanes occurring in 2004 and 2005. When we entered SST data from the days Katrina spent over the Gulf of Mexico into our computer, the resulting mod-

eled hurricane closely matched the track of the real one.

Assured by such results, we have also tried to discern how elevated SSTs affect the amount of rain hurricanes drop. In the case of Katrina, a one degree C increase in SST raised the ambient water vapor in the atmosphere by about 7 percent. The maximum winds rose, too, transporting more moisture into the storm and furthering evaporation. Together the effects of a one degree C increase in SST raised rainfall by about 19 percent within 400 kilometers of the model storm's eye.

It is fair to say, then, that global warming increases a cyclone's rainfall. The 0.6 degree C rise in SSTs that has occurred since 1970 from global warming means that climate change has increased water vapor in the atmosphere by 4 percent over the past 37 years. Consistent with those findings, microwave instruments on satellites have observed an actual rise of 2 percent since 1988 alone. Recall that in a cyclone, the added water vapor condenses and gives up latent heat, which increases the rising air and thus the inflowing winds by a comparable amount. A 4 percent rise in water vapor can lead to an 8 percent rise in precipitation rates.

Given these calculations, we can say that of the 30 centimeters (12 inches) of rain Katrina dumped onto New Orleans, about 2.5 centimeters (one inch), or 8 percent, can be attributed to global warming. No one can declare that a given cyclone was "caused" by global warming, but heating the planet clearly influences cyclone power and precipitation.

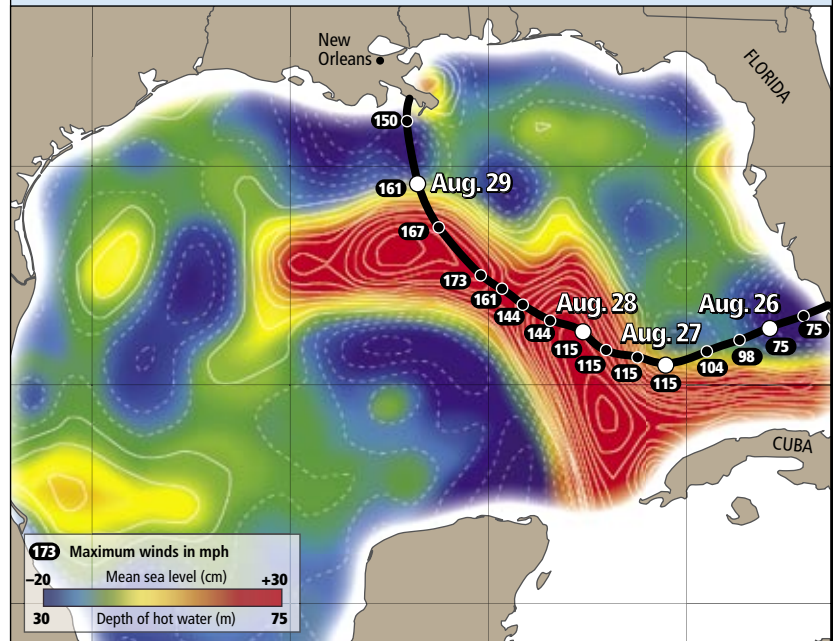
Trouble to Come

Both observations and theory therefore suggest that hurricanes are becoming more intense as the earth warms. It is difficult to say if the absolute number of cyclones is likely to increase, however, because tropical storms are much more effective than average thunderstorms at removing heat from the ocean. One big storm may also be more effective than two smaller ones, so it is possible or even likely that fewer cyclones might form, with those that do arise being larger and more intense. Once a strong storm is over, it leaves a cooler ocean behind, lowering the likelihood that more storms will flare up, at least immediately.

Questions remain about past observational data about storms, too; some scientists say that the historical data are too inconsistent to allow firm conclusions. Others say the data for the

HOT WATER FIRES UP STORMS

A cyclone mixes the ocean's top layer of water, down to 100 meters deep. After crossing Florida on August 26, 2005, Hurricane Katrina was barely a Category 1. But it latched onto a deep reservoir of warm water known as a loop current (red), which featured raised sea level and provided huge stores of energy as it mixed, pumping Katrina up to Category 5 in fewer than three days.



North Atlantic are solid (at least since 1944) but are less certain for the Pacific. One helpful step would be to reprocess all the satellite data that are stored in archives using modern techniques, to eke out more consistent information on past storm intensity, size, duration and other metrics of activity. Faster computers will further improve modeling, as will new knowledge from expanded field experiments. These advances will better establish how well our models perform and thus how credible they are in projecting the future.

Nevertheless, the continually improving scientific record indicates that global warming is raising sea-surface temperatures. That rise, in turn, will probably bolster the intensity of hurricanes, including those that target the Americas. In its landmark report in May, the Intergovernmental Panel on Climate Change concluded that "there is observational evidence for an increase of intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea-surface temperatures." As we continue to improve our models and observations, we all would be wise to plan for more extreme hurricane threats. ■

MORE TO EXPLORE

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