

HOME

THIS WEEK'S CONTENTS

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- [Table of Contents](#)
- [cen-chemjobs.org](#)
- [Today's Headlines](#)
- [Cover Story](#)
- [Editor's Page](#)
- [Business](#)
- [Government & Policy](#)
- [Science & Technology](#)
- [ACS News](#)
- [Calendars](#)
- [Books](#)
- [Career & Employment](#)
- [Special Reports](#)
- [Nanotechnology](#)
- [What's That Stuff?](#)

[Back Issues](#)

[Safety Letters](#)
[Chemyclopedia](#)

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COVER STORY

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CLIMATE CHANGE

Earth is warming, and the environmental changes--largely attributable to greenhouse gases--are dramatic and potentially dangerous in the Arctic

[BETTE HILEMAN](#), C&EN WASHINGTON

A miniature Christmas tree bulb dissipates about 1 watt, mostly as heat. Human-made greenhouse gases provide almost 2 watts of heat per square meter of Earth's surface. So the addition of such gases to the atmosphere through fossil fuel burning and other activities is equivalent to placing "two tiny bulbs over every square meter of Earth's surface, burning night and day," says James E. Hansen, director of the [National Aeronautics & Space Administration's Goddard Institute for Space Studies](#).

Much research confirms that something on the order of this amount of heat applied continuously for many years has contributed significantly to the rise in the global average surface air temperature of 0.7–0.8 °C (1.2–1.4 °F) observed since 1900. Study of climate history has shown that small forces, maintained long enough, can cause climate change. Unless huge reductions are made in fossil fuel use, the atmospheric CO₂ concentration, now at 370 ppm, is expected to reach 560–1,000 ppm by the end of this century. This will raise heating due to greenhouse gases to at least 3 W per m² and average global temperatures a further 1.4–5.8 °C (2.5–10.4 °F).

Clearly, Earth is warming. Surface air temperature records, radiosonde (a small instrument package suspended below a balloon) data, and



BREAKING UP The flow rate of the Jakobshavn Glacier on the western slope of Greenland has increased recently. The glacier currently moves about 10 km per year and calves a large number of icebergs into Baffin Bay. PHOTO BY KONRAD STEFFEN

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CLIMATE CHANGE

Earth is warming, and the environmental changes--largely attributable to greenhouse gases--are dramatic and potentially dangerous in the Arctic

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satellite observations all indicate that the planet has heated up over the past century. The 11 warmest years since the beginning of instrumental records have occurred since 1990. The warming observed in the Northern Hemisphere since 1900 has been greater than any other during the past millennium. At the same time, ocean temperatures have risen significantly since the mid-1950s.

Even without temperature records, there is strong evidence the planet is heating up. Mountain glaciers all over the world are retreating. Snow cover is decreasing. Snow is falling later in the season and melting earlier than it did a few decades ago.

Concomitant with the warming have been increases in cloud cover and precipitation at mid to high latitudes in the Northern Hemisphere, and decreases in precipitation in the subtropics. Droughts are more severe in Asia and Africa and in some parts of the U.S. and Europe. Since 1900, sea levels have risen 10 to 20 cm, from thermal expansion and melting glaciers. El Niño events--the periodic warming of the tropical Pacific that affects weather patterns around the world--have apparently become more intense and more frequent.

AT THE SAME TIME, there have been opposing and neutral trends. For example, most of Antarctica, not including the West Antarctic Peninsula, has grown cooler in the past few decades. So far, there is no evidence that hurricanes have increased in intensity or frequency. And data trends for tornadoes are ambiguous.



FROZEN IN TIME At a camp on Mount Kilimanjaro, Thompson (left) and Mary Davis examine an ice core drilled from the Kilimanjaro Glacier. COURTESY OF LONNIE THOMPSON, OHIO STATE UNIVERSITY

greener and darker shrubs and trees, says James E. Overland of the [National Oceanic & Atmospheric Administration's \(NOAA\) Pacific Marine Environmental Laboratory](#) in Seattle.

These developments were announced in 2001 by the [United Nations Intergovernmental Panel on Climate Change \(IPCC\)](#) in its [third assessment report](#). The assessment represents the work and review of thousands of leading climate scientists and other specialists from more than 40 countries.

The most striking evidence of climate change has appeared in the Arctic over the past three decades. Perennial or year-round sea ice in the North Polar region has decreased 3% per decade, and the area of the Greenland ice sheet surface that melts during summer has increased dramatically. The extent of tundra, which until recently covered about 24% of land in the Northern Hemisphere, has also declined steeply--15% since the 1970s. As permafrost melts, some of the grayish mosses that typically blanket the tundra are replaced by

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During the past two decades, temperatures have risen faster in the Arctic than anywhere else on the planet. Josefino Comiso, research scientist at NASA Goddard Space Flight Center, found that temperatures over Arctic summer sea ice increased 1.22 °C per decade beginning in 1980. The Arctic as a whole warmed eight times faster over the past two decades than over the past 100 years, he says.

The changes under way in the Arctic are likely to have profound, mostly negative consequences for the weather and economy in the continental U.S. and Europe, says Jonathan Overpeck, director of the [Institute for the Study of Planet Earth at the University of Arizona](#). It cannot be proven that Arctic changes are not solely the consequence of natural variability. But they are totally consistent with the predictions climate scientists made about 20 years ago. "At that time, we said the Arctic would be one of the first places to show noticeable changes from greenhouse gases," he explains.

Because trends in the Arctic are so dramatic and so unsettling in their rapidity, the National Science Foundation is leading a multiagency initiative to understand their full scope. It has established a program called [Study of Environmental Arctic Change \(SEARCH\)](#). In this program, scientists are investigating exactly how the observed changes relate to the Arctic's natural variability and if they indicate the start of a major climate shift in the North.

To be sure, there are uncertainties in the science of climate change. But the uncertainties are not about whether Earth has already warmed or whether greenhouse gases are responsible for a large part of this warming, says John P. Holdren, physicist and professor in the Kennedy School of Government at Harvard University. What they do concern "is the precise magnitude of the changes to be expected by 2030, or 2050, or 2100 if civilization does not change course," he explains. "The character, geographic distribution, and timing of damages to human well-being" from greenhouse warming are other uncertainties, he says.

Natural and human influences--called "forcings" in the climate-science community--alter the flow of radiant energy in the atmosphere, cooling and warming Earth by perturbing its energy balance. Positive forcings warm the planet while negative ones cool it.

One of these forcings is greenhouse gases, which alter the planet's energy balance by absorbing infrared radiation that would otherwise escape to space. The major greenhouse gases include CO₂, methane, nitrous oxide, tropospheric ozone, chlorofluorocarbons (CFCs), and water vapor. With the exception of water vapor, the concentrations of all the greenhouse gases are controlled more or less directly by human activities. (Water vapor levels depend on Earth's temperature and the availability of liquid water, and thus are indirectly affected by humans.)

Other forcings include reflective aerosols (mostly sulfate particles from burning of fossil fuel), black carbon particles (soot), land-cover changes, variations in solar output, and cloud-cover changes resulting from global temperature variations and aerosols.


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According to the IPCC third assessment report, the atmospheric concentrations of nearly all greenhouse gases have climbed more or less continuously since preindustrial times. The CO₂ concentration increased from 280 ppm in preindustrial times to 368 ppm in 2000, and there are no indications that its rate of increase is slowing greatly or stopping. IPCC projects that the CO₂ level will rise to 580 ppm by midcentury and about 840 ppm by 2100, if present trends continue.



GREEN INVASION Mann uses proxy temperature data to track long-term changes. COURTESY OF MICHAEL E. MANN

The methane level rose from about 700 ppb in preindustrial times to about 1,750 ppb in 2000. The abundance of nitrous oxide grew from 270 ppb to 314 ppb. The average level of tropospheric ozone increased from 25 dobson units to 34 dobson units (one dobson unit equals 2.7×10^{16} ozone molecules per cm³ of air). In contrast, the atmospheric abundances of most CFCs have been decreasing recently due to production cutbacks agreed to in the [Montreal Protocol on Substances That Deplete the Ozone Layer](#).

Although none of the greenhouse gases was measured continuously in the atmosphere before 1958, earlier levels have been determined by analyzing tiny air bubbles trapped in ice cores drilled from ice sheets and glaciers, especially those in Greenland and Antarctica. Every year, a new layer of snow accumulates on glaciers, and as the layers are compressed by overlying snow and ice, air bubbles are trapped. Ice cores thus yield stratigraphic information about atmospheric chemicals and particulates for each year of the glacier's existence.

FINE PARTICLES known as aerosols have complex effects on global temperatures that are not well understood or measured. Some aerosols, such as sulfates, are highly reflective and cool Earth, Hansen says. Also, reflective aerosols have indirect effects on clouds, making them brighter and therefore more likely to reflect sunlight, thus causing cooling as well.

But soot from incomplete burning of coal and diesel fuel acts primarily to heat the planet by warming the atmosphere. However, in regions where airborne soot is dense, it cools by reducing the amount of sunlight reaching the surface. Unlike CO₂, which has an atmospheric lifetime of about 100 years



ICE-CAPADE Sturm's research team heads across the North Slope of Alaska to scour the Alaskan tundra for clues to the role snow cover plays in climate change. The team analyzed the composition of the snow along the route to determine the source of the snow and how much it has been affected by aerosols that waft into the Arctic from more southerly latitudes.

NATIONAL SCIENCE FOUNDATION PHOTO

and therefore builds up in the atmosphere over long periods, aerosols are generally washed out by precipitation in two weeks or less.

When forests are replaced by cropland, the landscape becomes lighter and thus more reflective, so this has a cooling effect, Hansen says. On timescales of 1,000 years, the sun's irradiance has been fairly steady, varying up and down by a few tenths of a watt per square meter around a constant mean. Over the past century, it increased by a few tenths of a watt per square meter. The net sum of positive and negative forcings--those from greenhouse gases, aerosols, landscape

changes, and sun and cloud variations--is 1.6 ± 1 W per m^2 , Hansen estimates.

Although the uncertainties are great, there is evidence this net forcing is approximately correct, Hansen says. When this figure is used as an input in climate models, the average global temperatures predicted by the models closely match observed temperatures over the past several decades.

The net positive forcing has driven average Northern Hemisphere temperatures to levels not seen for almost 2,000 years, says [Michael E. Mann](#), professor of environmental sciences at the University of Virginia.

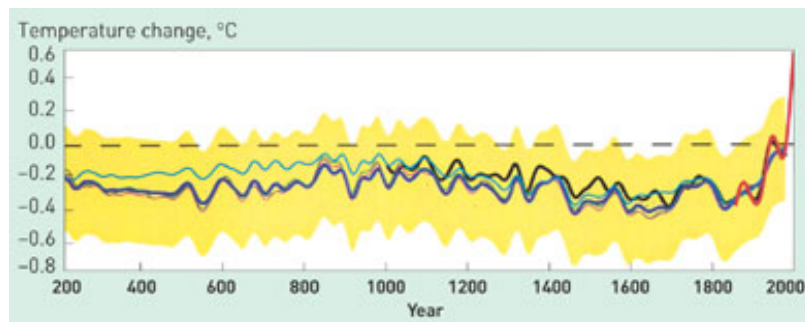
Mann used what are called proxy temperature data for eight distinct regions of the globe to construct a graph of Northern Hemisphere temperatures spanning nearly two millennia. The proxy indicators consist of tree-ring measurements and pollen records in sediments, as well as ice-core data. In warm years, trees tend to grow faster, so wider tree rings usually indicate higher temperatures.

The isotopic composition of the oxygen from the water in each ice layer also indicates what the global temperature was during the year when the layer was deposited. In warm years, the ratio of ^{18}O to ^{16}O is higher because the heavier isotope is more common in precipitation when temperatures are higher. Some roughly 2,800-meter-long ice cores drilled from Greenland and Antarctica provide climate history for the past 110,000 years.

Mann's graph shows that the late-20th-century warmth in the Northern Hemisphere is unprecedented for almost two millennia. The historical period from 800 to 1400 was moderately warmer than the periods preceding and following it, he concludes, "but this was dwarfed by the late-20th-century warming." For the Southern Hemisphere, however, there are not enough proxy data to make definitive statements about temperatures, he says.

The impacts of higher global temperatures include more precipitation, a larger part of the precipitation coming in extreme events, earlier snow melt, and more drought. As global temperatures rise, more water evaporates, so inevitably greater amounts of rain and snow fall over the planet as a whole. Global warming has already affected hydrological systems in many parts of the world. According to [Munich Re](#), a large reinsurance company that provides insurance to insurance firms, total global monetary losses from weather and flood catastrophes in the 1990s were more than three times what they were in the 1980s.

Analyses conducted in the past decade show that precipitation increased 5–10% over land areas of the Northern Hemisphere during the 20th century. At the same time, droughts have become more frequent and intense in parts of Asia and Africa and in some areas of the U.S. and Europe.



OUT OF BOUNDS In the Northern Hemisphere, the temperature in 2000 was higher than it had been at any time in almost two millennia. The dashed line shows the mean temperature for the period 1961–90. The different colored lines represent various estimates of Northern Hemisphere average temperatures based on slightly different subgroups of proxy data or on different methods of averaging the data. The yellow shading indicates the 95% confidence interval, meaning there is only a 5% probability that the true temperature values lie outside the yellow region. SOURCE: Michael E. Mann [*Geophys. Res. Lett.*, 30, 1820 (2003)]

RECENTLY, Pavel Groisman, a researcher at [NOAA's National Climatic Data Center](#), analyzed weather data spanning more than a century for the U.S., excluding Hawaii and Alaska. He reports in an upcoming article in the *Journal of Hydrometeorology* that since 1895 rainfall increased 7% over the lower 48 states. In most regions, precipitation rose, but it declined in the Southwest. He also finds that heavy rains increased much faster than the total amount of rainfall. Since 1895, the amount of rainfall coming in extreme events rose 14%, but most of the increase occurred during the past three decades.

Droughts have been more intense and frequent in the Southwest, in California in the spring--and surprisingly--in the Northeast, even though the total amount of annual precipitation there has risen, Groisman reports. In the West, spring now comes two to three weeks earlier than it did 50 years ago, he notes.

Outside the U.S., precise trend data for precipitation and drought over the past century are not available for most regions.

According to the IPCC third assessment report, El Niño events became "more frequent, persistent, and intense during the past 20 to 30 years," compared with earlier in the century. Some well-established effects of El Niño are enhanced rainfall over Peru, Ecuador, the southern U.S., and the central Pacific Ocean, and drought in Indonesia, Australia, southern Africa, and northeastern Brazil. When El Niños are very intense, floods and droughts in those regions can be catastrophic.

Beginning in the 1980s, some researchers began using computer models to reproduce the physics of the ocean and atmosphere as they evolve during El Niño events. These models are fully coupled mathematical simulations of the physics, chemistry, and biology of the atmosphere, land surface, cryosphere (the frozen part of Earth's surface), and oceans. They have been used to reproduce many of the oceanic and atmospheric effects of El Niños in the tropical Pacific and to predict the onset of such events months in advance.

In 1992, scientists at the [National Center for Atmospheric Research \(NCAR\)](#) used computer models to simulate the evolution of an El Niño when the atmospheric concentration of CO₂ is about 560 ppm, a level expected long before the end of this century. The results indicate that El Niños may become more intense as CO₂ concentrations rise.

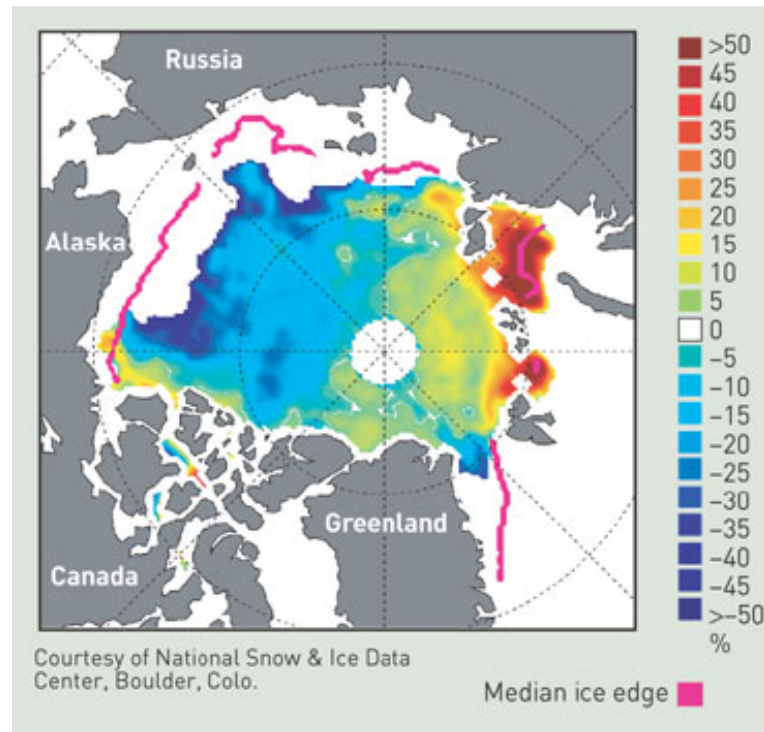
From the observational record, "we can say that El Niños have been more intense and more frequent in the past 30 years," says Kevin E. Trenberth, head of the climate analysis group at NCAR. There is evidence they are behaving in unusual ways, he says.

Also, Trenberth notes, there is evidence that the incidence of tornadoes has been increasing over the past few decades. "But it is very hard to tell if this represents a real increase or just that there are more people in more places to find them. You just can't get reliable tornado records to compare with," he explains.

One unambiguous feature of the warming Earth is that alpine (mountain) glaciers are melting all over the world. [Lonnie G. Thompson](#), professor of geological sciences at Ohio State University, has been studying glaciers in Peru, Bolivia, Antarctica, Greenland, China, Africa, Kyrgyzstan, and Russia for the past 25 years. On 45 expeditions, he and his team have drilled ice cores from glaciers in all these areas and taken them back to Ohio State's [Byrd Polar Research Center](#) for analysis. The analyses provide many clues to Earth's past climate.

From his expeditions and the work of other glaciologists, Thompson concludes that every tropical glacier on the planet is retreating and that the retreat of lower elevation tropical glaciers is accelerating.

For any individual glacier, "you could argue that the rapid melting is caused by something other than climate change," Thompson says. For example, in the case of Tanzania's Kilimanjaro, which is an ancient volcano, "some have suggested that extra heat is coming from the bedrock beneath, even though measurements show the bedrock is below freezing," he says. But the fact that tropical glacier retreat is so universal "argues for something bigger as a driver," he explains. "For me, it is the weight of the evidence that really makes a compelling case for large-scale human impact from greenhouse gases," he says.



MELTDOWN In September 2003, Arctic sea ice nearly reached the record minimum observed the previous year. The pink line shows the average sea ice cover for September. The colors on the map indicate how much the sea ice concentration deviated from the norm. For example, the concentration of sea ice in the dark blue areas north of Alaska is 30–40% below the norm, while yellow areas show where the ice concentration is above the average value for that time of year. Ice concentration is the percentage of a given area that is covered with ice.

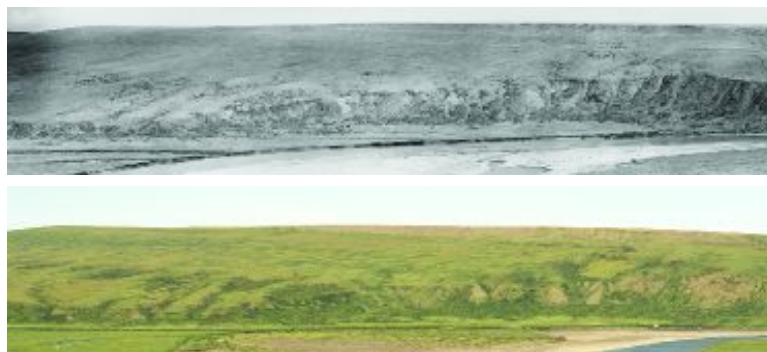
BY STUDYING MAPS and aerial photos that show the extent of the Kilimanjaro glacier at different times during the 20th century, Thompson estimates it will be gone by 2015–20.

In the Andes of Peru, the Quelccaya Glacier is not just retreating, but "what we see there is a very strong exponential acceleration in the rate of retreat," Thompson says. On the edge of the glacier, he recently

found a perfectly preserved nonwoody plant that looked as if it had been put in a freezer yesterday. Carbon-14 analyses at four separate labs dated the plant at about 5,200 years old. "This shows you the ice field has not been smaller than it is today for 5,200 years," he says.

"What you very clearly see from the individual and combined records from glacier cores is that what has happened in the past few decades is unusual, certainly in the context of the past 2,000 years," Thompson says. "What the melting glaciers and the isotopes are telling us is Earth is getting warmer," he says.

Thompson sees the loss of tropical ice as not just a vivid sign of a warming planet, but as a large loss of a way to study past climates. "You are losing the history of Earth as it is recorded in the ice," he says.



DOUBLE TAKE These two photos were taken from a helicopter at exactly the same location on Alaska's North Slope, as part of Sturm's research. The photo on top taken in 1948 shows tundra with virtually no shrubs. The photo on the bottom taken in 2002 shows that the tundra has been invaded by shrubs as air and ground temperatures have increased. PHOTO BY KEN TAPE

THE DISAPPEARANCE of glaciers can also cause severe economic disruption. For example, Kilimanjaro is the number one foreign currency generator for Tanzania. "There is a big debate about how many tourists will still come to this mountain if there is no ice on it," Thompson says. Also, "in Peru during the dry season, many hydroelectric plants depend on meltwater from the glaciers," he says. When the glaciers are gone, they will have to shut down in the dry season.

The changes in the Arctic over the past few decades are so striking and rapid that it would be hard to exaggerate them. Since 1970, temperatures in the Arctic have been increasing about twice as fast as the global average.

In 2002, "we saw sea ice thinning dramatically and retreating to the smallest area it has ever been in summer," says the University of Arizona's Overpeck. The reduction began about 30 years ago. In September 2002, the area covered by sea ice in the Arctic reached an all-time minimum--14% below the long-term average--and in 2003, the area was almost as small.

The extent of sea ice is measured by satellite with passive microwave imagery that detects radiation emitted from Earth's surface. Perennial sea ice has been decreasing 3% per decade since satellite records started in 1979, while summer sea ice has decreased 9% per decade. In summer, Arctic sea ice used to cover an area about the size of the U.S., so a 14% loss represents an area about the size of Colorado and New Hampshire combined.

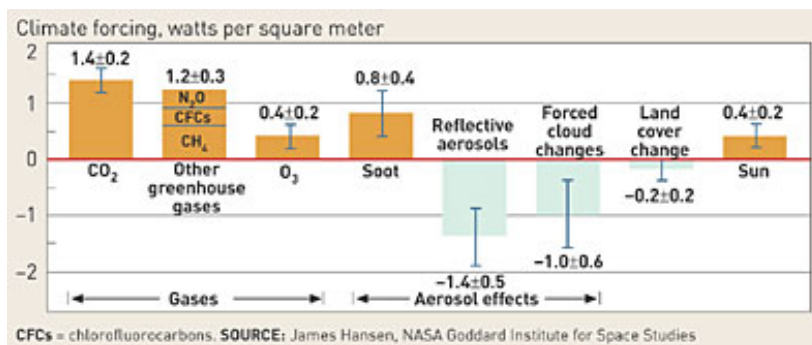
"In the past, if you had a record-low ice extent in one summer, quite typically it would be followed by a more normal year the next summer," says Mark C. Serreze of the [National Snow & Ice Data Center at the University of Colorado](#). The graphs of sea ice extent from year to year used to resemble a sawtooth around a constant mean, he says. This has not been happening recently. A minimum in one year is followed by another low that almost matches it.

At the same time that the extent of Arctic sea ice has shrunk, the ice has also thinned rapidly. Careful measurements taken by U.S. Navy submarines in some areas show the ice is much thinner than in the past. But submarines have not been used to measure ice thickness in all parts of the Arctic, Overland says.

Another dramatic change can be seen in the tundra. There has been a 15% loss of tundra in the Arctic since the 1970s. As tundra warms up, shrubs and trees replace some of the lichen and mosses growing there. Matthew Sturm, geophysicist at the [U.S. Army Cold Regions Laboratory](#), in Alaska, has been comparing photographs of tundra taken about 50 years apart on Alaska's North Slope. Photographs shot from helicopters at precisely the same location in 1948 and 2002, for example, show that some of the tundra has been invaded by shrubs.

Laboratory experiments demonstrate that as tundra warms, some of the mosses and lichens are replaced by shrubs. So this photographic evidence is a clear sign the tundra is warming, Sturm says.

Satellite photos also reveal that the tree line has moved north in the Arctic as tundra heats up and air temperatures increase.



CLIMATE PRODS These bars indicate in watts per square meter natural and human influences--called "forcings" in the climate-science community--that alter the flow of radiant energy in the atmosphere and cool or warm Earth by perturbing its energy balance. Positive forcings warm the planet, whereas negative ones cool it. The largest single positive forcing is CO₂. Without major changes in fossil fuel burning, the forcing from CO₂ is expected to grow much larger as the century progresses. Reflective aerosols, and the cloud changes that occur when clouds contain reflective aerosols, are negative forcings, but their magnitude is highly uncertain. Reflective aerosols include sulfates, nitrates, organic carbon, and soil dust.

MANY INVESTIGATORS have detected changes in temperatures in permafrost, the permanently frozen layer below the surface. For example, researchers at the U.S. Geological Survey have been measuring permafrost temperatures from deep holes drilled in northern Alaska since the late 1940s. Through the mid-1980s, permafrost in the region generally warmed 2–4 °C. There were brief periods of cooling in the early 1980s and from 1990–93, but the permafrost has since warmed. The overall trend from 1940 until today is toward warmer temperatures. Similar trends have been reported in Russia.

In most parts of northern Alaska, permafrost has not warmed up enough to melt, but in some Alaskan towns farther south, it has melted. In those places, buildings, roads, electric utility poles, and other structures built on permafrost have fallen over or collapsed as the ground sinks beneath them.

The summer melting of the Greenland ice sheet since 1979 is one of the most graphic alterations taking place in the Arctic. [Konrad Steffen](#), deputy director of the [Cooperative Institute for Research in Environmental Science](#) at the University of Colorado, uses passive microwave satellite data to detect the total area of surface melt on the ice sheet. From 1979 to 2003, the melted area as measured in September increased 16%. In 2002, the year of maximum melt, the melted area covered 264,400 sq miles. In 2003, it was almost as large.

One surprising aspect was that the melting extended up to an elevation of 2,000 meters (6,560 feet) on the northern and northeastern parts of the ice sheet, Steffen says. The conditions on the ice sheet are confirmed with 20 automatic weather stations that transmit data hourly via satellite. Using the Internet, anyone can access this weather information (http://cires.colorado.edu/steffen/aws/current_GC-Net_plots.html).

Another change is that the Greenland ice sheet is shrinking along the margins, the areas of the ice sheet near the coastline. NASA used an aircraft fitted with a highly sensitive laser altimeter that can measure elevation with an accuracy of 1 cm to detect elevation changes in Greenland. It conducted two missions over Greenland five years apart along the same path. Data from these flights show that the central

portion of the ice sheet, which is about 3 km thick, is basically stable, with little or no change in elevation.

But in some places along the margins of the ice sheet, the elevation of the surface is falling by more than 1 meter per year. This means that the margins, which are about 1 km thick, are losing more than 1 meter of thickness per year in some areas. Seventy percent of the ice sheet that has an elevation less than 2,000 meters is thinning significantly, Steffen says.

The loss of thickness cannot be explained by melting alone, Steffen says. There is not enough energy to melt that much ice. However, because there is so much meltwater on the surface of the ice sheet, it penetrates the ice and lubricates the interface between the ice and the bedrock, allowing the ice sheet to flow faster. The increased flow results in higher than normal iceberg production.



Serreze



Holdren

PHOTOS BY BETTE HILEMAN

Between winter and summer, the flow speed of some Greenland glaciers increases 10–15%, Steffen says, and when winter comes, the flow slows again. Flow speeds fluctuate with available meltwater.

The Jakobshavn Glacier, a major outlet of the ice sheet in western Greenland, flows 10 km per year into the ocean, Steffen says. "You can hear it flowing when you are sleeping [in camp] on the glacier," he says.

The melting in Greenland and increased flow of Greenland glaciers into the sea could cause a dramatic sea-level rise, even in the next 100 years, Overpeck says. "It could be more than a meter by 2100," he explains, "and over the next few centuries, up to 5–6 meters if much of Greenland melts."

Partly as a consequence of surface melting and accelerated ice flow from the Greenland ice sheet, "the North Atlantic Ocean is freshening dramatically around Greenland," Overpeck says. But the primary reason for this freshening is probably increased rainfall in the vicinity of the Arctic Basin, which means that the rivers flowing into Arctic waters have greatly increased flow.

Increased freshwater coming into the Arctic could result in climate change for regions outside the Arctic. Currently, the Gulf Stream, which resembles a large river of warm water on the ocean surface, flows north and warms Northern Europe. As it cools, the atmosphere gains heat, and the water becomes more dense. Then, the river descends to great depths in the Greenland, Iceland, and Norwegian Seas, and returns south.

This deep-water production is not just a function of temperature. It is also a function of salinity. The theory is that "if you could freshen the upper ocean enough, you could potentially shut down this deep-water production," called the thermohaline circulation, Serreze says.

There are several ways that could happen: with increased river discharge to the Arctic Ocean or with more meltwater and icebergs coming from the Greenland ice sheet, Serreze says.

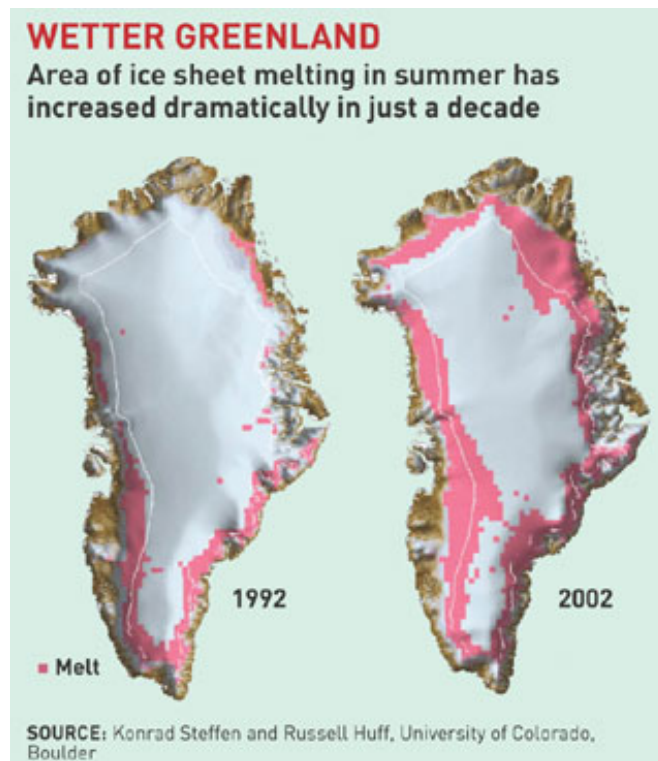
A recent paper in *Geophysical Research Letters* [30, 1911 (2003)] indicates that by 2080, so much meltwater and icebergs could come off the Greenland ice sheet that they would strongly slow the thermohaline circulation. If this happens, there would be a marked temporary cooling in eastern Greenland and the North Atlantic, which would make parts of northwestern Europe colder. However, if Earth as a whole continued to warm from rising levels of CO₂, this regional cooling would eventually be overwhelmed.

The aim of the 1992 UN Framework Convention on Climate Change is to stabilize atmospheric concentrations of greenhouse gases to prevent dangerous anthropogenic interference with climate. In a presentation to the U.S. Council on Environmental Quality in June, Hansen argued that "we are much closer to dangerous anthropogenic interference than is generally realized."

The IPCC third assessment report assumes that the great ice sheets in Greenland and Antarctica will remain stable over this century. Consequently, it estimates that sea level will rise only 20–50cm, on average, by 2100 as Earth warms several degrees Celsius.

Building up a great ice sheet takes a long time, Hansen pointed out. It is limited by the amount of snow that falls each year. In contrast, ice sheet breakup "is driven by highly nonlinear processes and feedbacks," he explained. One feedback is that as ice melts in Greenland, for example, the Arctic region grows darker and is thus able to absorb, rather than reflect, more sunlight. Meltwater absorbs more sunlight than ice.

About 14,000 years ago, as the planet was coming out of the last ice age, Hansen said, 14,000 km³ of ice melted each year for 400 years, which caused sea levels to rise 1 meter every 20 years during those centuries.



GIVEN HOW QUICKLY sea levels rose following the last ice age, when temperatures in Antarctica were only 1 °C higher than those in the mid-20th century, it may be incorrect to assume, as the IPCC report does, that sea levels will rise only moderately by 2100, Hansen said. For this reason, he said, allowing the average global temperature to rise more than 1 °C may constitute dangerous interference with climate.

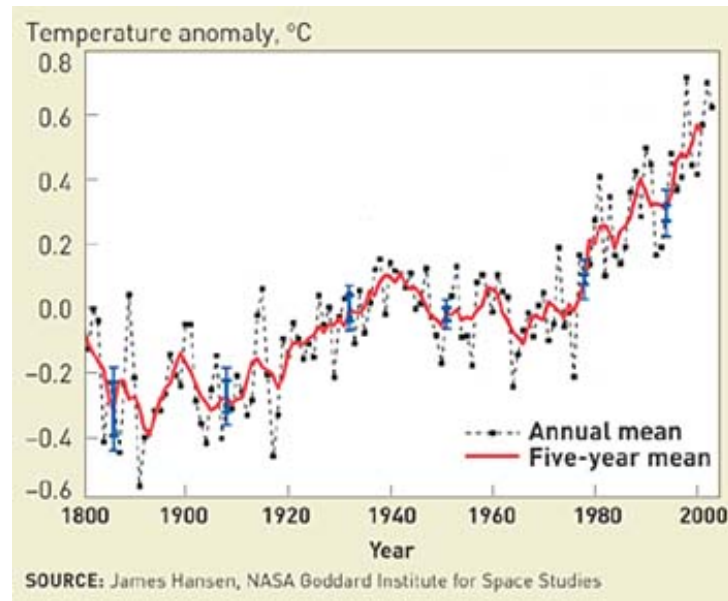
Research on the stability of the ice sheets deserves high priority, Hansen said. A satellite--IceSat--recently launched by NASA may provide useful data on ice sheet stability, he observed.

Hansen suggested controlling soot, tropospheric ozone, and methane, and stabilizing CO₂ emissions rather than trying during the next 50 years to make large reductions in CO₂ emissions.

Holdren, on the other hand, says there is no way to avoid controlling CO₂ in any strategy seeking to limit global change. "Under anything resembling 'business-as-usual' growth of economic activity and fossil-fuel use, CO₂'s importance relative to other influences on global climate will increase dramatically through the 21st century," he wrote in a background document in May. Although it is worthwhile to limit emissions of black soot and non-CO₂ greenhouse gases, "carbon dioxide is the 800-lb gorilla in the climate-change problem, and any sensible strategy must aim for large reductions" in its emissions, he observed.

Today, health researchers point out that there are 3 million largely preventable deaths from AIDS each year. But by the middle of this century or sooner, that toll may be dwarfed by fatalities from climate change. A large portion of the world's population lives only a few meters above sea level. In India, for example, a 0.88-meter rise in sea level would lead to 20 million to 60 million environmental refugees,

said IPCC Chairman Rajendra K. Pachauri in a speech this year. Much of South Florida is situated only 1 meter above sea level. If melting in Greenland continues to accelerate, tragedies could ensue in many parts of the world by midcentury.



HEATING UP There has been a strong warming in the past 30 years. Global average surface temperatures were generally higher after 1989 than they were earlier in the century. The temperatures represent degrees Celsius above and below the 1951–80 average temperature. The black squares represent annual mean temperatures, the red line shows the five-year running mean, and the blue bars show 95% confidence limits to account for incomplete spatial sampling, meaning there is only a 5% probability that the true temperature values lie above or below the blue bars.

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CLIMATE CHANGE

Earth is warming, and the environmental changes--largely attributable to greenhouse gases--are dramatic and potentially dangerous in the Arctic

CONFUSION

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'HEATED' DEBATE

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