Positive Feedbacks and "Tipping Points"

(Think Twin Towers)

Change in nature is fast, abrupt and usually violent—"stepwise" is the term that scientists like to use. Many believe the gravest risks posed by global warming do not lie in a gradual rise in temperature over the course of a few decades, but instead in some unpredictable catastrophic event. What might that be? Nobody can predict with certainty because, by definition, we don't know what we don't know. Nevertheless, there is compelling evidence that in areas where there are clearly linkages that could trigger runaway global warming, movement in that direction has begun.

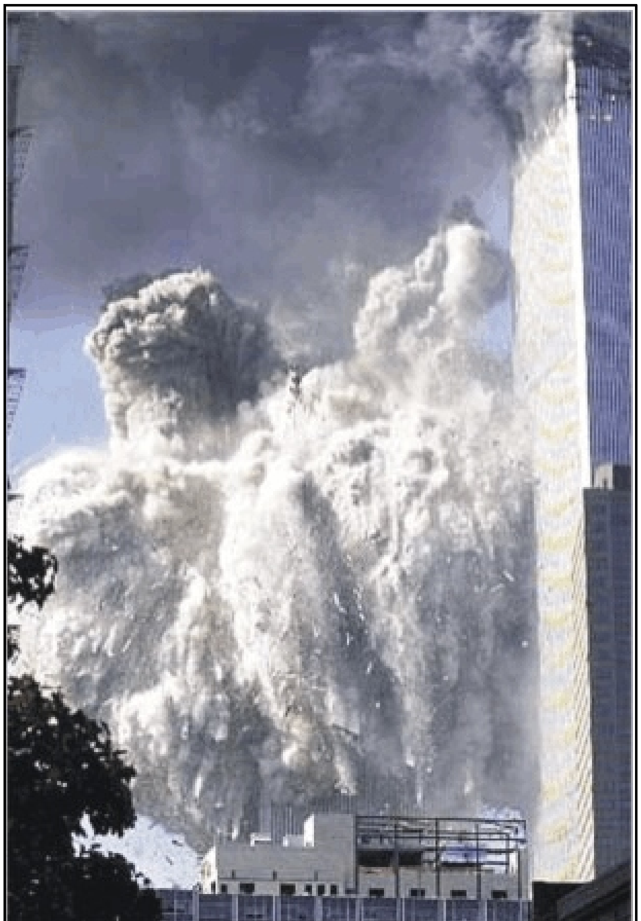

Figure 1 Collapse of the Twin Towers on Sep. 11, 2001 as a tipping point was reached. (Source: University of Sydney http://www.civil.usyd.edu.au/wtc.shtml)

The pieces of change fit together like the parts of a exquisitely complex and well oiled machine. The Arctic and Antarctic are warming and melting, triggering a slowing of the 1,000-year current that warms, cools and feeds the planet. With their supply of nutrient-rich water gone, the tiny plants and animals that form the base of the world's food chain, plankton, are disappearing. Their decline is hastened by the increasing acidity of an ocean in which carbon dioxide is being dissolved, forming carbonic acid. Permafrost is warming, thawing and rotting, releasing massive amounts of greenhouse gases, which in turn are speeding the warming further, causing still more releases of warming pollutants. In short, what the computer models predict should happen are, in fact, occurring. Humanity is standing at the base of a global Twin Towers, as it collapses on our future.

Has it happened in the past? Absolutely.

Consider, for example, the Antarctic ozone hole that opens over the frozen region each year. It was so unexpected that when the instruments of the British Antarctic Survey, which began measurements there in 1956, began reporting a dramatic drop in ozone levels in October, 1981, scientists refused to believe them.[1] The principal researcher, Richard Farman, believed the "reading was simply too low to suggest anything but an instrument malfunction" historians later wrote. Farman ordered a new instrument and had it shipped to the Antarctic. Its readings: same as those from the old device. But still the reading went unreported.

Nearly three years later, the *Nimbus 7* satellite operated by the National Aeronautics and Space Administration also documented the massive destruction of ozone in the Antarctic, a hole the size of North America and the height of Mt. Everest. "Everybody agreed it was an instrument problem," one scientist later explained. Eventually, in May, 1985, Farman stunned the global community of atmospheric scientists by reporting in an article published in *Nature* the annual losses of ozone. Even then, however, the community remained unable to explain why and how such a massive, catastrophic event could occur.

The explanation for the losses—and as important, why the world's best scientists were baffled—later proved to be not only quite simple, but obvious as well: the Antarctic gets cold—really, really cold. When temperature remain relatively warm by Antarctic standards, molecules of CFCs and ozone are floating in the air. If they collide, a CFC molecule will be destroyed.[1]

In the Antarctic spring, whoever, which begins in roughly mid-September, temperature fall so much that ice clouds are formed. The tiny particles of ice form solid surface on which the reaction of CFC and ozone molecules can occur. This "solid state"or "solid phase." chemistry is much faster the gas phase because molecules are no longer colliding my random chance. Instead they deposit on the ice surfaces, speeding the reaction a thousand-fold. These "step wise" or "tipping point changes in nature are the rule, and gradual and even ones the exception.

Lightning strikes after the accumulated electricity reaches a tipping point, just as snow avalanches down a hillside. Nuclear and thermonuclear explosions occur when a critical mass is reached. Similarly, the Twin Towers fell when a tipping point was reached, though it is unlikely that where and what will ever be known.

In the case of environmental threats such as global warming, the danger of reaching a tipping point is increased because of the number of changes that can feed on themselves, starting a spiral of heat. When tundra thaws, for example, it begins to decay, releasing both carbon dioxide and methane, which has 20 times the warming power of CO_2 on a molecule-for-molecule basis. They increase the temperature, which triggers still more releases of greenhouse gases, which, in turn, further boost warming. Thus the hotter it gets, the hotter it will get.

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[1] Actually 100,000 ozone molecules will be destroyed by the time a single CFC molecule exhausts its destructive capacity. The reaction is extremely complex, but in its final step, a new CFC molecule is created. That a single CFC molecule can destroy 100,000 ozone molecules helps explain why human activities can have consequences far more grave than might be assumed.

For myself, I believe that humanity has five or at most 10 years to reverse the warming trend. My political experience leads me to believe that corporations, especially the oil, coal, electricity and auto companies, have such a firm grip on political decision making in the United States that action will be taken either too late or not at all. Though it saddens me to write this, I believe my children and billions of others, will fail to live out their natural lives.

There are at least ten possible tipping points and positive feedbacks that have been identified, and movement is occurring in each. It would be bad enough for one of them to tip, but the catastrophic threat is that when one tips, it will trigger changes that will precipitate a tip in all ten, and probably others that haven't yet been identified. It is simply impossible to quantify the risk of reaching one or more tipping points, so ultimately the determination is both personal and subjective. For myself, I believe that humanity has five or at most 10 years to reverse the warming trend. My political experience leads me to believe that corporations, especially the oil, coal, electricity and auto companies, have such a firm grip on political decision making in the United States that action will be taken either too late or not at all. Though it saddens me to write this, I believe my children and billions of others, will fail to live out their natural lives.

ARCTIC WARMING AND MELTING

The danger of melting in the Arctic—or, for that matter, any area covered by snow and ice—is that as dark soils or waters are exposed they will absorb more sunlight, thus increasing warming that will melt more ice and snow, exposing still more dark surfaces. This has almost certainly begun in the Arctic—and the implications extend much further.

The Arctic has been warming for quite some time, but the insulating effect of the snow and ice, combined with the extremely long time frame required to change ocean temperatures, have masked some of the changes. Once movement starts, however, scientists say a feedback will be kicked in leading to, in the words of two snow and ice specialists, "a substantial increase" in Arctic Ocean air temperatures.[2] Recent studies show that melting has now begun, and is happening at two to three times the rates predicted by computer models.

A study published in 2007 in the journal *Geophysical Research Letters*, found that the actual rate at which summer sea ice had shrunk per decade during the past 50 years was more than three times faster than an average of 18 of the most highly regarded climate simulations. Arctic sea ice is now melting at a rate far quicker than predicted by climate change computer models and could disappear completely before the middle of the century.

Retreating Arctic ice is a key indicator of the pace of global warming, and one that could have devastating repercussions for the wider climate, including warmer oceans and rising sea levels.[3] The extent of summer sea-ice has decreased by nearly 40 percent compared to the 1979–2000 average. The ice is thinning[4] and 2008 is even worse.


Figure 2 The effects of an ice-free Arctic will not stop there. It will likely extend to the entire planet, possibly triggering a series of feedbacks that would leave the Earth irrevocably altered and hostile to life as we know it. (Source: freewebs.com)

The year started with Arctic ice covering a larger area than at the beginning of 2007, according to data from the U.S. National Snow and Ice Data Center (NSIDC). But by the beginning of the summer, ice levels had shrunk beyond those of June, 2007, a summer that broke records for sea ice loss.[5] Preliminary data showed that the vast expanse of ice at the top of the world was some 55,800 square miles smaller than it was on the same date in 2007.[6] Scientists on the project said much of the ice was so thin it melted easily, and that Arctic seas might be ice-free in summer within five to 10 years.[7]

The consequences, however, extend far beyond the Arctic—indeed to the entire planet. Melting, especially if reinforced by a five- to ten-year period of sudden, deep sea-ice meltbacks could be 3.5 times higher than climate models typically project, according to a study published in June, 2008 issue of *Geophysical Research Letters*.[8] It predicts that added warmth will extend 900 miles into the North American and Eurasian continents, thawing vast stretches of tundra and permafrost, setting off a second positive feedback. Again, as noted earlier, s these soils thaw, they decay, releasing the greenhouse gases carbon dioxide and methane. Those will accelerate warming further, causing more methane and carbon dioxide to enter the air and trap heat (see the discussion of tundra thawing below).

The reaction of the global community, however, has not been to undertake immediate action to halt or at least slow melting, but instead to squabble over the spoils. For example, as milder temperatures made exploration of the Arctic sea floor possible for the first time, Russia's biggest-ever research expedition to the region steamed in to explore the seabed in a search for oil and gas.[9]

Figure 3 Warmer temperatures and disappearing sea ice in the Southern Ocean appear to be causing food shortages that could threaten Antarctic whales, seals and penguins. The vanishing ice in the winter has resulted in an 80 percent drop in the number of Antarctic krill, a shrimp-like crustacean that is a major source of food for animals in the region. (Source: www.msnbc.msn.com/id/6398305/)

ANTARCTIC MELTING

The Antarctic Ice Sheet is vast, about 2,000 miles (3,000 kilometers) wide and up to 3 miles (4.5 kilometers) thick. It holds 90 percent of the world's ice, and the disappearance of even its smaller West Antarctic ice sheet would raise worldwide sea levels by an estimated 20 feet. If the entire Antarctic melted completely, sea levels would rise by about 210 feet (70 meters) worldwide, destroying virtually all of the world's coastal cities. Most scientists think such a large change is unlikely, except over thousands of years. However, a loss of even 5 percent would radically transform Earth's coastal regions.

Scientists seeking to determine how the Antarctic ice sheet has changed in recent years, have concluded that it is losing as much as 36 cubic miles of ice a year in a trend that they link to global warming, according to a new paper that provides the first evidence that the sheet's total mass is shrinking significantly.[10]

The new findings, using data from two NASA satellites called the Gravity Recovery and Climate Experiment (GRACE), suggest that global sea levels could rise substantially. They also concluded that the amount of water pouring annually from the ice sheet into the ocean, which is roughly equivalent to the amount that the United States uses in three months, is raising global sea levels by 0.4 millimeters a year.

TUNDRA THAWING

Figure 4 This huge expanse of western Siberia is thawing for the first time since its formation, 11,000 years ago. The area, which is the size of France and Germany combined, will release methane and carbon dioxide, both greenhouse gases, as it thaws, thus further accelerating warming. (Source: BBC.)

Time is ticking on a climate time bomb throughout Alaska, Canada, Siberia and other frozen regions as tundra, permafrost—permanently frozen ground—and other places where carbon has been stored for centuries begin to thaw. The evidence for this, whether anecdotal[11] or scientific, is compelling.

In addition to northern Alaska, the permafrost zone includes most other Arctic land, such as northern Canada and much of Siberia, as well as the higher reaches of mountainous regions such as the Alps and Tibet. All report permafrost thaw. To track these changes, the Global Terrestrial Network for Permafrost (GTNP) was created, and it shows a warming trend throughout the permafrost zone.

Some of these frozen soils are much richer in carbon than ordinary earth. They contain large amounts of grass roots, animal bones, and other materials resulting in average carbon contents of 2 percent to 5 percent—roughly 10 to 30 times that in deep, non-permafrost mineral soils.[12]

CHERSKY, Russia — Sergei Zimov waded through knee-deep snow to reach a frozen lake where so much methane belches out of the melting permafrost that it spews from the ice like small geysers.

In the frigid twilight, the Russian scientist struck a match to make a jet of the greenhouse gas visible. The sudden plume of fire threw him backward. Zimov stood up, brushed the snow off his parka and beamed.

"Sometimes a big explosion happens, because the gas comes out like a bomb," Zimov said. "There are a million lakes like this in northern Siberia."

Carbon, which has been stored in these soils for tens of thousands of years, is being released by rising temperatures, accelerating global warming. A study of so-called "thaw" lakes in Siberia, for example, estimated that methane emissions rose 58 percent from 1974 to 2000.[13] In Manitoba, Canada, a researcher reported that permafrost thaw had accelerated significantly since 1950,[14] as temperatures rose 1.32˚ Celsius. A 1999 study found general warming in Alaska from the late 1980s to 1996 ranging from 0.5˚ to 1.5˚ C, with an annual warming rate of 0.05˚ to 0.2˚ C.[15] Boreholes in Svalbard, Norway indicate that ground temperatures rose 0.4˚ C from 1994 to 2004, four times faster than they did in the previous century.[16]

Thawing permafrost can cause buildings and roads to collapse, pipelines to crack, landslides to increase in the soil-based permafrost of Canada, and destabilize in mountainous regions(e.g. the Alps), causing slope failures such as the Alps.[17]

INTERRUPTION OF ATLANTIC CONVEYER BELT

The world is warmed and cooled—in short, made liveable for humans—by a conveyor belt of ocean waters that travels tens of thousands of miles over a thousand years, shifting energy from the torrid Pacific and Indian Oceans to the frigid waters of the North Atlantic. If it stops, and there is persuasive evidence that it is at least slowing, the world as we know it will cease to exist.

Figure 5 The Gulf Stream brings warm tropical waters north, boosting the temperatures of Europe by about 18˚F (10˚C) in the winter. As it cools to freezing, the water sinks to the ocean floor, flows through the Atlantic Basin around South Africa, into the Indian Ocean past Australia into the Pacific Ocean Basin, where it rises to be rewarmed. The entire journey takes 1,000-1,200 years, and makes Europe habitable. If the current fails to sink because it is too warm or the salt level is lowered by melting fresh water from the Arctic ice and glaciers, Europe will likely enter a new Ice Age. (Sources: NASA and NOAA.)

The conveyor belt travels to the east of North America, where it is called the Gulf Stream, to the east of Greenland. There winds blowing over its surface extract water and energy, forming clouds that travel across western Europe to roughly Moscow, Russia, dropping energy-rich rain and snow in their wake. Now heavier because it is saltier and cooler, the current drops to the ocean to begin its return journey.

But this powerful ocean current bathing Britain and northern Europe in warm waters from the tropics has weakened dramatically in recent years, a consequence of global warming. And that could, regardless of what intuition might suggest, trigger more severe winters and cooler summers across the region—even a little ice age, like the one that caused temperatures in Europe to plument about 12 centuries ago.

As the belt rises to the surface, it carries with it the nutrients that feed plankton, the tiny plants and animals that are the base of the world's food chain. If the belt slows, plankton levels fall as they, in effect, are starved—and plankton levels have dropped sharply (see plankton decline, below).

Researchers on a scientific expedition in the Atlantic Ocean measured the strength of the current between Africa and the east coast of America and found that circulation has slowed by 30 percent since an expedition 12 years earlier. Previous expeditions to check the current flow in 1957, 1981 and 1992 found only minor changes in its strength, although a slowing was picked up in 1998.

As winds pass over the current, they drain its heat energy—the equivalent of about one teaspoon of sugar in every cubic centimeter—boosting European temperatures by 10˚ C in some regions. The researchers found that the circulation has dropped by 6 million tons of water per second.

Scientists believe that if the current remains in its weakened state, temperatures in Britain are likely to drop by an average of 1˚. Harry Bryden at the National Oceanography Centre in Southampton who led the study said that "Models show that if it shuts down completely, 20 years later, the temperature is 4˚ C to 6˚ C cooler over the UK and north-western Europe."[18]

PLANKTON DECLINE

The base of the global food chain is formed by trillions of tiny plants and animals, or plankton, most so small as to be barely visible to the human eye. If plankton die, so do the fish, whale and other sea creatures that feed on them, and satellite surveys have detected a sharp decline in plankton in several of the world's oceans—a situation that could threaten the marine food chain and undercut one of the world's natural buffers to global warming.

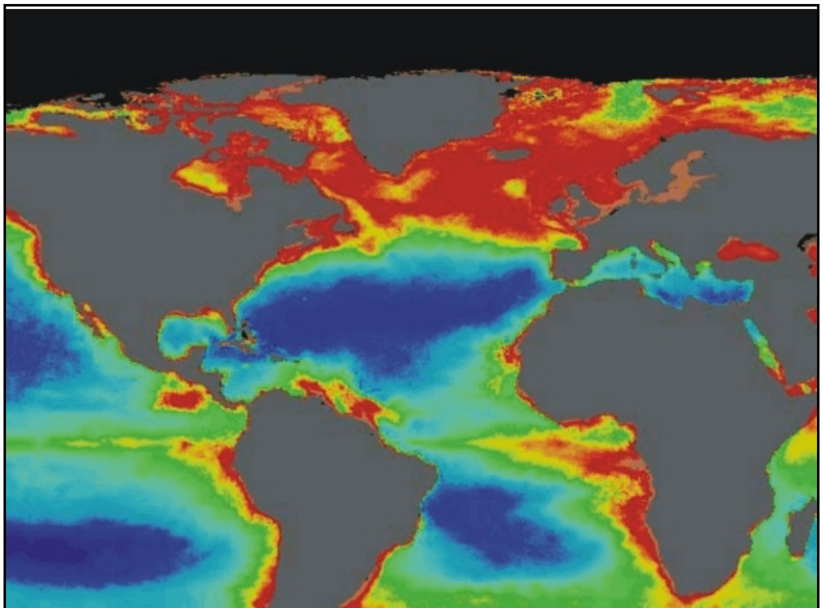


Figure 6 A check up of the Earth's planetary health reveals that the lowest rung in the ocean food chain is shrinking. For the past 20 years (early 1980s to present), phytoplankton concentrations declined as much as 30 percent in northern oceans. Scientists from NASA and the National Oceanic and Atmospheric Administration (NOAA) say warmer ocean temperatures and low winds may be depriving the tiny ocean plants of necessary nutrients. However, they still do not know if the loss of phytoplankton is a long-term trend or a climate oscillation.

Plankton include organisms such as diatoms,[19] dinoflagellates,[20] and krill,[21] as well as as the microscopic larva of crabs, sea urchins, and fish. Plankton also include tiny photosynthetic organisms that are so numerous and productive that they are responsible for generating more oxygen than all other plants on Earth combined.

The decline in these free-floating, microscopic organisms—the plants are called phytoplankton and the animals zooplankton—varies from ocean to ocean. The greatest decline is in the Northern Pacific Ocean, where summer levels have dropped by more than 30 percent since the 1980s.[22] The data was collected in the summers (July–September) from 1979–2000.

In the North Atlantic, phytoplankton concentrations dropped by 14 percent since the 1980s. Like the North Pacific, there is a lot of red representing a slight increase in phytoplankton but it does not make up for the large decreases shown in blue.

These declines are consistent with computer models of what will happen if the oceanic conveyor belt is interrupted (see above). In the computer simulations, a disruption of the belt leads to a collapse of the North Atlantic plankton stocks to less than half of their initial levels because the organisms are, in effect, starved when the nutrients in the deep oceans are no longer being brought to the surface by the conveyor.[23]

OCEAN ACIDIFICATION

In nature, there is no free lunch. Change has consequences, even when it appears that the change may be beneficial. One change triggers another, and it causes yet a third, and so it goes like a string of dominos, all falling because the one in front fell.

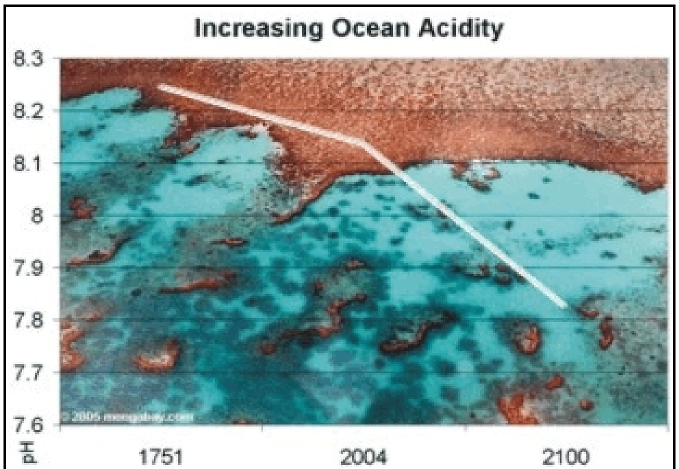


Figure 7 Observed and projected decline in global ocean pH, 1750–2100. Photo by Rhett A. Butler (Source: news.mongabay.com/2008/0522-oceans.html)

For many years, for example, scientists have been grateful that oceans absorb much of the carbon dioxide created by burning coal and oil. But the chemical doesn't disappear. It merely changes its identity: dissolved in ocean waters, carbon dioxide forms carbonic acid—a weak acid admittedly, but an acid nonetheless. It has increased the acidity of oceans by about 30 percent. This, in turn, reduces the amount of calcium carbonate required for coral, plankton and other creatures with shells to make them. Indeed, in studies mimicking future ocean acidification, the shells of aquatic animals began dissolving within a matter of two days.[24]

Deep ocean waters normally are more acidic and have higher CO_2 levels than shallow waters because decomposing organic matter sinks and makes deep water acidic, and deep water contains CO_2 absorbed when the water last circulated to the surface. However, changing temperature and circulation pulls deep waters to the surface, flushing it onto the continental shelves. When researchers with the National Oceanic and Atmospheric Administration's Pacific

Marine Environmental Laboratory sampled waters along 13 survey lines extending from British Columbia, Canada to Baja California, Mexico in the spring of 2007, they not only found that the water was more acidic than expected close to shore and near the surface, but that the entire water column was undersaturated in shell-forming carbonate down to 50 meters in places.[25] Researchers attributed this to continually rising levels of human-emitted CO_2.

This was the first time acidified ocean water has been found on the continental shelf of western North America, and it happened 100 years before computer models predicted it would. The lead scientist in the study termed the finding "truly astonishing." Another commented that it was one more "example where what's happening in the natural world seems to be happening much faster than what our climate models predict."[26]

The acidified water was last exposed to the atmosphere about 50 years ago, when carbon-dioxide levels were much lower. Water rising from the depths over the coming decades will have absorbed more carbon dioxide, and will be even more acidic. Models suggest this could reduce levels of carbonate by 50 percent.

CORAL BLEACHING

Humans die in heat, and so do sea creatures. Among the hardest hit are the world's corals. Global warming has reduced many reefs to rubble, a collapse that has deprived fish of food and shelter, causing fish diversity to fall by half in some areas, according to the first long-term study of the effects of warming-caused bleaching on coral reefs and fish.

Figure 8 Warmer waters kill the tiny algae that lend coral their colors and, most importantly, provide food. (Source: Photo by Ray Berkelmans, AIMS.)

Small but prolonged rises in sea temperature force coral colonies to expel the algae that lend them their color but, most importantly, provide food. The relationship between the corals and their algae is one of nature's most delicate and complex. Thriving coral are powerful enough to build the largest living organism on the planet, the Great Barrier Reef. Their health underpins the economies and living standards of many tropical nations and societies who harvest their food from the reefs or have developing tourism industries. When stressed, however, coral will expel their algae in a process known as bleaching that turns dying reefs ghostly white. Some reefs can recover from such events, but many do not.

In 1998, heat triggered a global bleaching and die off of coral, killing over 16 percent of the world's reefs in one year. The reefs near Africa's Seychelles islands, north of Madagascar, were particularly hard hit, so researchers returned eight years later to gauge the extent of the recovery. What they found were coral reefs still unable to recover.[27]

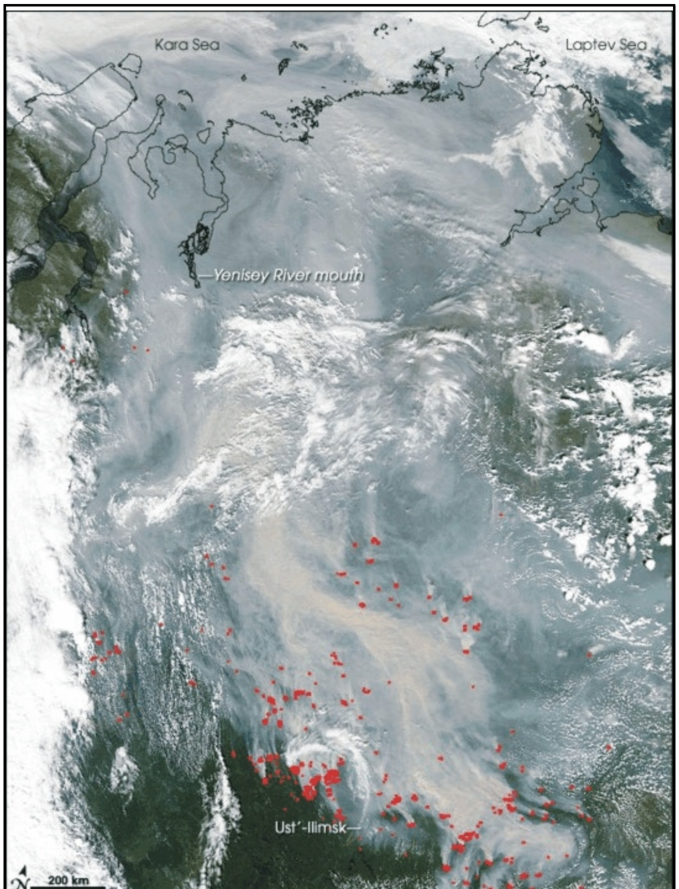


Figure 9 In 2006, forest fires were burning across a broad swath of the Central Siberian Plateau, pictured here from a NASA satellite, with actively burning fires marked in red. The shroud of smoke spreads over thousands of square miles, and is a major source of black carbon that is causing warming and melting in the Arctic. If this were imposed on a map of the United States, it would stretch east to west from California to the New Mexico-Texas state line, and north to south more than a hundred miles beyond the Mexico and Canadian borders. (Source: NASA.)

"The outlook for recovery is quite bleak for the Seychelles," said lead study author Nicholas Graham, a tropical marine biologist at England's University of Newcastle Upon Tyne.[28]

In the long term, heat-induced coral bleaching will almost certainly impact fisheries production. Some species are likely to die and go extinct, disrupting the food chain that sustains much of life on Earth. This, combined with the increasing acidification, may have devastating effects on fishery stocks.[29]

FOREST DIEBACK/FIRES

Forest fires in the western United States have been increasing "suddenly and dramatically," according to a 2006 study that examined a database of 1,166 forest wildfires from 1970 to 2003.[30] These fires representative another powerful feedback mechanism. They release not only prodigious amounts of carbon dioxide and methane, but also black carbon. The fires are thought to account for roughly 40 percent of global releases of BC, and much of it falls in the areas where it can do the most harm, the snow covered Arctic and the mountain regions, where they darken surfaces, thus increasing absorption of heat from sunlight.[31,b] By one estimate, the warming caused by black carbon is placed at roughly 40 percent

[b] The Arctic is especially susceptible to the impact of human-generated particles and other pollution. In recent years the Arctic has significantly warmed, and sea-ice cover and glacial snow have diminished. Likely causes for these trends include changing weather patterns and the effects of pollution. Black carbon has been implicated as playing a major role in melting ice and snow. When soot falls on ice, it darkens the surface and accelerates melting by increasing absorbed sunlight. Airborne soot also warms the air and affects weather patterns and clouds. See Flanner, M.G. et. al. Present-day climate forcing and response from black carbon in snow JGR, V. 112, D11202, doi:10.1029/2006JD008003, 2007.

of that from burning coal, oil and other fossil fuels.[32] Increased warming brought on by the fires dries trees and underbrush even further, making them even more susceptible to fire, thus producing more warming.

There is no doubt that the number and intensity of fires has increased. In the mid 1980's there was a jump of four times the average number of wildfires in the West compared with the early 1980's and 1970's. The total area burned was six-and-a-half times greater in the mid 1980's than the earlier years examined. The wildfire season has also extended by 78 days in the more recent period of 1987 to 2003 compared to 1970 through 1986.

The researchers also found that 56 percent of the wildfires and 72 percent of the total burnt area occurred during the years when the snow melted early. When the snowmelt season occurred later than average, only 11 percent of wildfires occurred.[33]

Figure 10 Forest fires have been on the rise in Alaska as well.

This trend will almost certainly accelerate. As part of the 4th Assessment of the Intergovernmental Panel on Climate Change (IPCC), seven general circulation models were used to predict future temperatures, and all projected June to August temperature increases of 2° to 5° C by 2040 to 2069 for western North America.[34] The models also project a decline in rain and snow of up to 15 percent. That is a June to August temperature increase of 3° C, or roughly triple the rise that has already caused the devastating wildfires of the past two decades.

These new sources of global warming pollutants will certainly accelerate the buildup of greenhouse gases and create a positive feedback, or as it is called by some, a "feed-forward" acceleration of global warming.[35]

The United States is by no means the only place fires are on the rise. Wildfire burn areas in Canada are expected to increase by 74 to 118 percent, in the next century.[36] Devastating forest fires in Siberia that send a pall of smoke worldwide are happening more frequently because of climate change and in turn accelerating the pace of global warming.[37]

In Central Siberia alone fires destroyed 15,000 square miles in 2003, triggering plumes which were linked with air pollution measured as far away as America. The forest fires send as much greenhouse gas into the atmosphere as the total EU reduction commitment under the Kyoto protocol. An international team, led by the Professor Heiko Balzter of the Department of


Figure 11 The formation of ozone, or smog, increases in lock step with temperature, so global concentrations will increase with global warming. Highly toxic to plants and humans alike, ozone causes forest decline and death, which in turn reduces the ability of trees and other plants to remove carbon dioxide and other pollutants from the air, leading to still higher temperatures. (Source: www.lexi-tv.de/lexikon/thema.as)

Geography at the University of Leicester, concluded that Siberian fires are being influenced by climate change.[38]

Balzter said "Last century a typical forest in Siberia had about 100 years after a fire to recover before it burned again. But new observations by Russian scientist Dr. Vyacheslav Kharuk have shown that fire now returns more frequently, about every 65 years. At the same time annual temperatures in Siberia have risen by almost two degrees Celsius, about twice as fast as the global average. And since 1990 the warming of Siberia has become even faster than before."[39]

Tropospheric Ozone or "Smog" Formation

In Los Angeles, the smog capital of America, there has never been a violation of the health standards for smog when the temperature was below 70° Fahrenheit—but there's never not been a violation when it's 90° or more. That's because ozone is formed in lock step with heat, with both rising in a straight line, which means that as the Earth's temperature rises, so too may concentrations of ozone, which already hover at levels toxic to plants throughout much of the world.[40]

There are several ways in which ozone might trigger a feedback.

First, because ozone is itself a greenhouse gas, higher temperatures could boost its formation, which might in turn accelerate warming. Although not subject to the Kyoto Protocol, ozone is a powerful cause of global warming, roughly equal to methane and black carbon.[41]

Ozone is formed when oxides of nitrogen, which is chiefly from vehicles and powerplants, reacts with unburnt gasoline fumes and other volatile organic compounds. The higher the temperature, the faster ozone is formed. One analysis of the effect of higher temperatures due to global warming concluded that ozone would increase 3 to 10 percent in various regions of California, and even with aggressive reduction if emissions of ozone precursors might be ineffective at bringing smog levels down in some regions, especially San Francisco.[42]

In addition, ozone poisons plants and suppresses photosynthesis. That, in turn, reduces their ability to absorb carbon dioxide from the atmosphere and sequester it in their tissues, especially in trees.[43]

Third, ozone's warming effects are especially strong in the Arctic, where it is thought to account for one-third to one-half of the observed warming during winter and spring.[44]

Whether due to global warming or some other cause, background levels of ozone are increasing in widely separated regions of the world. At Mace Head on the west coast of Ireland, concentrations rose about 0.5 parts per billion per year between 1987 and 2003.[45] In the United States, one model predicts that higher temperatures will cause the "severity and duration of summertime regional pollution episodes in the midwestern and northeastern United States increase significantly relative to the present, predicting that concentration will rise 5 to 10 percent and duration increase from 2 to 3 to 4 days.[46] The researchers observed that their results "imply that it may be equally important to consider the effects of a changing climate when planning for the future attainment of regional-scale air quality standard."[47]

DESERTIFICATION

In the sun-baked province of Murcia, Spain, lush fields of lettuce and hothouses of tomatoes line the roads and the landscape is dotted with plush pastel vacation homes that give way to wide sandy beaches. In a place where existence has been hardscrabble for centuries, prosperity has come calling—but the stay may be temporary.[48]

Figure 12 With higher temperatures, water evaporates from soils, leading to the formation and expansion of deserts. As the land in arid, semi-dry areas becomes degraded, soil loses its productivity and vegetation thins, causing prolonged droughts and floods. One major study predicts that over one-half of the world's land will be subject to drought by century's end. (Source: www.worldrevolution.org/)

Murcia, like many areas of the world, is running out of water, and as supplies dwindle the land becomes that most inhospitable of places, a desert. The feedback in desertification is fairly straightforward. As hotter air born of global warming sucks more and more moisture from the soils or shifts rainfall away from the lands and into oceans, a vicious cycle is set off. Huge swaths of land cease to grow plants, losing their ability to remove carbon dioxide from the air and store it in their tissues. With their growth suppressed, plants drop less and less litter, leaving the soil increasingly vulnerable to drying.[49] When rain does fall, the soils are unable to hold it, so floods are triggered.

As the land produces less and less food, pressure builds to farm and graze it more intensively, hastening its further decline. As desert shrubs invade, the barren areas between them lose soil fertility, so the soil is lost to erosion. Land that was once productive becomes instead a barren wasteland.[50]

Desertification directly triggers warming, increasing temperatures in one study by 0.7° C per decade.[51] One comprehensive analysis, the first of its kind, predicts that global warming is likely to push soils that are already weakened over the edge, triggering an increase in the area affected by the most extreme drought from 3 to 30 percent and areas of severe drought up from 8 to 40 percent of total land area It predicts that up to half of the earth's surface would be affected by moderate drought at any one time.[52]

1. Seth Cagin and Phillip Dray, Between earth and sky: how CFCs changed our world and endangered the ozone layer, Pantheon Books, New York, 1993, pp. 262-76.

2. Mark C. Serreze, M.C. & Francis, J.A. The Arctic Amplification Debate, J. Climatic Change. June, 2006. DOI10.1007/s10584-005-9017-y, p. 241-264.

Rises in surface air temperature (SAT) in response to increasing concentrations of greenhouse gases (GHGs) are expected to be amplified in northern high latitudes, with warming most pronounced over the Arctic Ocean owing to the loss of sea ice. Observations document recent warming, but an enhanced Arctic Ocean signal is not readily evident. This disparity, combined with varying model projections of SAT change, and large variability in observed SAT over the 20th century, may lead one to question the concept of Arctic amplification. Disparity is greatly reduced, however, if one compares observed trajectories to near-future simulations (2010–2029), rather than to the doubled-CO_2 or late 21st century conditions that are typically cited. These near-future simulations document a preconditioning phase of Arctic amplification, characterized by the initial retreat and thinning of sea ice, with imprints of low-frequency variability. Observations show these same basic features, but with SATs over the Arctic Ocean still largely constrained by the insulating effects of the ice cover and thermal inertia of the upper ocean. Given the general consistency with model projections, we are likely near the threshold when absorption of solar radiation during summer limits ice growth the following autumn and winter, initiating a feedback leading to a substantial increase in Arctic Ocean SATs.

3. http://www.cnn.com/2007/TECH/science/05/02/arctic.ice/.

5. Richard Black, “Arctic sea ice melt 'even faster',” BBC News, June 18, 2008, http://news.bbc.co.uk/1/hi/sci/tech/7461707.stm

6. Peter N. Spotts, “Arctic sea ice melting faster than expected,” Christian Science Monitor, June 12, 2008, http://features.csmonitor.com/environment/2008/06/12/arctic-sea-ice-melting-faster-than-expected/

7. Richard Black, “Arctic sea ice melt 'even faster',” BBC News, June 18, 2008, http://news.bbc.co.uk/1/hi/sci/tech/7461707.stm

8. Peter N. Spotts, “Arctic sea ice melting faster than expected,” *Christian Science Monitor*, June 12, 2008, http://features.csmonitor.com/environment/2008/06/12/arctic-sea-ice-melting-faster-than-expected/

9. Fred Weir, “As icecaps melt, Russia races for Arctic's resources,” *Christian Science Monitor*, July 31, 2007 http://www.csmonitor.com/2007/0731/p01s01-woeu.html.

10. Juliet Eilperin, “Antarctic Ice Sheet Is Melting Rapidly - New Study Warns Of Rising Sea Levels,” *The Washington Post*, March 3, 2006, p. A1

11. TK TK

12. Zimov, S.A., Schuur, E. A. G. & Chapin, F. S. III. Permafrost and the Global Carbon Budget. Science, June 16, 2006: Vol. 312. no. 5780, pp. 1612 - 1613, DOI:10.1126/science.1128908.
Climate warming will thaw permafrost, releasing trapped carbon from this high-latitude reservoir and further exacerbating global warming.

13. K. M. Walte et. al. Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature 443, 71-75, 7 September 2006. | doi:10.1038.
Large uncertainties in the budget of atmospheric methane, an important greenhouse gas, limit the accuracy of climate change projections1, 2. Thaw lakes in North Siberia are known to emit methane3, but the magnitude of these emissions remains uncertain because most methane is released through ebullition (bubbling), which is spatially and

temporally variable. Here we report a new method of measuring ebullition and use it to quantify methane emissions from two thaw lakes in North Siberia. We show that ebullition accounts for 95 per cent of methane emissions from these lakes, and that methane flux from thaw lakes in our study region may be five times higher than previously estimated3. Extrapolation of these fluxes indicates that thaw lakes in North Siberia emit 3.8 teragrams of methane per year, which increases present estimates of methane emissions from northern wetlands (< 6–40 teragrams per year; refs 1, 2, 4–6) by between 10 and 63 per cent. We find that thawing permafrost along lake margins accounts for most of the methane released from the lakes, and estimate that an expansion of thaw lakes between 1974 and 2000, which was concurrent with regional warming, increased methane emissions in our study region by 58 per cent. Furthermore, the Pleistocene age (35,260–42,900 years) of methane emitted from hotspots along thawing lake margins indicates that this positive feedback to climate warming has led to the release of old carbon stocks previously stored in permafrost.

14. Camill, P. Permafrost Thaw Accelerates in Boreal Peatlands During Late-20th Century Climate Warming. Climatic Change Volume 68, Numbers 1-2 , DOI 10.1007/s10584-005-4785-y, pp. 135-52, January, 2005.
Permafrost covers 25% of the land surface in the northern hemisphere, where mean annual ground temperature is less than 0˚C. A 1.4–5.8 ˚C warming by 2100 will likely change the sign of mean annual air and ground temperatures over much of the zones of sporadic and discontinuous permafrost in the northern hemisphere, causing widespread permafrost thaw. In this study, I examined rates of discontinuous permafrost thaw in the boreal peatlands of northern Manitoba, Canada, using a combination of tree-ring analyses to document thaw rates from 1941–1991 and direct measurements of permanent benchmarks established in 1995 and resurveyed in 2002. I used instrumented records of mean annual and seasonal air temperatures, mean winter snow depth, and duration of continuous snow pack from climate stations across northern Manitoba to analyze temporal and spatial trends in these variables and their potential impacts on thaw. Permafrost thaw in central Canadian peatlands has accelerated significantly since 1950, concurrent with a significant, late-20th-century average climate warming of +1.32 ˚C in this region. There were strong seasonal differences in warming in northern Manitoba, with highest rates of warming during winter (+1.39 ˚C to +1.66 ˚C) and spring (+0.56 ˚C to +0.78 ˚C) at southern climate stations where permafrost thaw was most rapid. Projecting current warming trends to year 2100, I show that trends for north-central Canada are in good agreement with general circulation models, which suggest a 4–8 ˚C warming at high latitudes. This magnitude of warming will begin to eliminate most of the present range of sporadic and discontinuous permafrost in central Canada by 2100.

15. Osterkamp, T. E. & Romanovsky,V. E. Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafrost and Periglacial Processes, V. 10 Issue 1, pages 17 - 37, May 18, 1999.
Data show that permafrost temperatures along a north-south transect of Alaska from Old Man to Gulkana and at Healy generally warmed in the late 1980s to 1996. This trend was not followed at Eagle, about 330 km east of the transect. Estimates of the magnitude of the warming at the permafrost table ranged from 0.5˚C to 1.5˚C. Warming rates near the permafrost table were about 0.05 to 0.2˚C a-1. No reliable trends in the depth of the base of ice-bearing permafrost or in the depth of the 0˚C isotherm could be detected. Thermal offset allowed mean annual temperatures at the permafrost table to remain below 0˚C with ground surface temperatures up to 2.5˚C for a period of 8 years. The observed warming has probably caused discontinuous permafrost in marginal areas to begin thawing. Thawing permafrost and thermokarst have been observed at several sites. Thawing rates at the permafrost table at two sites were about 0.1 m a-1, indicating time scales of the order of a century to thaw the top 10 metres of ice-rich permafrost. Calculated thawing rates at the permafrost base are an order of magnitude smaller. Calibrated numerical models indicate that the permafrost warmed in the late 1960s and early 1970s in response to changes in air temperatures and snow covers. Additional warming in the late 1970s was caused by an increase in air temperatures beginning in 1977. Permafrost temperatures were nearly stable during the 1980s and then warmed again from the late 1980s to 1996, primarily in response to increased snow depths. This interpretation appears to be valid for all the sites in the region of the transect and at Healy

16. Molly Bentley, “Earth's permafrost starts to squelch,” BBC News, Dec. 29, 2004, http://news.bbc.co.uk/2/hi/science/nature/4120755.stm.

17. A colorful account of thawing in Siberia follows:

By| Tribune correspondent

12:38 AM CDT, May 5, 2008

CHERSKY, Russia — Sergei Zimov waded through knee-deep snow to reach a frozen lake where so much methane belches out of the melting permafrost that it spews from the ice like small geysers.

In the frigid twilight, the Russian scientist struck a match to make a jet of the greenhouse gas visible. The sudden plume of fire threw him backward. Zimov stood up, brushed the snow off his parka and beamed.

"Sometimes a big explosion happens, because the gas comes out like a bomb," Zimov said. "There are a million lakes like this in northern Siberia."

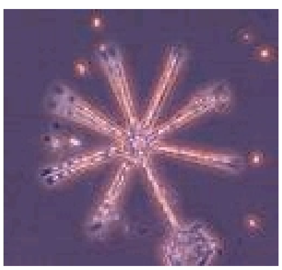
In a country where many scientists scoff at the existence of global warming, Zimov has been waging a lonely campaign to warn the world about Russia's melting permafrost and its nexus with climate change. His laboratory is the vast expanse of tundra and larch forest along the East Siberian Sea, an icy corner of the world that Zimov has scrutinized almost entirely on his own for 28 years.

Far from the archetypal scientist, the beefy, 53-year-old Russian with a mound of gray-brown hair and piercing blue eyes reigns over his patch of Siberia not with pipette and beaker, but with the swagger of a Cossack and an encyclopedic knowledge of his surroundings.

Alex Rodriguez , "Freezing to show warming trend - Though dismissed in Russia, scientist's climate research in remote Siberia is heating up discussions in the West," May 5, 2008.
http://www.chicagotribune.com/news/nationworld/chi-siberia-loner_rodriguezmay05,0,7326792.story

18. Ian Sample, "Alarm over dramatic weakening of Gulf Stream," *The Guardian*, Dec. 1, 2005
http://www.guardian.co.uk/environment/2005/dec/01/science.climatechange

19.



20.

21.

22. Mike Toner, "Plankton Declining in Oceans, Study Finds," *Atlanta Journal-Constitution* Aug. 20, 2002. See also Goddard Space Flight Center, National Oceanic and Atmospheric Administration, "Phytoplankton in Northern Oceans Have Declined from 1980s Levels," Aug. 08, 2002, http://www.gsfc.nasa.gov/topstory/20020801plankton.html.

23. Schmittner, A. Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation. *Nature* 434, 628-633, 31 March 2005, | doi:10.1038/nature03476.
Reorganizations of the Atlantic meridional overturning circulation were associated with large and abrupt climatic changes in the North Atlantic region during the last glacial period1, 2, 3, 4. Projections with climate models suggest that similar reorganizations may also occur in response to anthropogenic global warming5, 6, 7. Here I use ensemble simulations with a coupled climate–ecosytem model of intermediate complexity to investigate the possible consequences of such disturbances to the marine ecosystem. In the simulations, a disruption of the Atlantic meridional overturning circulation leads to a collapse of the North Atlantic plankton stocks to less than half of their initial biomass, owing to rapid shoaling of winter mixed layers and their associated separation from the deep ocean nutrient reservoir. Globally integrated export production declines by more than 20 per cent owing to reduced upwelling of nutrient-rich deep water and gradual depletion of upper ocean nutrient concentrations. These model results are consistent with the available high-resolution palaeorecord, and suggest that global ocean productivity is sensitive to changes in the Atlantic meridional overturning circulation.

24. James C. Orr, J.T. et. al. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437, 681-686, Sep. 29, 2005, doi:10.1038/nature04095.
Today's surface ocean is saturated with respect to calcium carbonate, but increasing atmospheric carbon dioxide concentrations are reducing ocean pH and carbonate ion concentrations, and thus the level of calcium carbonate saturation. Experimental evidence suggests that if these trends continue, key marine organisms—such as corals and some plankton—will have difficulty maintaining their external calcium carbonate skeletons. Here we use 13 models of the ocean–carbon cycle to assess calcium carbonate saturation under the IS92a 'business-as-usual' scenario for future emissions of anthropogenic carbon dioxide. In our projections, Southern Ocean surface waters will begin to become undersaturated with respect to aragonite, a metastable form of calcium carbonate, by the year 2050. By 2100, this undersaturation could extend throughout the entire Southern Ocean and into the subarctic Pacific Ocean. When live pteropods were exposed to our predicted level of undersaturation during a two-day shipboard experiment, their aragonite shells showed notable dissolution. Our findings indicate that conditions detrimental to high-latitude ecosystems could develop within decades, not centuries as suggested previously.

25. Richard A. Feely, R.A. et. al. Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf. *Science,* June 13, 2008: Vol. 320. no. 5882, pp. 1490 - 1492, DOI: 10.1126/science.1155676.
The absorption of atmospheric carbon dioxide (CO2) into the ocean lowers the pH of the waters. This so-called ocean acidification could have important consequences for marine ecosystems. To better understand the extent of this ocean acidification in coastal waters, we conducted hydrographic surveys along the continental shelf of western North America from central Canada to northern Mexico. We observed seawater that is undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching depths of ~40 to 120 meters along most transect lines and all the way to the surface on one transect off northern California. Although seasonal upwelling of the undersaturated waters onto the shelf is a natural phenomenon in this region, the ocean uptake of anthropogenic CO2 has increased the areal extent of the affected area.

26. Sandi Doughton, "Acidified ocean water rising up nearly 100 years earlier than scientists predicted," *Seattle Times*, May 22, 2008.

27. Nicholas A. J. Graham , N.A.J. et. al. Dynamic fragility of oceanic coral reef ecosystems. Proceedings of the National Academy of Sciences, Washington, D.C., May 18, 2006.
As one of the most diverse and productive ecosystems known, and one of the first ecosystems to exhibit major climate-warming impacts (coral bleaching), coral reefs have drawn much scientific attention to what may prove to be their Achilles heel, the thermal sensitivity of reef-building corals. Here we show that climate change-driven loss of live coral, and ultimately structural complexity, in the Seychelles results in local extinctions, substantial reductions in species richness, reduced taxonomic distinctness, and a loss of species within key functional groups of reef fish. The importance of deteriorating physical structure to these patterns demonstrates the longer-term impacts of bleaching on

reefs and raises questions over the potential for recovery. We suggest that isolated reef systems may be more susceptible to climate change, despite escaping many of the stressors impacting continental reefs.

28. Sean Markey, “Global Warming Has Devastating Effect on Coral Reefs, Study Shows,” National Geographic News, May 16, 2006 http://news.nationalgeographic.com/news/2006/05/warming-coral.html.

29. K. M. Brander, K.M. Global fish production and climate change. Proceedings of the National Academy of Sciences, Dec. 11, 2007, vol. 104,| no. 50, 19709-19714.
Current global fisheries production of {approx}160 million tons is rising as a result of increases in aquaculture production. A number of climate-related threats to both capture fisheries and aquaculture are identified, but we have low confidence in predictions of future fisheries production because of uncertainty over future global aquatic net primary production and the transfer of this production through the food chain to human consumption. Recent changes in the distribution and productivity of a number of fish species can be ascribed with high confidence to regional climate variability, such as the El Niño–Southern Oscillation. Future production may increase in some high-latitude regions because of warming and decreased ice cover, but the dynamics in low-latitude regions are governed by different processes, and production may decline as a result of reduced vertical mixing of the water column and, hence, reduced recycling of nutrients. There are strong interactions between the effects of fishing and the effects of climate because fishing reduces the age, size, and geographic diversity of populations and the biodiversity of marine ecosystems, making both more sensitive to additional stresses such as climate change. Inland fisheries are additionally threatened by changes in precipitation and water management. The frequency and intensity of extreme climate events is likely to have a major impact on future fisheries production in both inland and marine systems. Reducing fishing mortality in the majority of fisheries, which are currently fully exploited or overexploited, is the principal feasible means of reducing the impacts of climate change.

30. Westerling, A.L. Warming and Earlier Spring Increases Western U.S. Forest Wildfire Activity. *Science*, Aug. 18, 2006: Vol. 313. no. 5789, pp. 940 - 943, DOI: 10.1126/science.1128834
Western United States forest wildfire activity is widely thought to have increased in recent decades, but surprisingly, the extent of recent changes has never been systematically documented. Nor has it been established to what degree climate may be driving regional changes in wildfire. Much of the public and scientific discussion of changes in western United States wildfire has focused rather on the effects of 19th and 20th century land-use history. We compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it to hydro-climatic and land-surface data. Here, we show that large wildfire activity increased suddenly and dramatically in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. The greatest increases occurred in mid-elevation, Northern Rockies forests, where land-use histories have relatively little effect on fire risks, and are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.

31. Flanner, M.G. et. al. Present-day climate forcing and response from black carbon in snow JGR, V. 112, D11202, doi:10.1029/2006JD008003, 2007.
We apply our Snow, Ice, and Aerosol Radiative (SNICAR) model, coupled to a general circulation model with prognostic carbon aerosol transport, to improve understanding of climate forcing and response from black carbon (BC) in snow. Building on two previous studies, we account for interannually varying biomass burning BC emissions, snow aging, and aerosol scavenging by snow meltwater. We assess uncertainty in forcing estimates from these factors, as well as BC optical properties and snow cover fraction. BC emissions are the largest source of uncertainty, followed by snow aging. The rate of snow aging determines snowpack effective radius (r e), which directly controls snow reflectance and the magnitude of albedo change caused by BC. For a reasonable r e range, reflectance reduction from BC varies threefold. Inefficient meltwater scavenging keeps hydrophobic impurities near the surface during melt and enhances forcing. Applying biomass burning BC emission inventories for a strong (1998) and weak (2001) boreal fire year, we estimate global annual mean BC/snow surface radiative forcing from all sources (fossil fuel, biofuel, and biomass burning) of +0.054 (0.007–0.13) and +0.049 (0.007–0.12) W m-2, respectively. Snow forcing from only fossil fuel + biofuel sources is +0.043 W m-2 (forcing from only fossil fuels is +0.033 W m-2), suggesting that the anthropogenic contribution to total forcing is at least 80%. The 1998 global land and sea-ice snowpack absorbed 0.60 and 0.23 W m-2, respectively, because of direct BC/snow forcing. The forcing is maximum coincidentally with snowmelt onset, triggering strong snow-albedo feedback in local springtime. Consequently, the “efficacy” of BC/snow forcing is more than three times greater than forcing by CO_2. The 1998

and 2001 land snowmelt rates north of 50˚N are 28% and 19% greater in the month preceding maximum melt of control simulations without BC in snow. With climate feedbacks, global annual mean 2-meter air temperature warms 0.15 and 0.10˚C, when BC is included in snow, whereas annual arctic warming is 1.61 and 0.50˚C. Stronger high-latitude climate response in 1998 than 2001 is at least partially caused by boreal fires, which account for nearly all of the 35% biomass burning contribution to 1998 arctic forcing. Efficacy was anomalously large in this experiment, however, and more research is required to elucidate the role of boreal fires, which we suggest have maximum arctic BC/snow forcing potential during April–June. Model BC concentrations in snow agree reasonably well (r = 0.78) with a set of 23 observations from various locations, spanning nearly 4 orders of magnitude. We predict concentrations in excess of 1000 ng g-1 for snow in northeast China, enough to lower snow albedo by more than 0.13. The greatest instantaneous forcing is over the Tibetan Plateau, exceeding 20 W m-2 in some places during spring. These results indicate that snow darkening is an important component of carbon aerosol climate forcing.

32. van der Werf, G.R. et. al. Continental-Scale Partitioning of Fire Emissions During the 1997 to 2001 El Niño/La Niña Period. *Science* 2 January 2004:Vol. 303. no. 5654, pp. 73 - 76
DOI: 10.1126/science.1090753.
During the 1997 to 1998 El Niño, drought conditions triggered widespread increases in fire activity, releasing CH_4 and CO_2 to the atmosphere. We evaluated the contribution of fires from different continents to variability in these greenhouse gases from 1997 to 2001, using satellite-based estimates of fire activity, biogeochemical modeling, and an inverse analysis of atmospheric CO anomalies. During the 1997 to 1998 El Niño, the fire emissions anomaly was 2.1 ± 0.8 petagrams of carbon, or 66 ± 24% of the CO_2 growth rate anomaly. The main contributors were Southeast Asia (60%), Central and South America (30%), and boreal regions of Eurasia and North America (10%).

33. Westerling, A.L. Warming and Earlier Spring Increases Western U.S. Forest Wildfire Activity. *Science*, Aug. 18, 2006: Vol. 313. no. 5789, pp. 940 - 943, DOI: 10.1126/science.1128834
Western United States forest wildfire activity is widely thought to have increased in recent decades, but surprisingly, the extent of recent changes has never been systematically documented. Nor has it been established to what degree climate may be driving regional changes in wildfire. Much of the public and scientific discussion of changes in western United States wildfire has focused rather on the effects of 19th and 20th century land-use history. We compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it to hydro-climatic and land-surface data. Here, we show that large wildfire activity increased suddenly and dramatically in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. The greatest increases occurred in mid-elevation, Northern Rockies forests, where land-use histories have relatively little effect on fire risks, and are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.

34. I ntergovernmental Panel on Climate Change (IPCC) - Working Group 2, http://www.ipcc.ch/ipccreports/ar4-wg2.htm.

35. Steven W. Running, S.W. Is Global Warming Causing More, Larger Wildfires? *Science*, Aug. 18, 2006: Vol. 313. no. 5789, pp. 927 - 928 DOI: 10.1126/science.1130370.

36. Flannigan, M.D., et. al. Future Area Burned in Canada. Climatic Change. V 72, N 1-2 / September, 2005.
Historical relationships between weather, the Canadian fire weather index (FWI) system components and area burned in Canadian ecozones were analysed on a monthly basis in tandem with output from the Canadian and the Hadley Centre GCMs to project future area burned. Temperature and fuel moisture were the variables best related to historical monthly area burned with 36–64% of the variance explained depending on ecozone. Our results suggest significant increases in future area burned although there are large regional variations in fire activity. This was especially true for the Canadian GCM where some ecozones show little change in area burned, however area burned was not projected to decrease in any of the ecozones modelled. On average, area burned in Canada is projected to increase by 74–118% by the end of this century in a 3 × CO_2 scenario. These estimates do not explicitly take into account any changes in vegetation, ignitions, fire season length, and human activity (fire management and land use activities) that may influence area burned. However, the estimated increases in area burned would have significant ecological, economic and social impacts for Canada.

37. Roger Highfield, “Siberian forest fires due to climate change,” Jan. 1, 2007, *London Telegraph*, http://www.telegraph.co.uk/earth/main.jhtml?xml=/earth/2007/08/01/scisiberia101.xml

38. Balzter, H., Gerard, F., Weedon, G., Grey, W., Combal, B., Bartholome, E., Bartalev, S. and Los, S., 2007, Coupling of vegetation growing season anomalies with hemispheric and regional scale climate patterns in Central and East Siberia, Journal of Climate 20:15, 3713--3729, doi: 10.1175/JCLI4226

39. Roger Highfield, “Siberian forest fires due to climate change,” Jan. 1, 2007, *London Telegraph*, http://www.telegraph.co.uk/earth/main.jhtml?xml=/earth/2007/08/01/scisiberia101.xml

40. Hopkin, M. Carbon sinks threatened by increasing ozone. Nature 448, 396-397 (26 July 2007) | doi:10.1038/448396b; Published online 25 July 2007.
Pollutant poisons plants and hampers photosynthesis.

Rising levels of ozone pollution over the coming century will erode the ability of plants to absorb carbon dioxide from the atmosphere, a new climate-modelling study predicts.Ozone is already known to be a minor greenhouse gas, but the new calculations highlight another, indirect way in which it is likely to influence global warming by 2100.

41. National Oceanic and Atmospheric Administration, Greenhouse Gases, Frequently Asked Questions, http://www.ncdc.noaa.gov/oa/climate/gases.html#oz.

42. Steiner, A.L. Influence of future climate and emissions on regional air quality in California. JG R, V. 111, D18303, doi:10.1029/2005JD006935, 2006 http://www.agu.org/pubs/crossref/2006/2005JD006935.shtml.
Using a chemical transport model simulating ozone concentrations in central California, we evaluate the effects of variables associated with future changes in climate and ozone precursor emissions, including (1) increasing temperature; (2) increasing atmospheric water vapor; (3) increasing biogenic VOC emissions due to temperature; (4) projected decreases in anthropogenic NOx, VOC, and CO emissions in California for 2050; and (5) the influence of changing ozone, CO, and methane at the western boundary. Climatic changes expected for temperature, atmospheric water vapor, and biogenic VOC emissions each individually cause a 1–5% increase in the daily peak ozone. Projected reductions in anthropogenic emissions of 10–50% in NOx and 50–70% in VOCs and CO have the greatest single effect, reducing ozone by 8–15% in urban areas. Changes to the chemical boundary conditions lead to ozone increases of 6% in the San Francisco Bay area and along the west coast but only 1–2% inland. Simulations combining climate effects predict that ozone will increase 3–10% in various regions of California. This increase is partly offset by projected future emissions reductions, and a combined climate and emissions simulation yields ozone reductions of 3–9% in the Central Valley and almost no net change in the San Francisco Bay area. We find that different portions of the model domain have widely varying sensitivity to climate parameters. In particular, the San Francisco Bay region is more strongly influenced by temperature changes than inland regions, indicating that air quality in this region may worsen under future climate regimes.

43. Hopkin, M. Carbon sinks threatened by increasing ozone. Nature 448, 396-397 (26 July 2007) | doi:10.1038/448396b; July 25, 2007.
Pollutant poisons plants and hampers photosynthesis.

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44. NASA News Stories Archive, “NASA STUDY LINKS “SMOG” TO ARCTIC WARMING,” March 15, 2006, http://earthobservatory.nasa.gov/Newsroom/NasaNews/2006/2006031521918.html

45. P. G. Simmonds, P.G. Significant growth in surface ozone at Mace Head, Ireland, 1987–2003. Atmos. Env. V. 38, Issue 28, Sep. 2004, pp. 4769-4778, doi:10.1016/j.atmosenv.2004.04.036
Background ozone O_3 observations at Mace Head on the west coast of Ireland since 1987 show a significant positive trend of 0.49±0.19 ppb year-1 through to 2003. Increasing trends are observed for all seasons, with the largest trends

during the winter season, 0.63±0.31 ppb year-1 and the smallest trends during the summer, 0.39±0.25 ppb year–1. However, this growth rate has not been consistent over time with a major anomaly evident in 1998–1999. This major O3 perturbation is correlated with variations of CO2, CO, CH4, H2 and CH3Cl, which are likely due to large-scale biomass burning events in tropical and boreal regions during 1997–1999 coupled with an intense El Niño event.

46. Mickley, L.J. et. al. Effects of future climate change on regional air pollution episodes in the United States. Geophys. Res. Lett. Vol. 31, no. 24, [np]. Dec
We examine the impact of future climate change on regional air pollution meteorology in the United States by conducting a transient climate change (1950-2052) simulation in a general circulation model (GCM) of the Goddard Institute of Space Studies (GISS). We include in the GCM two tracers of anthropogenic pollution, combustion carbon monoxide (COt) and black carbon (BCt). Sources of both tracers and the loss frequency of COt are held constant in time, while wet deposition of BCt responds to the changing climate. Results show that the severity and duration of summertime regional pollution episodes in the midwestern and northeastern United States increase significantly relative to present. Pollutant concentrations during these episodes increase by 5-10% and the mean episode duration increases from 2 to 3-4 days. These increases appear to be driven by a decline in the frequency of mid-latitude cyclones tracking across southern Canada. The cold fronts associated with these cyclones are known to provide the main mechanism for ventilation of the midwestern and northeastern United States. Mid-latitude cyclone frequency is expected to decrease in a warmer climate; such a decrease is already apparent in long-term observations. Mixing depths over the midwest and northeast increase by 100-240 m in our future-climate simulation, not enough to compensate for the increased stagnation resulting from reduced cyclone frequency.

47. C. Hogrefe, et. al. Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions JGR, VOL. 109, D22301, doi:10.1029/2004JD004690, 2004.
To simulate ozone (O3) air quality in future decades over the eastern United States, a modeling system consisting of the NASA Goddard Institute for Space Studies Atmosphere-Ocean Global Climate Model, the Pennsylvania State University/National Center for Atmospheric Research mesoscale regional climate model (MM5), and the Community Multiscale Air Quality model has been applied. Estimates of future emissions of greenhouse gases and ozone precursors are based on the A2 scenario developed by the Intergovernmental Panel on Climate Change (IPCC), one of the scenarios with the highest growth of CO2 among all IPCC scenarios. Simulation results for five summers in the 2020s, 2050s, and 2080s indicate that summertime average daily maximum 8-hour O3 concentrations increase by 2.7, 4.2, and 5.0 ppb, respectively, as a result of regional climate change alone with respect to five summers in the 1990s. Through additional sensitivity simulations for the five summers in the 2050s the relative impact of changes in regional climate, anthropogenic emissions within the modeling domain, and changed boundary conditions approximating possible changes of global atmospheric composition was investigated. Changed boundary conditions are found to be the largest contributor to changes in predicted summertime average daily maximum 8-hour O3 concentrations (5.0 ppb), followed by the effects of regional climate change (4.2 ppb) and the effects of increased anthropogenic emissions (1.3 ppb). However, when changes in the fourth highest summertime 8-hour O3 concentration are considered, changes in regional climate are the most important contributor to simulated concentration changes (7.6 ppb), followed by the effect of increased anthropogenic emissions (3.9 ppb) and increased boundary conditions (2.8 ppb). Thus, while previous studies have pointed out the potentially important contribution of growing global emissions and intercontinental transport to O3 air quality in the United States for future decades, the results presented here imply that it may be equally important to consider the effects of a changing climate when planning for the future attainment of regional-scale air quality standards such as the U.S. national ambient air quality standard that is based on the fourth highest annual daily maximum 8-hour O3 concentration.

48. Elisabeth Rosenthal, "In Spain, Water Is a New Battleground," *The New York Times*, June 3, 2008, http://www.nytimes.com/2008/06/03/world/europe/03dry.html?scp=1&sq=global+warming+Desertification&st=nyt.

49. "Desertification Alters Regional Ecosystem Climate Interactions," *ScienceDaily*, Jan. 27, 2005, http://www.sciencedaily.com/releases/2005/01/050125091447.htm.

50. William H. Schlesinger, W.H. et. al. Biological Feedbacks in Global Desertification. *Science*, March 2, 1990: Vol. 247. no. 4946, pp. 1043 - 1048, DOI: 10.1126/science.247.4946.1043.
Studies of ecosystem processes on the Jornada Experimental Range in southern New Mexico suggest that longterm grazing of semiarid grasslands leads to an increase in the spatial and temporal heterogeneity of water, nitrogen, and

other soil resources. Heterogeneity of soil resources promotes invasion by desert shrubs, which leads to a further localization of soil resources under shrub canopies. In the barren area between shrubs, soil fertility is lost by erosion and gaseous emissions. This positive feedback leads to the desertification of formerly productive land in southern New Mexico and in other regions, such as the Sahel. Future desertification is likely to be exacerbated by global climate warming and to cause significant changes in global biogeochemical cycles.

51. Nasrallah, H.A. & Balling Jr., R.C. Impact of desertification on temperature trends in the Middle East. Environmental Monitoring and Assessment, Volume 37, Numbers 1-3, Pages265-271 Jan. 1995, DOI 10.1007/BF00546894.
The intense interest in desertification and climate change has stimulated detailed studies of temperature records in many areas of the world. In this investigation, the temperature records from the Middle East region are analyzed over the period 1950–1990. Results reveal a linear, statistically significant temperature increase of 0.07 ˚C/decade over the 41-year period. An analysis of spatial controls on these temperature changes reveals a warming effect associated with both overgrazing and the degree of human-induced desertification. The results of this study are consistent with theoretical and empirical studies predicting and demonstrating a warming signal associated with these land surface changes in the world's dryland areas.

52. Burke, E. J., Brown, S. J., and Christidis, N., 2006: Modeling the recent evolution of global drought and projections for the 21st century with the Hadley Centre climate model. J Hydrometeorol, 7, 1,113-1,125. doi: 10.1175/JHM544.1.