WHAT'S GOING ON HERE?

OCEANS LASH OUR COASTS. DESERTS BURN. THE SKY PROVIDES NO SHELTER. TURMOIL OF BIBLICAL PROPORTIONS THREATENS NOT JUST OUR WEATHER BUT LIFE ITSELF. GLOBAL WARMING IS UPON US

In the final days of 2004 the cities of the world received some astonishing news: Beginning at its northern tip, Antarctica was turning green. Antarctic hair grass (*Deschampsia antarctica*) is one of just two kinds of higher plants that occur south of the 56th degree of latitude. Hitherto it had barely eked out a living as sparse tussocks crouched behind the north face of a boulder or some other sheltered spot. Over the southern summer of 2004, however, great green swards of the stuff began to appear, forming extensive meadows in what was once the home of the blizzard.

Climate change is a breaking story. Just over 30 years ago climatologists were at loggerheads about whether the earth was warming or cooling, unable to decide whether an icehouse or a greenhouse future was on the way. By 1975, however,

THE EMISSION OF GREENHOUSE GASES... IS CAUSING GLOBAL WARMING AT A RATE THAT BEGAN AS SIGNIFICANT, HAS BECOME ALARMING AND IS SIMPLY UNSUSTAINABLE IN THE LONG TERM. AND BY LONG TERM I DO NOT MEAN CENTURIES AHEAD. I MEAN WITHIN THE LIFETIME OF MY CHILDREN, CERTAINLY, AND POSSIBLY MY OWN. AND BY UNSUSTAINABLE I DO NOT MEAN A PHENOMENON CAUSING PROBLEMS OF ADJUSTMENT. I MEAN A CHALLENGE SO FAR-REACHING IN ITS IMPACT AND IRREVERSIBLE IN ITS DESTRUCTIVE POWER THAT IT ALTERS RADICALLY HUMAN EXISTENCE.... THERE IS NO DOUBT THAT THE TIME TO ACT IS NOW.
—U.K. PRIME MINISTER TONY BLAIR

BY TIM FLANNERY

In the shadow of an iceberg, a crabeater seal hunts for plankton off the Antarctic coast. According to the National Snow and Ice Dat Center, 150 miles of Antarctic coastline have changed dramatically during the past 16 years. The most notable shift occurred in 2002 wi the collapse of the Larsen B ice shelf, an area of surface ice almost the size of Rhode Island, on the eastern edge of the continent.

the first sophisticated computer models were suggesting that a doubling of carbon dioxide (CO_2) in the atmosphere would lead to an increase in global temperature of around five degrees Fahrenheit. Still, concern among scientists was not significant. There was even a period of optimism when some researchers believed that extra CO_2 in the atmosphere would fertilize the world's croplands and produce a bonanza for farmers. But by 1988 climate scientists had become sufficiently worried about CO_2 to establish a panel staffed with the world's leading experts to report twice each decade on the issue. Their third report, issued in 2001, sounded a note of sober alarm, yet many governments and industry leaders were slow to take an interest. Even today the general public is unaware of the increasing number of danger signs that are harbingers of the monumental changes looming in our planet's near future.

What follows is a concise survey of just some of these monumental changes: the melting of ice near the poles, which has the potential to disrupt aquatic food chains and lead to the extinction of polar bears, penguins, seals and whales; an elevation of temperatures in other regions, which could lead to the extinction of perhaps half the species of animal life; and an increase in ocean temperatures, which will bring greater rainfall and flooding to some regions and an increase in the number and ferocity of hurricanes in others. These changes will cause loss of life, an impoverishment of our natural heritage, economic disruption and social disorder. New Orleans after Katrina will be just the start.

DISAPPEARING ICE

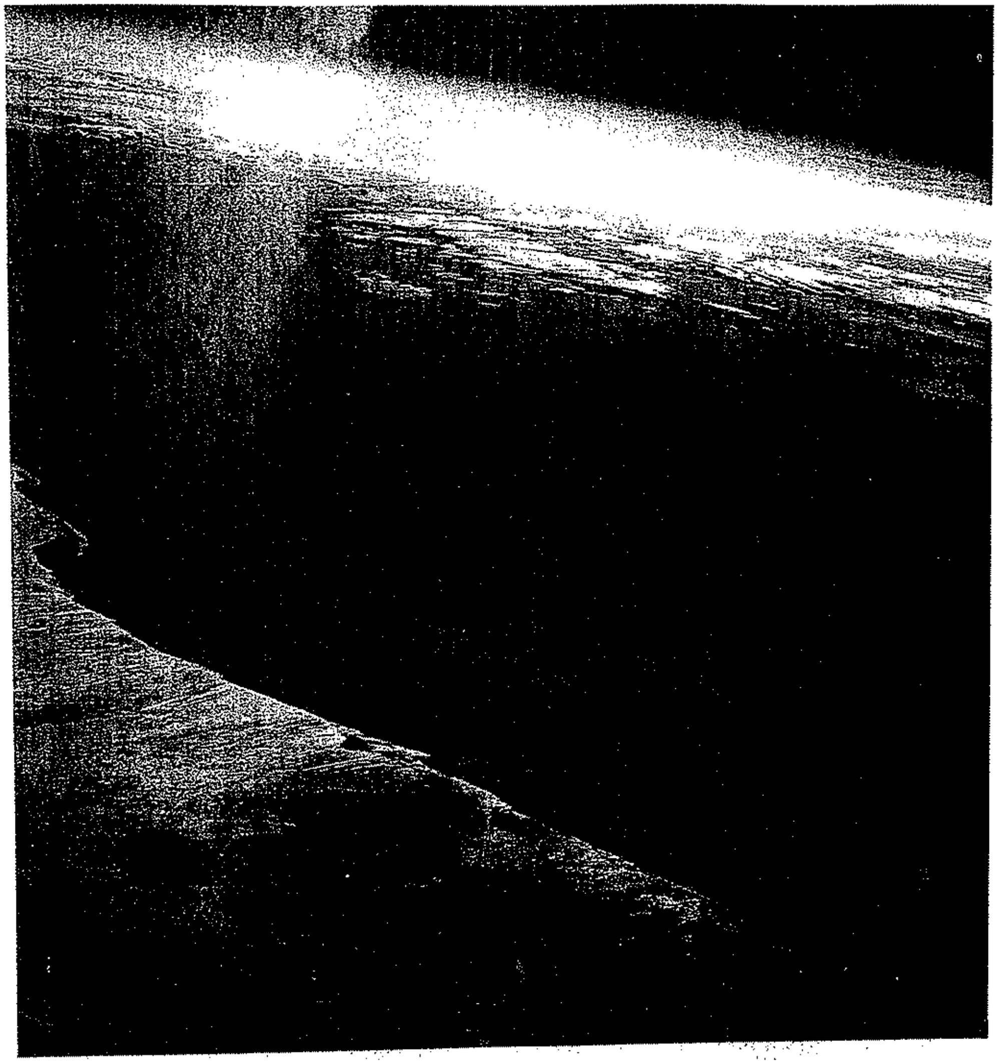
It's hard to imagine anything more emblematic of the transformations occurring at the ends of our earth than the greening of Antarctica. Climate change is occurring now at the poles at twice the rate seen anywhere else. Yet terrestrial changes pale into insignificance whe compared with those occurring at sea for the sea ice is disappearing.

The subantarctic seas are some of th richest on earth, and there is a genu ine paradox here because that richnes exists despite an almost total absenc of the nutrient iron. The presence of se ice somehow compensates for this. Th semifrozen edge between the saltwate and floating ice promotes remarkabl growth of the microscopic plankton tha is the base of the food chain. Despit months of winter darkness, plankto thrives under the ice, allowing the kril that feed on it to complete their seven year life cycle. And wherever krill are i abundance, penguins, seals and grea whales are likely to be present. Indeed so miraculous is the influence of sea ice on plankton—and therefore on kril and the creatures they feed—that there is almost as much difference betweer the ice-covered and ice-free portions o the Southern Ocean as there is betweer the sea and the near-sterile Antarctic continent itself.

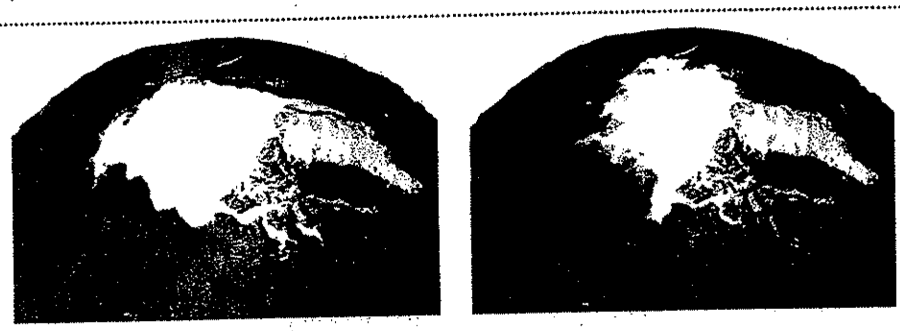
Angus Atkinson of the British Antarctic Survey is deeply interested in the relationship between plankton, krill and the mammals that feed on them. Atkinson and his colleagues examined records of krill catches from the research vessels of eight countries working in the southwest Atlantic sector of the Southern Ocean. This is the true home of the krill; more than half their total southern hemisphere population resides here. Atkinson and his colleagues found a significant decline in krill numbers since the late 1970s, at a rate of nearly 40 percent a decade. As Atkinson and his colleagues tell us, "This is not a localized, short-term effect; it relates to around 50 percent of the [krill] stock, and the data span 1926 to 2003."

Year-to-year population appeared to fluctuate with the extent of sea ice the previous winter; extensive sea ice meant plenty of winter food for the krill. Research reveals that the extent of sea ice was stable from 1840 to 1950 but has sharply decreased to such an extent that the northern boundary of the ice has shifted southward, from latitude 59.3 degrees south to 60.8 degrees south. This corresponds to a 20 percent decrease in sea ice extent. The reduction in krill numbers, plus the link between krill abundance and winter sea ice cover, suggests that climate change is threatening the world's most enigmatic ocean and the unique creatures that exist and feed there.

Already there are signs that some Antarctic fauna are feeling the pinch. The emperor penguin population is half what it was 30 years ago, while the number of Adélie penguins has declined by 70 percent. Such studies suggest that in the near future a point will be reached at which one krill-dependant species after another will be unable to feed. The humpbacks that traverse the world's oceans likewise will no longer be able to fill their capacious bellies nor will the innumerable seals and penguins that cavort in southern seas. Instead we'll have an ocean full of jellylike salps (a nutrient-poor species thriving in the wake of disappearing plankton), the ultimate inheritors of a defrosting cryosphere.



A light-blue plankton bloom appears in the southern Atlantic (above). The size of the plankton population is linked to the amount of sea ice in the Southern Ocean. As plankton declines, so does the quantity of the nutrient-rich krill (bottom) that feed on it, a trend that threatens krill-dependent species such as penguins, seals and whales. Meanwhile the ice cap at the north pole has been receding rapidly. Below, satellite images from 1979 and 2003.



THE LAST OF THE POLAR BEARS

The Arctic is a region that is almost a mirror image of the south, for while the Antarctic is a frozen continent surrounded by an immensely rich ocean, the Arctic is a frozen ocean almost entirely surrounded by land. It's also home to 4 million people, which means it is better studied. Most of the Arctic's inhabitants live on its fringe, and there, in places such as southern Alaska, winters are 4°F to 5°F warmer than they were just 30 years ago.

Fossil-fuel-fired power plants release CO_2 into the atmosphere (above). As CO_2 increases, so does the amount of moisture in the air, which then traps radiant heat. This phenomenon is only partially offset by the cooling effect of sunlight-reflecting cumulus clouds.

If anything symbolizes the Arctic, it is surely *nanuk*, the great white bear. He is a wanderer, a hunter and a fair match for man in the white infinity of his polar world. Every inch of the Arctic lies within his grasp: *Nanuk* has been sighted 1.2 miles up on the Greenland ice cap; he has been found denning at the bottom of the Hudson Bay, at a latitude of just 53 degrees north, and purposefully striding the ice within 100 miles of the true pole itself. "I used to think the land would stop them," remarked Canadian polar bear biologist Ray Schweinsburg, "but I think they can cross any terrain. The only thing that stops them is a place where there is no food." And for polar bears, having sufficient food to live means having lots of sea ice.

Polar bears, it's true, will deign to catch lemmings or scavenge dead birds if the opportunity presents itself, but sea ice and *netsik*, the ringed seal that lives and breeds there, are at the core of the creature's economy.

The plight of the harp seals (*Pagophili groenlandici*) living in the Gulf of St. Lawrence gives us a clear idea of the shape of things to come. Like the ringed seal, the harp seal can raise no pups when little or no sea ice is present—which happened in 1967, 1981, 2000, 2001 and 2002. The run of pupless years that opened this century is worrying. When the run of ice-free years exceeds the reproductive life of a female ringed seal—perhaps a dozen years at most—the Gulf of St. Lawrence population, which is genetically separate from the rest of the species, will become extinct. Ringed, ribbon and bearded seals also give birth and nurse on the sea ice. Even the mighty walrus lives under the spell of the frozen sea, for the highly productive ice edge is its prime habitat.

The great bears are slowly starving as each winter becomes warmer than the one before. A long-term study of 1,200 bears living in the south of their range around the Hudson Bay reveals that they are already 15 percent skinnier on average than they were a few decades ago. The feeding season has become too short for the bears to find enough food, and 15 percent is a lot of body fat to lose before hibernation. With each year, starving females give birth to fewer cubs. Some decades ago triplets were common; they are now unheard of. And back then around half the cubs were weaned and feeding themselves at 18 months; today the number is fewer than one in 20. Even females that successfully give birth face dangers unknown in times past. Increasing winter rains in some areas may collapse birthing dens, killing the mother and cubs sleeping within, and the early breakup of the ice can separate denning and feeding areas. When young cubs cannot swim the distances required to find food, they will simply starve to death.

As Schweinsburg says, the only thing that stops *nanuk* is a place where there is no food. And in creating an Arctic with dwindling sea ice, we are creating a monotony of open water and dry land where, for *nanuk* at least, there *is* no food. Without a thick fall of snow, he has nowhere to make his winter den, and without ice, snow and *nanuk*, what will it mean to be Inuit—the people who named him and who understand him like no other? When *nanuk* is fit and well fed he will strip the blubber from a fat seal, leaving the rest to a retinue of camp followers including the arctic fox, the raven, and the ivory and glaucous Thayer's gulls. At certain times and places many of these creatures depend on *nanuk*, for there is no other giver of bounty in this forbidding land. As the Arctic fills with hungry white bears, what will become of these lesser creatures? Some, such as the ivory gull and little auk, also depend on sea ice. Indeed the ivory gull has already declined by 90 percent in Canada in the past 20 years and will not see out the century if that rate continues. It looks as if the loss of *nanuk* may mark the beginning of the collapse of the entire Arctic ecosystem.

If nothing is done to limit greenhouse gas emissions, it seems certain that sometime this century a day will dawn when no summer ice will be seen in the Arctic—just a vast, dark, turbulent sea. My guess is that the world will not have to wait even that long to be done with *nanuk*, for before the last ice melts, the bears will *(continued on page 68)*

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In a few decades' time there will be no glaciers left in America's Glacier National Park.

have lost their constellation of den sites, feeding grounds and migration corridors, without which they cannot breed. Perhaps a cohort of elderly bears will linger on, each year becoming thinner than they were the previous. Or perhaps a dreadful summer will arrive when the denning seals are nowhere to be found. A few ingenious hunters may eke out a living on a diet of lemming, carrion and sea-caught seals, but they'll be so thin that they will not wake from winter's sleep.

GLACIAL MELT

The changes we're witnessing at the poles are of the runaway type, meaning that unless greenhouse gases can be limited—and quickly—there will be no winners among the fauna and flora unique to the region. Instead we should expect that the realm of the polar bear, narwhal and walrus will simply be replaced by the largest habitat on earth—the great temperate forests of the taiga and the cold, ice-free oceans of the north. In areas where forest does not take over, increasing temperatures (and thus increasing evaporation) will give rise to polar deserts, for surprisingly large areas of the Arctic receive very little precipitation.

All that remains of the great northern hemisphere ice caps today is the Greenland ice sheet, the sea ice of the Arctic Ocean and a few continental glaciers, and some signs suggest these 8,000-year-old remnants are beginning to melt away. Alaska's spectacular Columbia Glacier has retreated 7.5 miles in the past 20 years, and in a few decades' time there will be no glaciers left in America's Glacier National Park. In summer 2002 the Greenland ice cap, along with the Arctic ice cap, shrank by more than 386,000 square miles, the largest decrease ever recorded. Two years later it was discovered that Greenland's glaciers were melting 10 times faster than previously thought.

The greatest extent of ice in the northern hemisphere is the sea ice covering the polar sea, and since 1979 its extent in summer has contracted by 20 percent. Furthermore the remaining ice has greatly thinned. Measurements taken using submarines reveal that it is only 60 percent as thick as it was four decades earlier. This prodigious melting, however, does not result in rising seas any more than a melting ice cube raises the level of liquid in a glass of scotch.

Although the melting of the sea ice has no direct effect on sea levels, its indirect effects are important. At its current rate of decline, little if any of the Arctic ice cap will be left by the end of this century, and this will significantly change the earth's albedo, the rate at which it reflects light. One third of the sun's rays falling on earth are reflected back to space. Ice, particularly at the poles, is responsible for much of that albedo, for ice reflects into space up to 90 percent of the sunlight hitting it. Water, in contrast, is a poor reflector. When the sun is overhead, water reflects a mere five to 10 percent of light back to space, though as you may have noticed while watching a sunset by the sea, the amount increases as the sun approaches the horizon. Replacing Arctic ice with a dark ocean will result in a lot more of the sun's rays being absorbed at the earth's surface and reradiated as heat, creating local warming that, in a classic example of a positive feedback loop, will hasten the melting of the remaining continental ice.

PEOPLE IN GREENHOUSES

If you want a visceral understanding of how greenhouse gases work, visit New York City in August. It's a time of year when the heat and humidity leave those who still trudge the streets in a lather. Trapped in a crowded, built-up environment of concrete, hard edges, parched asphalt and sticky human bodies, the heat feels so unhealthful that it is almost insupportable. And the worst of it comes at night, when humidity and a thick layer of clouds lock in the heat.

Suddenly you'll long to be in a dry, clear desert where no matter how hot the day, the clear skies at night bring blessed relief. The difference between a desert and New York City at night is a single greenhouse gas, the most powerful of them all: water vapor.

It's testimony to human ignorance that as recently as 30 years ago, less than half the greenhouse gases had been identified and scientists were still divided about whether the earth was warming or cooling. Yet without these gas molecules our planet would be dead cold, a frigid sphere with an average surface temperature of –4°F. But we *have* known for some time that these gases have been accumulating. Scientists now recognize the indisputable fact that since 1950 the temperature of the earth has increased by 1°F, and it will continue to rise.

Carbon dioxide is the most abundant of the "trace" greenhouse gases, and it's produced whenever we burn something or when things decompose. In the 1950s a climatologist named Charles Keeling climbed Mauna Loa in Hawaii to record CO_2 concentrations in the atmosphere. From this study he created a graph known as the Keeling curve, which is one of the most wonderful things I've ever seen. In it you can see our planet breathing. During every northern spring, as the sprouting greenery extracts CO_2 from our atmosphere, the great aerial ocean, our earth begins a massive inspiration, which is recorded on Keeling's graph as a fall in CO_2 concentration. Then in the northern autumn, as decomposition generates CO_2, there is an exhalation that enriches the air with the gas. But Keeling's work revealed another trend. He discovered that each exhalation left a little more CO_2 in the atmosphere than the one before. This innocent perkiness in the Keeling curve was the first definitive sign that the great aerial ocean might prove to be the Achilles' heel of our fossil-fuel-addicted civilization. Looking back I see that graph as the *Silent Spring*—the best-selling book that helped kick-start the grassroots environmental movement—of climate change. One need do nothing more than trace the graph's trajectory forward in time to realize that the 21st century would see a doubling of CO_2 in the atmosphere, from the three atoms per 10,000 that existed in the early 20th century to six. And that increase has the potential to heat our planet by around 5°F and perhaps by as much as 11°F.

When scientists first realized that levels of CO_2 in the atmosphere were linked to climate change, some were puzzled. They knew that CO_2 absorbs radiation only at wavelengths longer than about 12 microns (a human hair is around 70 microns thick) and that a small amount of the gas captured all the radiation available at those bandwidths. In experiments, increasing its concentration seemed to cause no real difference in the amount of heat trapped. Besides, there was so little of the gas it seemed inconceivable that CO_2 could change the climate of the entire planet. What scientists did not commonly realize then is that at very low temperatures—such as those found over the poles and high in the atmosphere—more heat travels at the bandwidths where CO_2 is most effective. Most important, they discovered that rather than being the sole agent responsible for climate change, CO_2 acts as a trigger for that potent greenhouse gas, water vapor. It does this

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by heating the atmosphere just a little, allowing it to take up and retain more moisture, which then warms the atmosphere further. So a positive feedback loop is created, forcing our planet's temperature to even higher levels.

Although it is a greenhouse gas, water vapor is also an enigma in the climate-change arena, for it forms clouds, which can both reflect light energy and trap heat. By trapping heat more than they reflect light, high thin clouds tend to warm the planet; low thick clouds have the reverse effect. No single factor contributes more to the uncertainty of future climate-change predictions.

Many greenhouse gases are in some way or another generated by human activity. Although scarce and weak in its capacity to capture heat, CO_2 remains in the atmosphere a long time: Around 56 percent of all the CO_2 that humans have liberated by burning fossil fuel is still aloft, which is the cause—direct and indirect—of around 80 percent of all global warming.

OVERSPENDING THE CARBON BUDGET

The fact that a known proportion of CO_2 remains in the atmosphere allows us to calculate in very round numbers a carbon budget for humanity. Prior to the start of the Industrial Revolution there were about 280 parts per million of CO_2 in the atmosphere, which equates to around 586 gigatons of CO_2. (Figures such as these relate only to the carbon in the CO_2 molecule. The actual weight of the CO_2 would be 3.7 times greater.) Today the figures are 380 parts per million, or around 790 gigatons. If we wished to stabilize CO_2 emissions at twice the level that existed before the Industrial Revolution (widely considered the threshold of dangerous change), we would have to limit all future human emissions to around 600 gigatons. Just over half of this would stay in the atmosphere, raising CO_2 levels to around 1,100 gigatons, or 550 parts per million, by 2100. This, incidentally, would be a tough budget for humanity to abide by, for if we use fossil fuels for only another century, that equates to a budget of six gigatons a year. Compare this with the average of 13.3 gigatons of CO_2 that accumulated each year throughout the 1990s (half of this from burning fossil fuel), and add the projection that the human population is set to rise to 9 billion by mid-century, and you can see the problem.

Our servants, the billions of engines we've built to run on fossil fuels such as coal, gasoline, oil-based fuels and natural gas, play the leading role in manufacturing CO_2. Most dangerous of all are power plants that use coal to generate electricity. Black coal (anthracite) is composed of at least 92 percent carbon, while dry brown coal is around 70 percent carbon and five percent hydrogen.

Carbon and oxygen, the components of CO_2, are close neighbors on the periodic table, meaning they have similar atomic weights. Because two oxygen atoms combine with one carbon atom to form CO_2, around three and a half tons of the gas are created for every ton of anthracite consumed. Some power plants burn through 500 tons of coal an hour, and so inefficient are they that around two thirds of the energy created is wasted. And to what purpose is the coal burned? Simply to boil water, which generates steam that moves the colossal turbines to create the electricity that powers our homes and factories. Like the atmosphere itself, these Dickensian machines are invisible to most of us, who have no idea that 19th century technology makes 21st century gadgets whir.

The places that the carbon goes when it leaves the atmosphere are known as carbon sinks. You and I and all living things are carbon sinks, as are the oceans and some of the rocks under our feet. Some of these sinks are very large, but they are not infinite, nor is their size steady through time. Over aeons much CO_2 has been stored in the earth's crust. This occurs as dead plants are buried and carried underground, where they become fossil fuels. On a shorter time scale, a lot of carbon can be stored in soil, where it forms the black mold beloved of gardeners.

For the past couple of decades scientists have been monitoring where the CO_2 that humans produce by burning fossil fuels goes. They can do this because the gas derived from fossil fuels has a unique chemical signature and can be tracked as it circulates around the planet. In very round figures, two gigatons is absorbed by the oceans and a further 1.5 gigatons is absorbed by life on land annually. The contribution made by the land results partly from an accident of history: America's frontier phase of development, which gave some land plants a ravenous hunger for carbon. Mature forests don't take in much CO_2 because they are in balance, releasing CO_2 as old vegetation rots, then absorbing it as new vegetation grows. For these reasons the world's largest forests, the coniferous ones of Siberia and Canada and the tropical rain forests, are not good carbon sinks, but new, vigorously growing forests are.

THE MAGIC GATES

Global warming changes the climate in jerks, during which climate patterns jump from one stable state to another. Because of the atmosphere's telekinetic nature, these changes can manifest themselves instantaneously across the globe. The best analogy is perhaps that of a finger on a light switch. Nothing happens for a while, but if you slowly increase the pressure, a certain point is reached, a sudden change occurs, and conditions swiftly alter from one state to another.

Climatologist Julia Cole refers to the leaps made by the climate as "magic gates," and she argues that since temperatures began rising rapidly in the 1970s our planet has seen two such events, in 1976 and 1998. These dates are important, for again and again they mark the onset of remarkable phenomena.

Between 1945 and 1955 the temperature of the surface of the tropical Pacific commonly dipped below 67°F, but since the magic gate opened in 1976 it has rarely been below 77°F. The central Pacific is an important location because it is where El Niños, which are a major climate force across the globe, are first detected. "The western tropical Pacific is the warmest area in the global ocean and is a great regulator of climate," says Martin Hoerling of the Earth System Research Laboratory in Boulder, Colorado. Among other things, that area controls most tropical precipitation and the position of the jet stream, whose winds bring snow and rain to North America. In 1977 *National Geographic* ran a feature on the crazy weather of the previous year, which included unprecedented mild conditions in Alaska and blizzards in the lower 48 states.

The 1998 magic gate is also tied up with the El Niño–La Niña cycle, a two-to-eight-year cycle that brings extreme climatic events to much of the world. During the La Niña phase, which until recently seemed to be the dominant part of the cycle, winds blow westward across the Pacific, accumulating the warm surface water off the coast of Australia and islands lying to its north. With the warm surface waters blown westward, the cold Humboldt Current is able to surface off the most prolific fishery in the world, the anchoveta. The El Niño part of the cycle begins with a weakening of tropical winds, allowing the warm surface water to flow back eastward, overwhelming the Humboldt and releasing humidity into the atmosphere that brings floods to the normally arid Peruvian deserts. Cooler water now upwells in the far western Pacific, and because it does not evaporate as readily as warm water, drought strikes Australia and southeast Asia. When an El Niño is extreme enough, it can afflict two thirds of the globe with droughts, floods and other extreme weather.

The 1997–98 El Niño year was immortalized by the World Wide Fund for Nature (now the WWF) as "the year the world caught fire." Drought had a stranglehold on a large part of the planet, and fires burned on every continent, but in the normally wet rain forests of southeast Asia the conflagrations reached their peak. There more than 10 million hectares burned, of which half was ancient rain forest. On the island of Borneo 5 million hectares were lost—an area almost the size of the Netherlands. Many of the burned forests will never recover on a time scale meaningful to human beings, and the impact of this on Borneo's unique fauna will, in all probability, never be fully known.

Climatologist Kevin Trenberth and his colleagues believe that the 1997–98 event was an extreme manifestation of the more general impact global warming has had on the El Niño–La Niña cycle. Ever since 1976 the cycles have been exceptionally long—one would expect such long cycles only once in several years—and there has been an imbalance between the phases, with five El Niños and only two La Niñas. Computer-based modeling supports their research, indicating that as greenhouse gas concentrations increase in the atmosphere, a semipermanent El Niño–like condition will result.

Indeed, some of the changes spawned in 1998 were permanent; ever since then the waters of the central western Pacific have frequently reached 86°F, while the jet stream has shifted toward the north pole. So the question is, how has our changing climate affected various plant and animal populations?

One of the most powerful tools available to researchers wishing to document the response of nature to climate change is the jottings of birders, fishermen and other nature watchers. Some of these records are very long; one English family recorded the date of the first frog and toad croaks it heard on its estate every year between 1736 and 1947. This type of record is of the utmost importance in revealing how things stood when the curtain separating the stable climate of the past 8,000 years from our brave new future began to lift. In 2003 the journal *Science* published a huge study drawing on such natural-history observations that reveals the immense scale of the shifts now under way.

The database has information on more than 1,700 historically recorded species. The information includes etailed records of the migration, reeding habits and distribution of rds compiled by amateur birdwatch-s, the jottings of botanists about the owering and shooting of plants, and iptains' logs from whaling ships.

Prior to 1950 there is little evidence f any trend, but since that date, a very rong pattern has emerged around the lobe. This manifests itself as a pole-ard shift in species' distribution of, on verage, around four miles a decade, a etreat up mountainsides of 20 feet a ecade and an advance of spring activ-y by two days a decade. These trends ccord so strongly with the scale and irection of temperature increases rought about by greenhouse gas emis-ions that they have been hailed as con-tituting a globally coherent fingerprint f climate change. While such trends nay seem small when compared with he rate of change seen over geological time, they are in fact so rapid and decisive, it's as if the researchers had caught CO_2 in the act of driving nature poleward with a lash.

HURRICANE WATCH

In the troposphere—the lowest atmospheric layer, which extends from the earth's surface to around seven miles up and is the most influential on global weather patterns—ever-increasing levels of greenhouse gases are trapping more heat, causing it to expand.

As the troposphere has warmed in the past decade, the world has seen the most powerful El Niño ever recorded (1997–98), the most devastating hurricanes in 200 years (Mitch, in 1998, followed by Katrina, in 2005), the hottest European summer on record (2003), the first south Atlantic hurricane ever recorded (2002) and one of the worst storm seasons ever experienced (2005). This series of events, many would argue, indicates that the potential for the new climate to generate extremes is already increasing.

Where do you think the energy to power a hurricane comes from? "A hurricane," Frederick Lutgens and Edward Tarbuck tell us in their atmospheric-studies textbook, "is a heat engine that is fueled by the latent heat liberated when huge quantities of water vapor condense. To get this engine started, a large quantity of warm, moist air is required, and a continuous supply is needed to keep it going." We're all familiar with the principle that evaporation can carry heat into the atmosphere: On a hot day we all perspire, and as our sweat evaporates it carries heat from our body into the air. It's a highly effective form of heat transfer, for the evaporation of just one gram of water from our skin is sufficient to transfer 580 calories of heat. Think of the difference in scale between your body and an entire ocean and you can sense the power that heat energy derived from evaporation carries into the atmosphere.

It's not widely appreciated just how much extra latent heat the hot air engendered by climate change can carry. For every 18°F increase in temperature, the amount of water vapor the air can hold doubles; thus air at 86°F can hold four times as much hurricane fuel as air at 50°F.

There are disturbing signs that hurricanes are becoming more frequent in North America. Hurricane Mitch tore through the Caribbean in October 1998, killing 10,000 people and making up to 1 million homeless. With its wind speeds reaching 180 miles an hour, Mitch was the fourth strongest Atlantic Basin hurricane ever recorded, along with 1969's Camille. At the time, Mitch was the most damaging storm to hit the Americas in 200 years, but the severity of its impact was surpassed a mere seven years later when Hurricane Katrina swamped New Orleans. It was with remarkable prescience that the U.S. National Weather Service predicted that the 2005 hurricane season was likely to be more destructive than usual.

Many of the homes damaged by these storms are still uninhabitable. With hurricane fuel increasing in the atmosphere, it is only a matter of time before the storms return with redoubled fury.

Anyone looking only at the number of hurricanes that occur in the Americas each year may think Katrina and Rita are just part of a natural cycle. This is because there are cycles in Atlantic hurricane activity that mask more significant trends. By affecting the Gulf Stream, the Atlantic Multidecadal Oscillation brings variations in hurricane activity every 60 to 70 years. Another cycle alters hurricane activity each decade or so. Both cycles have complex causes relating to ocean currents and the state of the atmosphere.

Many of the most devastating impacts of any individual hurricane are unrelated to global warming. Whether Katrina was a little weaker or stronger, whether it struck 30 miles or 100 miles from the city and whether it struck a week earlier or later are all matters of chance. But equally, evidence is growing that global warming is changing the conditions in the atmosphere and oceans in ways that will make hurricanes even more destructive in the future.

The impact of climate change on the later phases of the hurricane life cycle is more certain than its effect on the initial formation of storms. Satellite measurements reveal that the oceans are rapidly warming from the top down as the result of additional heat coming from the atmosphere. Already the oceans have warmed on average by just under 1°F, though some areas, such as the Gulf of Mexico, have warmed far more. (During the summer of 2005 the surface waters of the northern Gulf were exceptionally hot—around 87°F.) In response to this, the amount of water vapor—hurricane fuel—in the air over the oceans has increased by 1.3 percent per decade since 1988. Both the warmer ocean and the increased water vapor augment the energy available for all manner of storms, from thunderstorms to hurricanes. But they are especially important in transforming tropical storms into hurricanes and in feeding category 1 hurricanes so they become category 5s. With this enhancement of hurricane fuel, Katrina was an accident just waiting to happen.

What is increasingly perplexing and astonishing to meteorologists is that, in the real world, we are already seeing an increase in hurricane intensity and numbers far in advance of that suggested by computer modeling. Kerry Emanuel of the Massachusetts Institute of Technology has found that the total amount of energy released by hurricanes worldwide has increased by 60 percent in the past three decades. And Peter Webster of the Georgia Institute of Technology in Atlanta has discovered that more of that energy is going into the most powerful hurricanes. Since 1974 the number of category 4 and 5 hurricanes recorded has almost doubled.

Some commentators believe that the discrepancy between the computer models and conditions in the real world somehow indicates that global warming is not responsible for the increasing hurricane activity. Others, however, believe it suggests what they have long suspected: that the global circulation models used to simulate future changes in climate are deeply conservative. If those latter researchers are correct, the current heat imbalance of the earth has been sufficient to shift our planet's climate into a new, more dangerous phase.

Much hangs on this scientific debate. When Hurricane Ivan roared through the Gulf of Mexico in 2004, the oil industry considered it to be a once-in-2,500-years event, but then came Katrina and Rita. "We're seeing 100-year events happening every few years," one oil industry executive said.

It's worth recording that the United States already has the most varied weather of any country on earth, with more intense and damaging tornadoes, flash floods, thunderstorms, hurricanes and blizzards than anywhere else. With the intensity of such events projected to increase as our planet warms, the United States would seem to have more to lose from climate change in purely human terms than any other large nation. Indeed, the ever-spiraling insurance bill resulting from severe weather events and the growing water shortages in the West mean that the U.S. is already paying dearly for its CO_2 emissions.

Because extreme weather events by their very nature are rare, a long time can pass before sufficient data accumulate to detect a trend. Less extreme changes in temperature and rainfall are a lot easier to quantify, and with climate records going back centuries, Europe is a great place to start looking for these impacts. The 1990s was the warmest decade in central England since records began to be kept in the 1660s; 1998 was the warmest year ever and 2001 the third warmest. As a result, the growing season for plants has been extended by a month, heat waves have become more frequent, and winters are much wetter, with heavier rain. The Hadley Center, a world-leading institution set up in Exeter, U.K. to predict and examine climate-change impacts, has determined that the U.K. has experienced a significant increase in severe winter storms, a trend that is predicted to continue.

On the Continent more alarming events have occurred. The European summer of 2003 was so hot that, statistically speaking, such an outlandish event should occur no more than every 46,000 years. It was worsened by water stress to plants, which restricted their moisture emissions. With less of the sun's heat used up in evaporation, more of it warmed the air. The heat wave was so extreme that 26,000 people died during June and July, when temperatures exceeded 104°F across much of the continent. Heat waves, incidentally, kill a large number of people worldwide each year; even in the climatically turbulent U.S., heat-related deaths exceed those from all other weather-related causes combined. And just one year after the European heat wave, Egypt experienced one of its highest recorded temperatures: 124°F.

A MESSAGE FROM THE GOLDEN TOAD

The Monteverde Cloud Forest Preserve in Costa Rica, with its Golden Toad Laboratory for Conservation, is blessed with an abundance of researchers. Soon after our fragile planet passed through the climatic magic gate of 1976, abrupt and strange events were observed by the ecologists who spend their life conducting detailed field studies in these pristine forests.

During the winter dry season of 1987, in the mossy rain forests that clothe the mountain's slopes nearly one mile above the sea, 30 of the 50 species of frogs known to inhabit the 12-square-mile study site vanished. Among them was a spectacular toad the color of spun gold. Aptly named the golden toad (*Bufo periglenes*), the creature lived only on the upper slopes of the mountain, but there it was abundant, and at certain times of the year the brilliant males could be seen by the dozen gathering around puddles on the forest floor to mate. The toad's disappearance particularly worried researchers, for it is one of the most spectacular of the region's amphibians and was found nowhere else.

The golden toad was discovered and named in 1966. Only the males are golden; the females are mottled black, yellow and scarlet. For much of the year it's a secretive creature, spending its time underground in burrows amid the mossy root masses of the elfin woodland. Then, as the dry season gives way to the wet in April and May, it appears aboveground en masse, for just a few days or weeks. With such a short time to reproduce, the males fight with each other for the top spot and take every opportunity to mate—even if it's only with a field-worker's boot.

In her book *In Search of the Golden Frog* (perhaps *toad* was too off-putting for a title) amphibian expert Marty Crump tells us what it was like to see the creature in its mating frenzy:

> As I round a bend, I slide to a halt. In front of me is one of the most incredible sights I've ever seen. Congregated in and around the small pools at the bases of stunted trees sit over 100 dazzling bright orange toads poised like statues, jewels scattered about the dim understory.

On April 8, 1987 Crump made a note in her field diary that was to have historic significance:

> We see a large orange blob with legs flailing in all directions: a writhing mass of toad flesh. Closer examination reveals three males, each struggling to gain access to the female in the middle. Forty-two brilliant orange splotches poised around the pool are unmated males, alert to any movement and ready to pounce. Another 57 unmated males are scattered nearby. In total we find 133 toads in the neighborhood of this kitchen-sink-size pool.

On April 20:

> Breeding seems to be over. I found the last female four days ago, and gradually the males have returned to their underground

retreats. Every day the ground is drier and the pools contain less water. Today's observations are discouraging. Most of the pools have dried completely, leaving behind desiccated eggs already covered in mold. Unfortunately, the dry weather conditions of El Niño are still affecting this part of Costa Rica.

As if they knew the fate of their eggs, the toads attempted to breed again in May. This was, as far as the world knows, the last great toad orgy ever to occur, and Crump had the privilege to record it. Despite the fact that 45,300 eggs were deposited in the 10 pools she studied, only 29 tadpoles survived for longer than a week, for the pools once again quickly dried.

The following year Crump was back at Monteverde for the breeding season, but this time things were different. After a long search, on May 21 she located a single male. By June, Crump, still searching, was worried: "The forest seems sterile and depressing without the bright orange splashes of color I've come to associate with this [wet] weather. I don't understand what's happening. Why haven't we found a few hopeful males, checking out the pools in anticipation?" Yet even after the season closed without another sighting, there was no undue pessimism. A year was to pass before, on May 15, 1989, a solitary male was again sighted. As it was sitting just 10 feet from where Crump made her sighting 12 months earlier, it was almost certainly the same male who for the second year running was holding a lonely vigil, waiting for the arrival of his fellows. He was, as far as we know, the last of his species, for the golden toad has not been seen since.

Suspecting that some odd weather event might have been the cause of the changes, researchers began to pore over the monthly records of the region's climate. It would be 10 years from the last sighting before they published their findings, but in 1999 they announced that they had identified the cause of Monteverde's despoliation.

Examination of the meteorological record revealed that ever since the earth had passed through its first climatic magic gate, in 1976, the number of mistless days experienced each dry season had grown until they coalesced into runs of mistless days. By the dry season of 1987 the number of consecutive mistless days had passed some critical threshold. It was apparently so subtle as to be undetectable to the researchers working on the mountain, yet it had plunged the entire ecosystem of the mountaintop into crisis. Mist, you see, brought vital moisture, and without it the forest dried out sufficiently to trigger a landslide of catastrophic changes that swept before it mountain birds, anoles, golden toads and other amphibians alike.

Why, the researchers wanted to know, had the mist forsaken Monteverde? Beginning in 1976 the cloud line, the level at which clouds sit against mountainsides and bring misty conditions, had risen until it was above the level of the forest. The change had been driven by the abrupt rise in sea surface temperatures in the central western Pacific that heralded the magic gate of 1976. A hot ocean had perhaps heated air, elevating the condensation point for moisture in it. By 1987 the rising cloud line had on many days forsaken the mossy forest altogether and hung about in the sky above, bringing shade but no mist.

The golden toad's permeable skin and its propensity to wander in daylight hours had left it extremely vulnerable to the desiccation brought on by the run of mistless days. By the time the study was published in 1999, this wondrous creature had been extinct for a decade.

It's always devastating when you witness the extinction of a species, because what you are seeing is the dismantling of ecosystems and irreparable genetic loss. The golden toad's extinction, however, was not in vain, for when the explanation of its demise was published in *Nature*, the scientists could make their point without equivocation. The golden toad was the first documented victim of global warming. We had killed it with our profligate use of coal-fired electricity and our oversize cars just as surely as if we had flattened its forest with bulldozers.

As the reason for the extinction of the golden toad became thoroughly comprehensible, frog researchers worldwide began to reevaluate their experiences; since 1976 many had observed amphibian species vanishing before their eyes without being able to determine the cause. Could climate change, they wondered, be responsible?

The answer, sadly, is yes. When the first global survey of amphibians was completed in 2004, it revealed that almost a third of the world's 6,000-odd species were threatened with extinction. Many of these endangered species began their decline after 1976, and according to Simon Stuart of the International Union for the Conservation of Nature, "there's almost no evidence of recovery."

MASS EXTINCTION

Another way to try to understand how climate change is affecting the planet's ecosystems is to mass together the available data, which involve observations of more than 1,000 species of trees, crustaceans and mammals, and see what they say statistically as a whole. This was the approach taken by a group of researchers, led by Chris Thomas of the University of Leeds, that published its findings in *Nature* in late 2004.

Drawing from locations covering 20 percent of the earth's surface, including Mexico, South Africa, Europe, South America and Australia, and using a range of current predictions for climate change, the project examined the likely fate of 1,103 plant and animal species, from proteas to primates, by the year 2050.

Thomas and his colleagues found that at the lowest possible degree of global warming—between 1°F and 3°F—around 18 percent of the species sampled will, in the dispassionate language favored by science journals, be "committed to extinction," or, in other words, doomed. At the midrange predictions—3°F to 4°F—around a quarter of all species will be extirpated, while at the high range of predicted temperature rises (more than 4°F) more than a third of species will become extinct.

Believe it or not, this is the good news; in these analyses it is assumed that species can migrate. But what chance does a protea have of dispersing across the populated coastal plain of South Africa's Cape Province, or a golden lion tamarin monkey of crossing the agricultural fields that have all but obliterated the Brazilian Atlantic rain forests? The answer is very little indeed, and for species that cannot disperse, the likelihood of extinction is roughly doubled. This means that at the high range of predicted temperature changes, more than half (58 percent) of the 1,103 species examined are committed to extinction.

Extrapolating from Thomas's data set, it appears that at least one out of every five living things on this planet is committed to extinction by the existing levels of greenhouse gases. The WWF, the Peter Scott Trust for Educational Research Into Conservation and the Nature Conservancy have worked for decades to save, in real terms, relatively few species. Now it seems countless thousands will be swept away by a rising tide of climate change unless greenhouse gas emissions are reduced.

We must remember, however, that if we act now, it lies within our power to save *two* species for every one that is currently doomed. If we carry on with business as usual, in all likelihood three out of every five species will not be with us at the dawn of the next century.

TURNING UP THE HEAT

The most recent study of climate change, the largest ever undertaken, was published in early 2005 by a team led from Oxford University. Using the downtime on more than 90,000 personal computers, it focused on the temperature implications of doubling CO_2 in the atmosphere. The average result of the many runs made indicated that this would lead to a warming of 6°F. Overall, however, there was an astonishingly wide range of possibilities—from 3°F to 20°F of warming, the higher end of which had not been predicted earlier.

As I read these results, an anomaly that had long niggled at me resurfaced. At the end of the last ice age, 20,000 to 10,000 years ago, CO_2 levels increased by 100 parts per million, and the earth's average surface temperature rose by 9°F. It is the fastest rise in the earth's recent history and occurred at almost 2°F per 1,000 years. Today we face a rate of change that is an astonishing 30 times faster. This suggests that CO_2 is a powerful influence on global temperature. Yet in most computer analyses, an increase in CO_2 almost three times as large (doubling preindustrial levels) results in a predicted temperature rise of only 5°F.

This anomaly has serious implications for the survival of our civilization and countless species. Scientists now working on aerosols think they may have the answer. Direct measurement of evaporation rates, which are influenced primarily by sunlight, indicates that the amount of sunlight reaching the earth's surface has declined significantly—up to 22 percent in some areas—in the past three decades. It is as if we had been stopping up that small "window" in the atmosphere through which visible light passes.

This phenomenon is called global dimming, and it operates in two ways: Aerosols such as soot increase the reflectivity of clouds, and the contrails left by jet aircraft create a persistent cloud cover. Soot particles change the reflective properties of clouds by fostering the formation of many tiny water droplets rather than fewer larger ones, and these tiny water droplets allow clouds to reflect far more sunlight back into space than do larger drops. The story with contrails is different. In the three days following September 11, 2001, the entire U.S. jet fleet was grounded, over which time climatologists noted an unprecedented increase in daytime temperatures relative to nighttime temperatures. This resulted, they presume, from the additional sunlight reaching the ground in the absence of contrails.

If 100 parts per million of CO_2 really can raise surface temperatures by 9°F, and if aerosols and contrails have counterbalanced this so that we have experienced only 1°F of warming, then their influence on climate must be enormously powerful. It is as if two great forces, both unleashed from the world's smokestacks, are tugging the climate in opposite directions, but CO_2 is slightly more powerful.

This leaves us with a grave problem. Particle pollution lasts only days or weeks, while CO_2 is difficult to clean up and lasts a century or more. Facing the prospect of a 4°F or a 9°F rise in temperature, we have only one option if our understanding of global dimming is correct. We *must* start extracting CO_2 from the atmosphere.

When we consider the fate of the planet as a whole, we must be under no illusions as to what is at stake. Earth's average temperature is around 59°F, and whether we allow it to rise by two degrees or five will decide the fate of hundreds of thousands of species and most probably billions of people. Never in the history of humanity has there been a cost-benefit analysis that demands greater scrutiny.

From Tim Flannery's new book, The Weather Makers, published by Grove/Atlantic.