focus A

The science of climate change

The climate is changing—that is now indisputable. There is a scientific consensus that the world is becoming a warmer place principally attributable to human activities. In the words of the Intergovernmental Panel on Climate Change (IPCC) in its fourth assessment report: "Warming of the climate system is unequivocal."[1] *For nearly 1 million years before the Industrial Revolution, the carbon dioxide (CO_2) concentration in the atmosphere ranged between 170 and 280 parts per million (ppm). Levels are now far above that range—387 ppm—higher than the highest point in at least the past 800,000 years, and the rate of increase may be accelerating.*[2] *Under high-emissions scenarios, concentrations by the end of the 21st century could exceed those experienced on the planet for tens of millions of years.*

Article 2 of the United Nations Framework Convention on Climate Change sets the objective of achieving a "stabilization of greenhouse gas emissions at a level that would prevent dangerous anthropogenic interference with the climate system."[3] To the extent that avoiding "dangerous" interference is defined in the convention, it is described as keeping emissions to levels that "allow ecosystems to adapt naturally to climate change, ensure that food production is not threatened and enable economic development to proceed in a sustainable manner." It is not clear that this objective is fully achievable because the warming already observed has been linked to increases in droughts, floods, heat waves, forest fires, and intense rainfall events that are already threatening human and natural systems.

There is convincing evidence that the capacity of societies and ecosystems to adapt to global warming is severely tested beyond warming of 2°C.[4] If the world is able to limit the human-caused temperature increase to about 2°C above its preindustrial level, it might be possible to limit significant loss from the Greenland and West Antarctic ice sheets and subsequent sea-level rise; to limit the increase of floods, droughts, and forest fires in many regions; to limit the increase of death and illness from the spread of infectious and diarrheal diseases and from extreme heat; to avoid extinction of more than a quarter of all known species; and to prevent significant declines in global food production.[5]

But, even stabilizing global temperatures at 2°C above preindustrial levels will significantly change the world. Earth has warmed 0.8°C on average from preindustrial times, and high-latitude regions are already experiencing environmental and cultural disruption; further impacts will be unavoidable as warming continues. A 2°C warming will cause more frequent and stronger extreme weather events, including heat waves, increased water stress in many world regions, declining food production in many tropical regions, and damaged ecosystems, including widespread loss of coral reefs from warming and ocean acidification.

Unless the world acts quickly to alter emissions pathways, models project that by 2100 the global average temperature will increase to 2.5–7°C above preindustrial levels,[6] depending on the amount and rate of energy growth, limits on fossil-fuel energy sources, and the pace of development of carbon-free energy technologies (see chapter 4). Although this temperature may seem like a modest increase compared with seasonal variations, the lower end of this range is the equivalent of moving from Oslo to Madrid. The upper end is equivalent to the warming that has occurred since the peak of the last glacial age, which led to the melting of two-kilometer thick ice that covered northern Europe and North America.[7] For the next few decades, the global average temperature is projected to increase 0.2–0.3°C a decade,[8] a rate of change that will tax the ability of species and ecosystems to adapt (see focus B on biodiversity).

Defining "dangerous anthropogenic interference" will be a political decision, not a scientific determination. A decade after the Kyoto Protocol, as we enter the first period of rigorous accounting of emissions by developed countries, the world is negotiating the course of action for the coming decades that will largely determine whether our children inherit a planet that has stabilized around 2°C warmer or is on a path to much higher temperatures. The term "dangerous" involves several components—the total magnitude of change, the rate of change, the risk of sudden or abrupt change, and the likelihood of crossing irreversibly harmful thresholds. What is determined to be a dangerous degree of climate change can be expected to depend on the effects on human and natural systems and their capacity to adapt. This focus looks at how the climate system works, at the changes observed to date, what a 2°C warmer world versus a 5°C or warmer world portends, the risks of crossing irreversible thresholds, and the challenge to limit warming to 2°C.

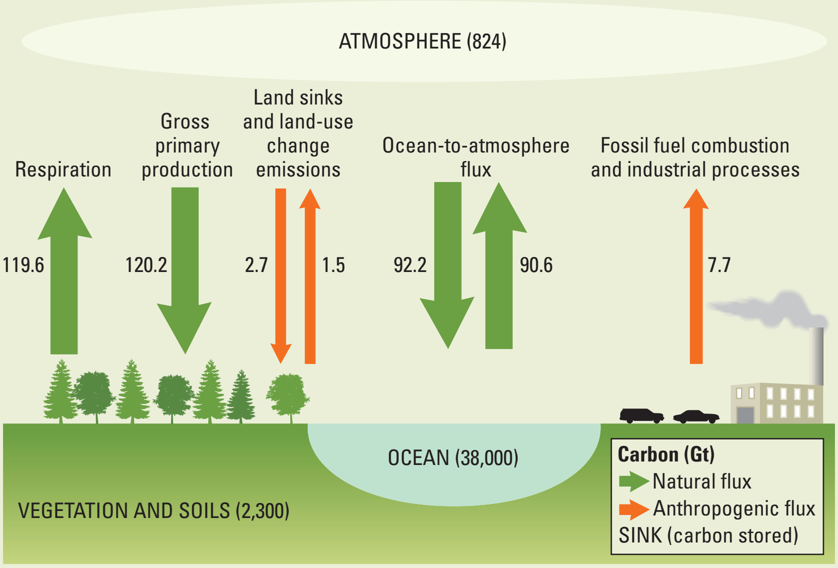
How the climate system works

The climate of Earth is determined by the incoming energy from the Sun, the outgoing energy radiated from Earth, and exchanges of energy among the atmosphere, land, oceans, ice, and living things. The composition of the atmosphere is particularly important because some gases and aerosols (very small particles) affect the flow of incoming solar radiation and outgoing infrared radiation. Water vapor, CO_2, methane

(CH_4), ozone (O_3), and nitrous oxide (N_2O) are all greenhouse gases (GHGs) naturally present in the atmosphere. They warm Earth's surface by impeding the escape of infrared (heat) energy into space. The warming effect created by the natural levels of these gases is "the natural greenhouse effect." This effect warms the world about 33°C more than it would be otherwise, keeps most of the world's water in the liquid phase, and allows life to exist from the equator to near the poles.

Gases released from human activities have greatly amplified the natural greenhouse effect. The global average atmospheric CO_2 concentration has increased significantly since the beginning of the Industrial Revolution, especially in the past 50 years. Over the 20th century, the CO_2 concentration increased from about 280 ppm to 387 ppm—almost 40 percent—mainly because of the burning of carbon-based fossil fuels and, to a lesser extent, deforestation and changes in land use (box FA.1). The combustion of coal, oil, and natural gas now contributes about 80 percent of the CO_2 emitted annually, with land-use changes and deforestation accounting for the remaining 20 percent. In 1950 the contributions from fossil fuels and land use were about equal; since then, energy use has grown by a factor of 18. The concentrations of other heat-trapping gases, including methane and nitrous oxide, have also increased significantly as a result of fossil-fuel combustion, farm-

BOX FA.1 *The carbon cycle*



Source: Adapted from IPCC 2007b.

The amount of carbon dioxide (CO_2) in the atmosphere is controlled by biogeochemical cycles that redistribute carbon among the ocean, land, living material, and atmosphere. The atmosphere currently contains about 824 gigatons (Gt) of carbon. Human-caused emissions of carbon in 2007 totaled about 9 Gt of carbon, of which about 7.7 Gt (or 28.5 Gt of CO_2) were from the combustion of fossil fuel and the rest were from changes in land cover. (One Gt equals a billion metric tons. To convert carbon emissions and fluxes to CO_2 amounts, multiply the amount of carbon by 3.67.)

The atmospheric concentration of CO_2 is currently increasing at a rate of about 2 parts per million (ppm) a year, which is equivalent to an increase in the atmospheric loading of carbon by about 4 Gt of carbon a year (in other words, about half of the fossil-fuel emissions of CO_2 lead to a long-term increase in the atmospheric concentration). The rest of the CO_2 emissions are being taken up by "carbon sinks"—the ocean and terrestrial ecosystems. The oceans take up about 2 Gt of carbon a year (the difference between the 90.6 and the 92.2 indicated in the figure, plus a small land-to-ocean flux). The net uptake of carbon by oceans and by terrestrial systems (photosynthesis minus respiration) and the estimates of emissions from land-use change and fossil-fuel combustion would result in atmospheric concentrations higher than are recorded. It appears that terrestrial ecosystems are currently taking up the excess. A 2.7 Gt "residual sink," as it is termed, is assumed to result mainly from changes in land cover (net increases in forest cover from reforestation and afforestation in excess of deforestation) and increased carbon uptake because of enhanced growth of the world's forests in response to higher CO_2 concentrations (known as the CO_2 fertilization effect).

Terrestrial ecosystems hold about 2,300 Gt of carbon—roughly 500 Gt in above-ground biomass and about three times that amount in the soils. Reducing deforestation needs to be an important component of slowing emissions growth. While every effort should be made to increase land storage of carbon, there will be challenges as the climate changes and the frequency of fire, pest infestations, drought, and heat stress increases. If fossil-fuel emissions continue on a business-as-usual path, uptake of emissions by forests and other terrestrial ecosystems may slow and even reverse, with these ecosystems becoming a net source of emissions by the end of the century, according to some models. And warmer oceans will absorb CO_2 more slowly, so a greater fraction of fossil-fuel emissions will remain in the atmosphere.

Sources: Fischlin and others 2007; IPCC 2000; IPCC 2001; Canadell and others 2007; Houghton 2003; Prentice and others 2001; Sabine and others 2004.

ing and industrial activities, and land-use changes (figure FA.1).[9]

Some of the pollutants introduced by humans warm Earth, and some cool it (figure FA.2). Some are long-lived, and some short-lived. By trapping infrared radiation, carbon dioxide, nitrous oxide, and halocarbons[10] warm Earth, and because the increased concentrations of these gases persist for centuries, their warming influence causes long-term climate change. In contrast, the warming influence of methane emissions persists for only a few decades, and the climatic influences of aerosols—which can either be heat-trapping such as black carbon (soot) or heat-reducing such as reflective sulfates[11]—persist for only days to weeks.[12] So while a sharp decline in the CO_2 emissions from the combustion of coal in coming decades would reduce long-term warming, the associated reduction in the cooling effect from sulfur emissions caused mainly by coal combustion would lead to an increase of perhaps 0.5°C.

Temperatures today are already 0.8°C above preindustrial levels (figure FA.3). Were it not for the cooling influence of reflective particles (such as sul-

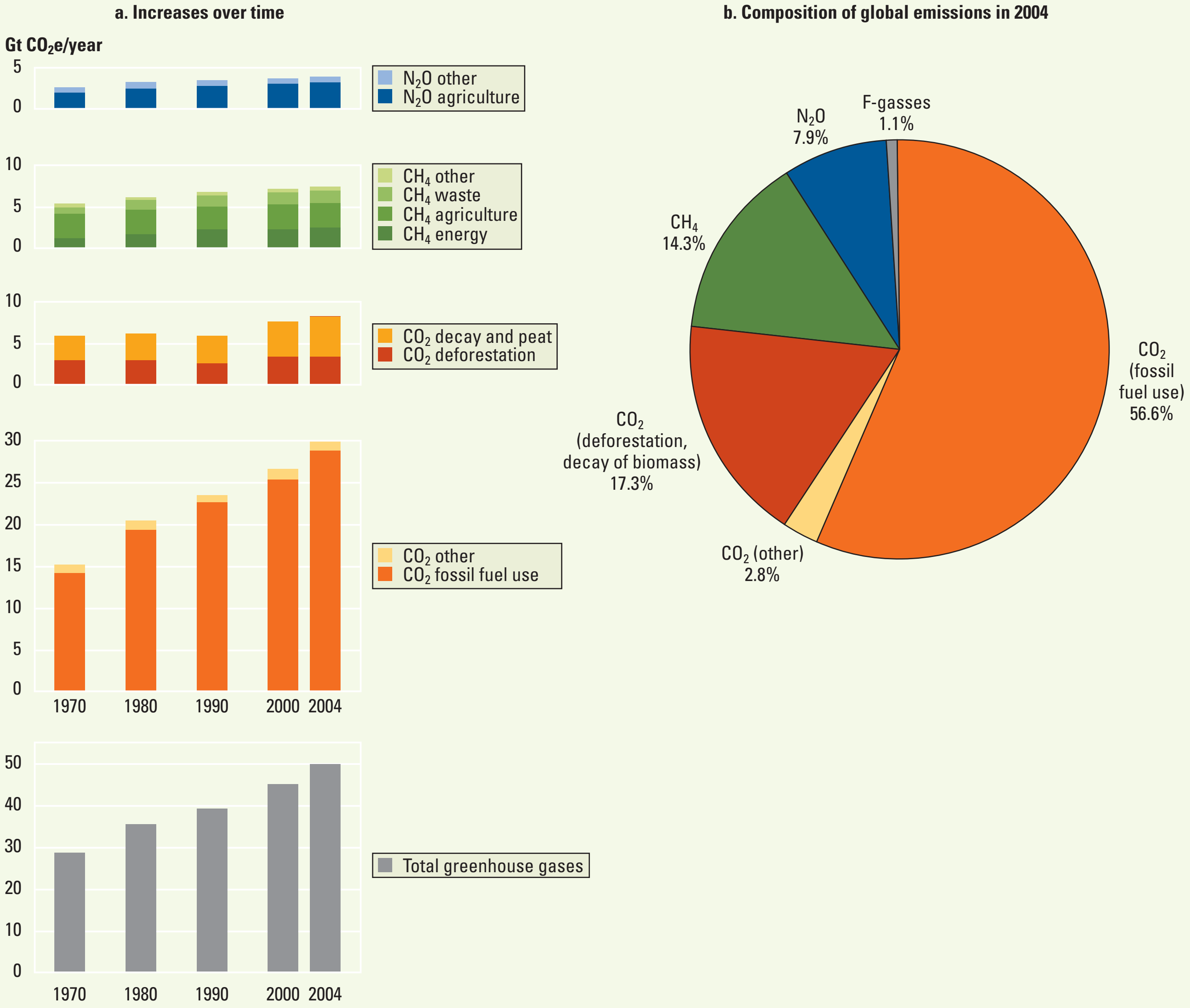


Figure FA.1 Global emissions of greenhouse gases have been increasing

a. Increases over time

b. Composition of global emissions in 2004

Source: Reproduced from Barker and others 2007.

Note: This figure shows the sources and growth rates of some of the medium- to long-term greenhouse gases. Fossil fuels and land-use change have been the major sources of CO_2, while energy and agriculture contribute about equally to emissions of CH_4. N_2Ocomes mainly from agriculture. Additional greenhouse gases not included in the figure are black carbon (soot), tropospheric ozone, and halocarbons. The comparisons of the equivalent emissions of different gases are based on the use of the 100-year Global Warming Potential; see note 9 for explanation.

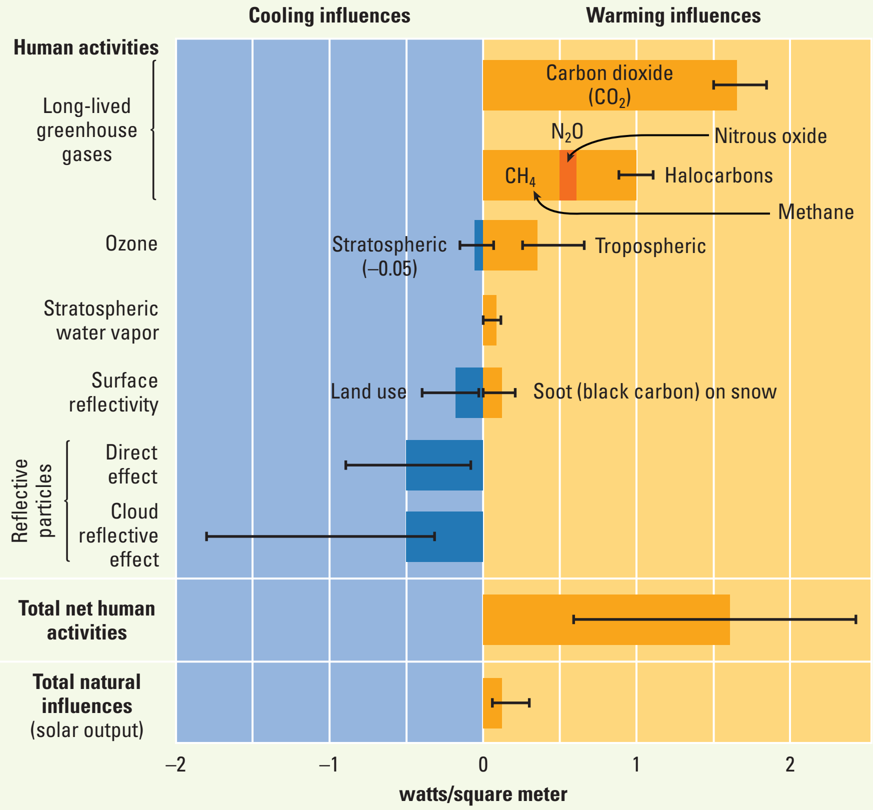
fate aerosols) and the decades that it takes ocean temperatures to come into equilibrium with the increased trapping of infrared radiation, the global average temperature increase caused by human activities would likely already be about 1°C warmer than it is today. Thus the current elevated concentrations of greenhouse gases alone are near to committing the world to a 2°C warming, a level beyond which the world can expect to experience very disruptive, even “dangerous” consequences.[13]

Changes observed to date and the implications of our changing understanding of the science

The effects of changes in climate since the mid-19th century are particularly evident today in the observations of higher average air and ocean temperatures; the widespread melting of snow and ice around the world, particularly in the Arctic and Greenland (figure FA.4); and the increase in global sea level. Cold days, cold nights, and frosts have become less frequent, while the frequency and intensity of heat waves have increased. Both floods and droughts are occurring more frequently.[14] The interiors of continents have tended to dry out despite an overall increase in total precipitation. Globally, precipitation has increased, as the water cycle of the planet has been sped up by warmer temperatures, even while the Sahel and Mediterranean regions have seen more frequent and more intense droughts. Heavy rainfall and floods have become more common, and there is evidence that the intensities of storms and tropical cyclones have increased.[15]

These impacts are not distributed evenly across the globe (map FA.1). As expected, temperature changes are greater at the poles, with some regions of the Arctic warming 0.5°C in just the past 30 years.[16] At low latitudes—those close to the equator—a greater fraction of the trapped infrared energy goes into evaporation, limiting warming but providing

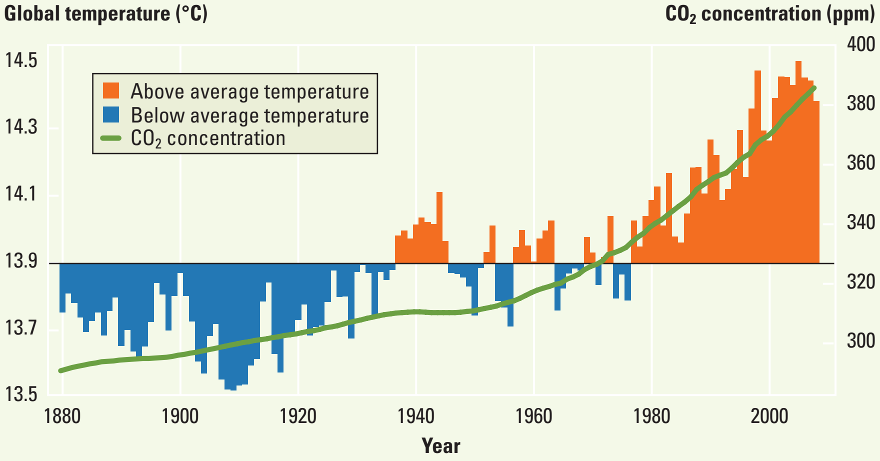
Figure FA.2 Major factors affecting the climate since the Industrial Revolution



Source: Adapted from Karl, Melillo, and Peterson 2009.

Note: The figure above shows the amount of warming influence (orange bars) or cooling influence (blue bars) that different factors have had on Earth’s climate since the beginning of the industrial age (from about 1750 to the present). Results are in watts per square meter. The top part of the box includes all the major human-induced factors, while the second part of the box includes the Sun, the only major natural factor with a long-term effect on climate. The cooling effect of individual volcanoes is also natural but is relatively short-lived (2 to 3 years), thus their influence is not included in this figure. The bottom part of the box shows that the total net effect (warming influences minus cooling influences) of human activities is a strong warming influence. The thin lines on each bar provide an estimate of the range of uncertainty.

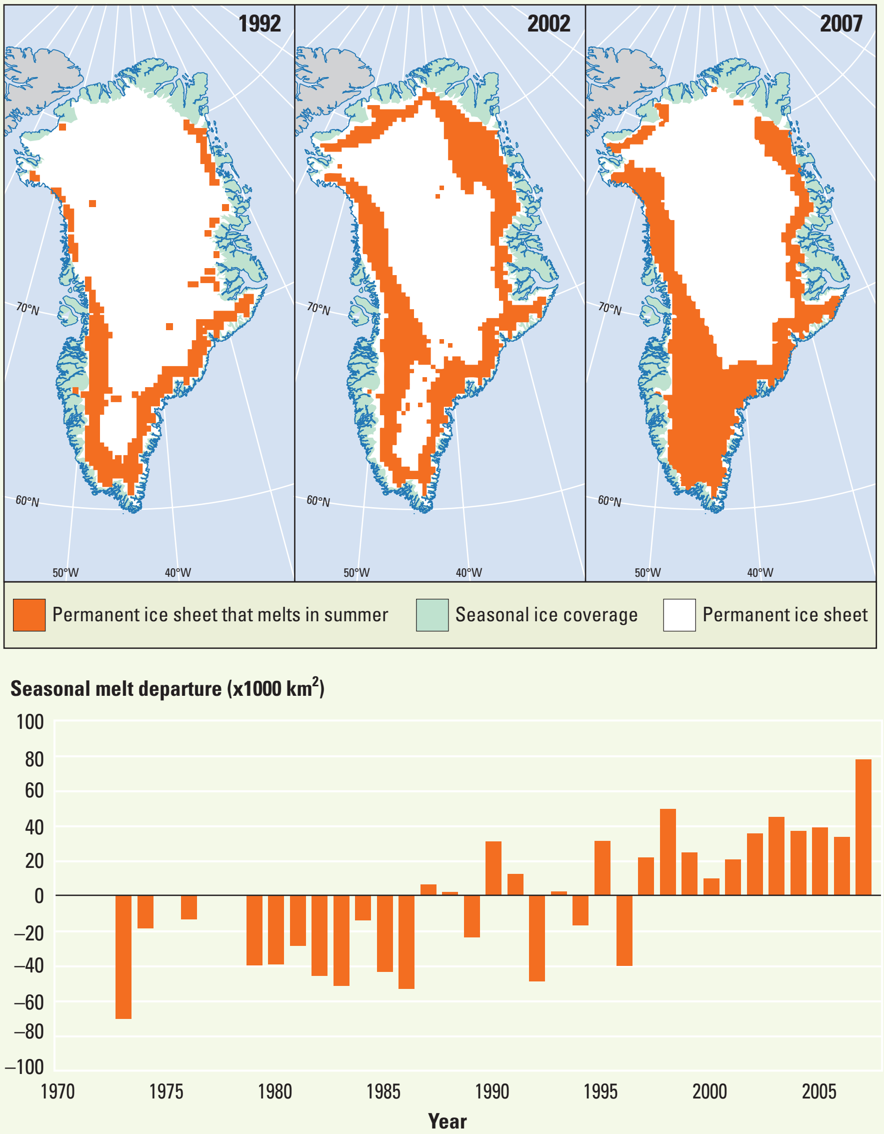
Figure FA.3 Global annual average temperature and CO_2 concentration continue to climb, 1880–2007



Source: Adapted from Karl, Melillo, and Peterson 2009.

Note: Orange bars indicate temperature above the 1901–2000 average, blue bars are below average temperatures. The green line shows the rising CO_2 concentration. While there is a clear long-term global warming trend, each individual year does not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are attributable to natural processes, such as the effects of El Niños, La Niñas, and volcanic eruptions.

Figure FA.4 Greenland's melting ice sheet



Sources: Top panel: Adapted from ACIA 2005 and Cooperative Institute for Environmental Sciences (CIRES), http://cires.colorado.edu/steffen/greenland/melt2005/ (accessed July, 2009). Bottom panel: Reproduced from Mote 2007.

Note: The orange areas on the maps of Greenland show the extent of summer ice melt, which has increased dramatically in recent years. Ten percent more ice was lost in 2007 than in 2005. The bar chart shows that despite annual variation in ice cover, significant loss has occurred for more than a decade.

an increase in water vapor that pours out as more intense rains from convective storms and tropical cyclones.

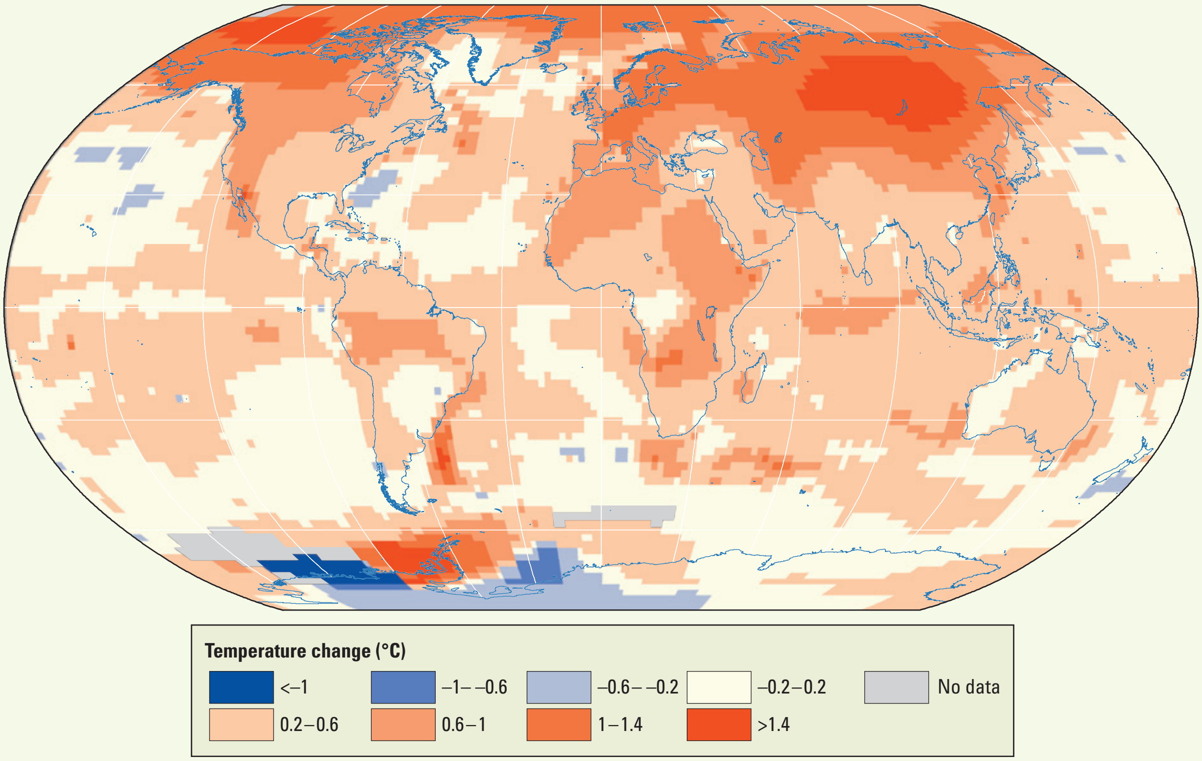
The resilience of many ecosystems is likely to be exceeded in the coming decades by a combination of the effects of climate change and other stresses, including habitat degradation, invasive species, and air and water pollution. Major changes are projected in ecosystems as climate change shifts the ideal geographic ranges of plant and animal species. Productivity of agriculture, forests, and fisheries will be affected as will other ecological services.[17] Already 20,000 datasets show a wide range of species on the move, with changes averaging about six kilometers a decade toward the poles or six meters a decade up mountains as an apparent result of the increase in temperatures.[18] These rapid changes are leading to asynchrony in many of the long-established predator-prey relationships, with some species arriving too early or too late to find their traditional food sources.

Over the past 20 years, our understanding of the science of climate change has greatly improved. In 1995, for example, the IPCC concluded: "The balance of evidence suggests a discernible human influence on global climate."[19] In 2001 the IPPC concluded: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[20] Six years later, in 2007, the IPCC concluded: "Warming of the climate system is unequivocal. Most of the observed increase in globally-averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."[21]

In 2001 and 2007 the scientific community summarized the best understanding of climate change impacts or reasons for concern in five categories: unique species/threatened ecosystems, extreme events, breadth of impacts, total economic impacts, and large-scale discontinuities. In the "burning ember" charts, the intensity of the red shading signifies the degree of concern over the effect in question (figure FA.5). Comparing column B in the left and right panels shows how the change in the best available information from 2001 to 2007 moved the red area closer to the zero degree line for extreme events—that is, at the current global average temperature, extreme events are already increasing. A comparison of the two E columns shows that the threat of discontinuous events, such as changes in the ocean conveyor-belt heat-distribution system or catastrophic thawing of the Arctic leading to massive releases of methane, becomes much larger if the world warms another 2°C over today's levels.

Map FA.1 Regional variation in global climate trends over the last 30 years

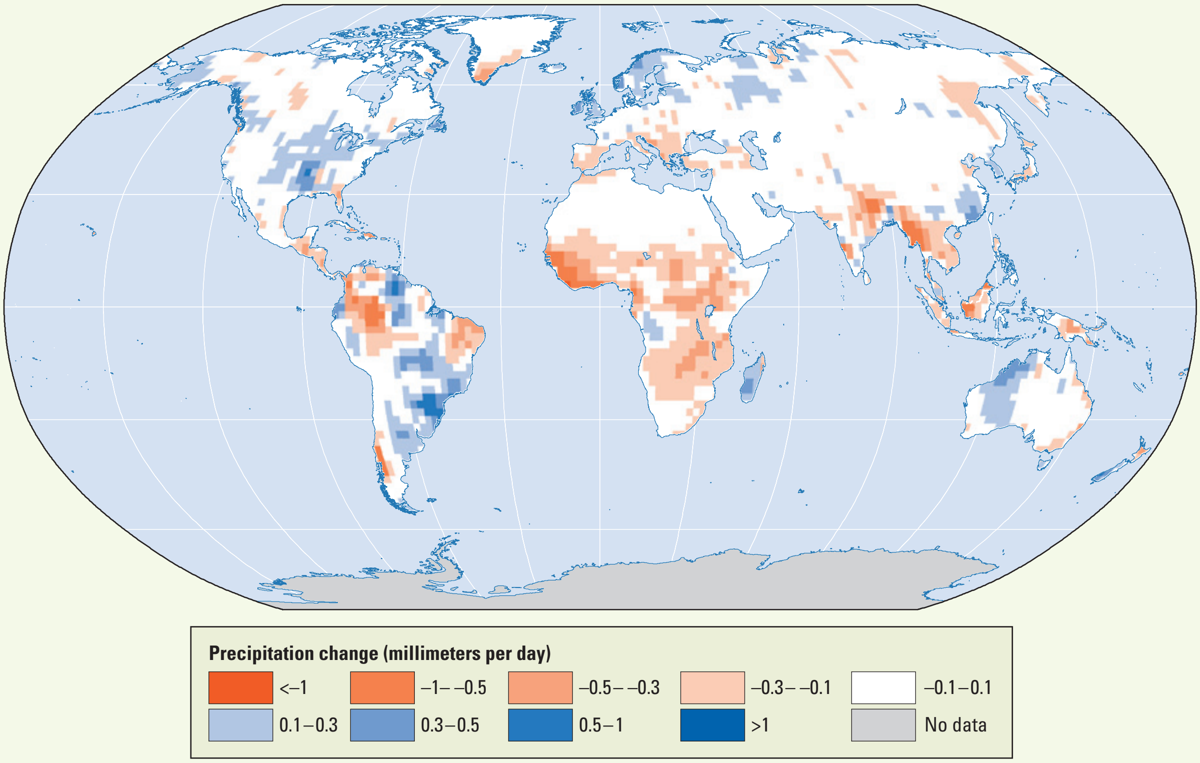
a. Temperature



Source: Goddard Institute for Space Studies, http://data.giss.nasa.gov/cgi-bin/gistemp/do_nmap.py?year_last=2009&month_last=07&sat=4&sst=1&type=anoms&mean_gen=07&year1=1990&year2=2008&base1=1951&base2=1980&radius=1200&pol=reg (accessed July 2009).

Note: Yellow, orange, and red colors denote average increases in temperatures (°C) from 1980 to the present compared with the previous three decades. Warming has been greatest at high latitudes, especially in the Northern Hemisphere.

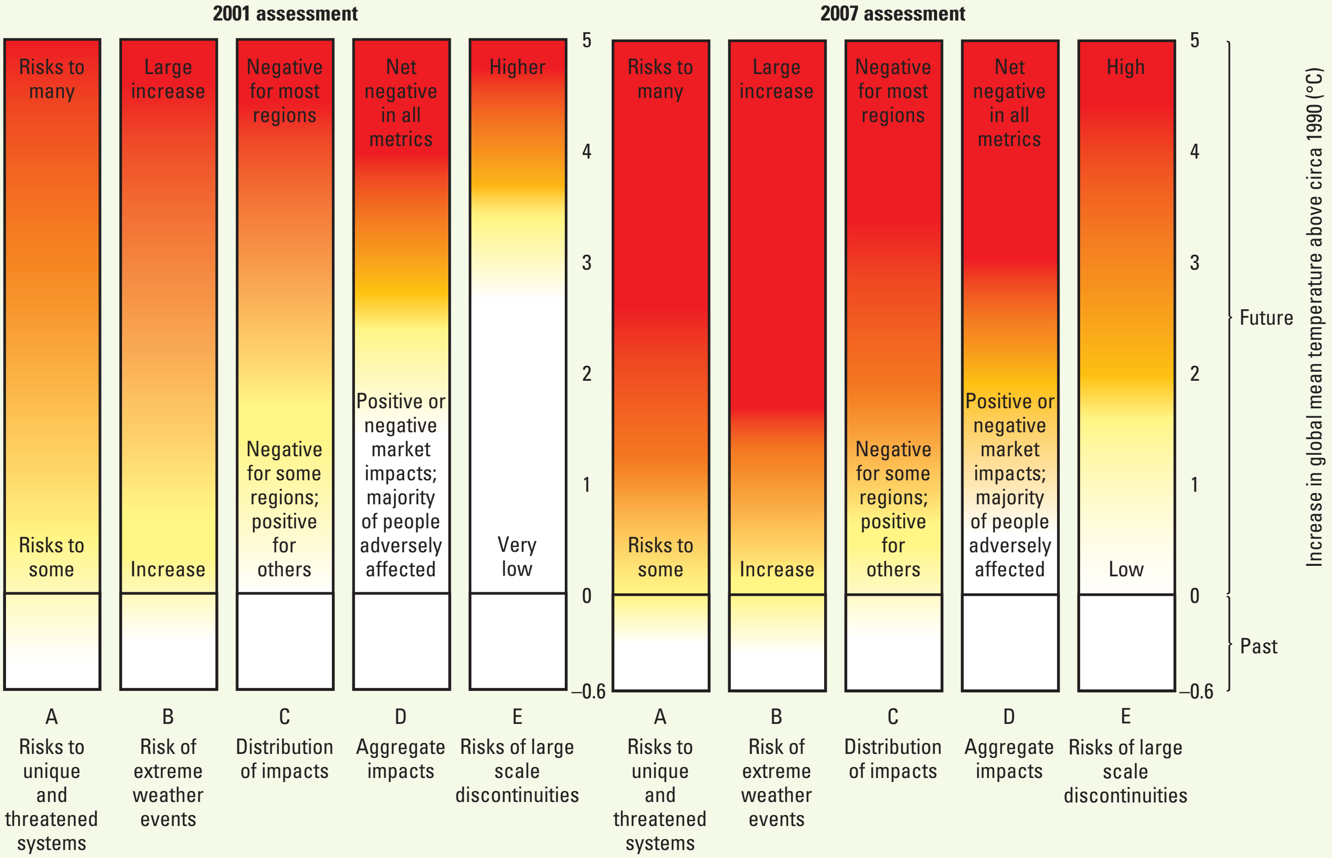
b. Precipitation



Source: Goddard Institute for Space Studies, http://data.giss.nasa.gov/cgi-bin/precipcru/do_PRCmap.py?type=1&mean_gen=0112&year1=1980&year2=2000&base1=1951&base2=1980 (accessed May 2009).

Note: Yellow denotes increased precipitation in millimeters a day; blue denotes decreases from 1980 to present compared with the previous three decades. Drying has been greatest in continental interiors, while rainfall has become more intense in many coastal areas. The changing geographic distribution of rainfall has serious implications for agriculture.

Figure FA.5 Embers burning hotter: Assessment of risks and damages has increased from 2001 to 2007



Source: Reproduced from Smith and others 2009.

Notes: The figure shows risks from climate change, as described in 2001 (left) compared with updated data (right). Climate-change consequences are shown as bars and the increases in global mean temperature (°C) above today's levels (0 degrees to 5 degrees). Each column corresponds to a specific kind of impact. For example, "unique and threatened systems," such as alpine meadows or arctic ecosystems, are the most vulnerable (illustrated by the shading in column A) and only a small change in temperature may lead to great loss. The color scheme represents progressively increasing levels of risk from yellow to red. Between 1900 and 2000 global average temperature increased by ~0.6°C (and by nearly 0.2°C in the decade since) and has already led to some impacts. Since 2001 the assessed risk of damages has increased even for temperatures of an additional 1°C above today's levels, or about 2°C total above preindustrial levels.

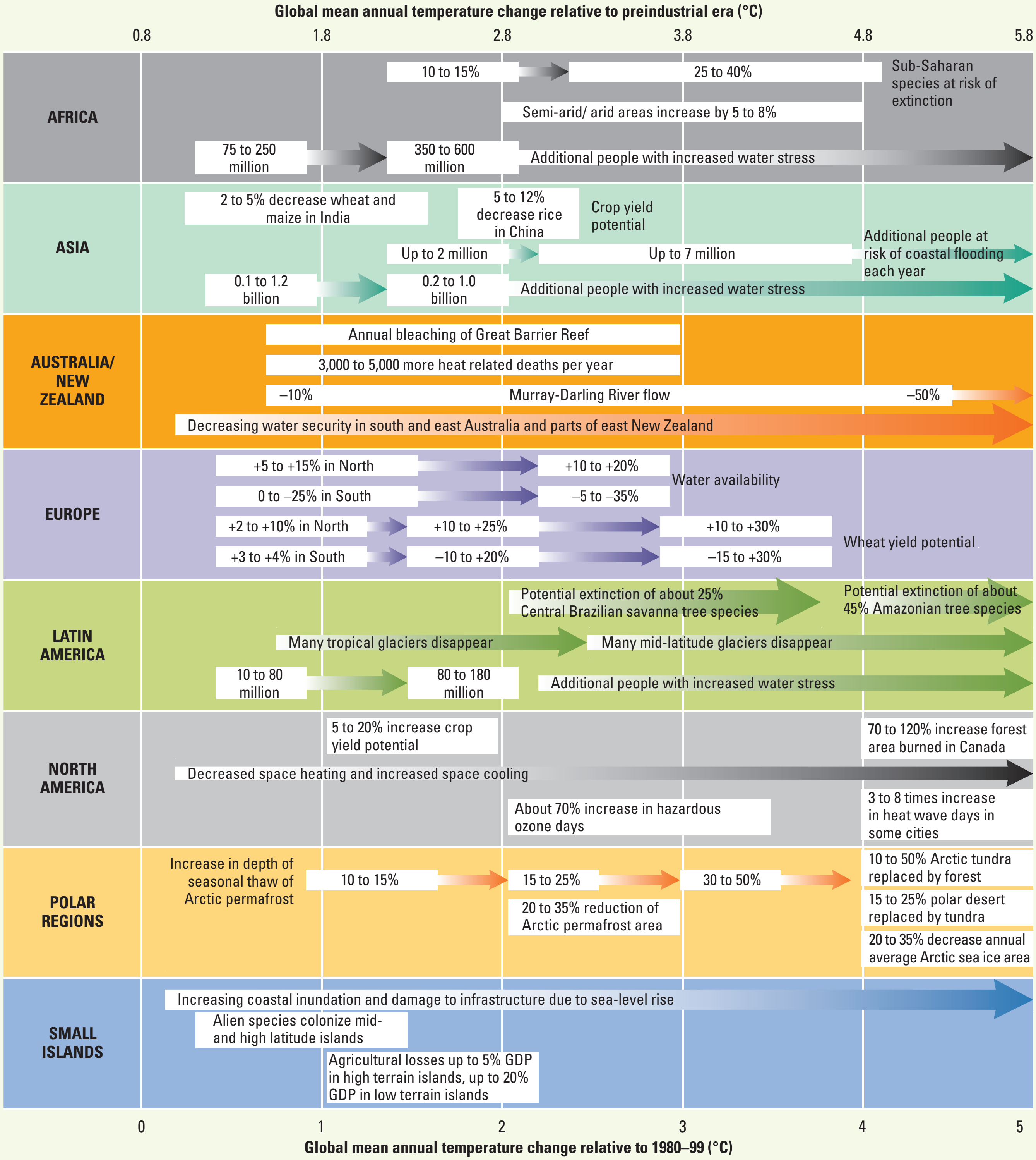
Since the finalization of the IPCC's fourth assessment report in 2007, new information has further advanced scientific understanding. This information includes updated observations of recent changes in climate, better attribution of observed climate change to human and natural causal factors, improved understanding of carbon-cycle feedbacks, and new projections of future changes in extreme weather events and the potential for catastrophic change.[22] Many risks are now assessed to be greater than previously thought, particularly the risks of large sea-level rise in the current century and of increases in extreme weather events.

Future changes if the temperature increase exceeds 2°C

The physical impacts of future climate change on humans and the environment will include increasing stresses on and even collapses of ecosystems, biodiversity loss, changing timing of growing seasons, coastal erosion and aquifer salinization, permafrost thaw, ocean acidification,[23] and shifting ranges for pests and diseases. These impacts are shown for different temperatures and world regions in figure FA.6.

The physical effects of future climate change will have varying impacts on people and the environment at different temperature increases and in different regions (see figure FA.6). If temperatures reach 2°C above preindustrial levels, water availability will be reduced for another 0.4–1.7 billion people in midlatitudes and semiarid low latitudes. Those affected by severe water shortages will be mainly in Africa and Asia. At these higher temperatures, most coral reefs would die (box FA.2), and some crops, particularly cereals, could not be successfully grown in the altered climates prevailing in low-latitude regions. About a quarter of plant and animal species are likely to be at increased risk of extinction (see

Figure FA.6 Projected impacts of climate change by region



Source: Adapted from Parry and others 2007.

BOX FA.2 *Ocean health: Coral reefs and ocean acidification*

The oceans will become more acidic over the coming decades and centuries as a direct chemical consequence of the increasing atmospheric concentration of CO_2. Absorption of approximately one-third of manmade emissions of CO_2 over the past 200 years has decreased the pH of surface seawater by 0.1 units (pH, the degree of acidity or alkalinity, is measured on a logarithmic scale, and a 0.1 decrease in pH represents a 30 percent increase in ocean acidity). Projected pH decreases in ocean surface waters over the next 100 years range from 0.3 to 0.5 units, which would make the ocean more acidic than it has been in many tens of millions of years.[a] One of the most important implications of the changing acidity of the oceans is the problem that it may cause for the many marine photosynthetic organisms and animals, such as corals, bivalves, and some plankton species that make their shells and plates out of calcium carbonate. The process of "calcification" will be inhibited as the water becomes more acidic. Some of the most abundant life forms that will be affected are plankton, which form the base of the marine food chain and are a major food source for fish and marine mammals. From the evidence available, there is significant uncertainty about whether marine species and ecosystems will be able to acclimate or evolve in response to such rapid changes in ocean chemistry. At this stage, research into the impacts of high concentrations of CO_2 in the oceans is still in its infancy.

But for coral reefs, the adverse consequences are already becoming evident. Coral reefs are among the marine ecosystems most vulnerable to the changing climate and atmospheric composition and are threatened by a combination of direct human impacts and global climate change. Their loss would directly affect millions of people. Coral reefs, both tropical and deep cold water, are global centers of biodiversity. They provide goods and services of roughly $375 billion a year to nearly 500 million people. About 30 million of the world's poorest people directly rely on coral reef ecosystems for food.

Coral reefs are already being pushed to their thermal limits by recent temperature increases. Higher sea surface temperatures stress corals and cause coral bleaching (the loss or death of symbiotic algae), frequently resulting in large-scale mortality. An ecological "tipping point" is likely to be crossed in many areas if ocean temperatures increase to more than 2°C above their preindustrial levels, especially as ocean acidification reduces carbonate concentrations, inhibiting reef accretion. Once the corals die, macroalgae colonize the dead reefs and prevent regrowth of corals. Poor management can amplify these dynamics, because overfishing of herbivore reef fish leads to greater macroalgae abundance, and sediment and nutrient runoff from deforestation and poor agricultural practices promote macroalgae growth, exacerbating damage to corals.

Sources: Barange and Perry 2008; Doney 2006; Fabry and others 2008; Wilkinson 2008.

a. Monaco Declaration, http://ioc3.unesco.org/oanet/Symposium2008/MonacoDeclaration.pdf (accessed May 2009).

focus B).[24] Communities will suffer more heat stress, and coastal areas will be more frequently flooded.[25]

What if temperatures rise to 5°C above preindustrial levels? About 3 billion additional people would suffer water stress, corals would have mostly died off, some 50 percent of species worldwide would eventually go extinct, productivity of crops in both temperate and tropical zones would fall, about 30 percent of coastal wetlands would be inundated, the world would be committed to several meters of sea-level rise, and there would be substantial burden on health systems from increasing malnutrition and diarrheal and cardiorespiratory diseases.[26] Terrestrial ecosystems are expected to shift from being carbon "sinks" (storage) to being a source of carbon; whether this carbon is released as carbon dioxide or methane, it would still accelerate global warming.[27] Many small island states and coastal plains would be flooded by storm surges and sea-level rise as the major ice sheets deteriorate and the traditional ways of life of Arctic peoples would be lost as the sea ice retreats.

Recent evidence indicates that loss of sea ice, the melting of the Greenland and Antarctic ice sheets, the rate of sea-level rise, and the thawing of the permafrost and mountain glaciers are faster than expected when the IPCC 2007 report was completed.[28] New analyses suggest that droughts in West Africa[29] and a drying of the Amazon rain forest[30] may be more probable than previously thought.[31]

While scientific uncertainty has often been cited as a reason to wait for more evidence before acting to control climate change, these recent surprises all illustrate that uncertainty can cut the other way as well and that outcomes can be worse than expected. As the overview and chapter 1 highlight, the existence of uncertainties warrant a precautionary approach to climate change given the potential for irreversible impacts and the inertia in the climate system, in infrastructure and technology turnover, and in socioeconomic systems.

Crossing thresholds?

These impacts do not fully capture the probability and uncertainty of an increase in extreme events or define the thresholds of irreversible catastrophic events. Although climate change is often characterized as a gradual increase in global average temperature, this depiction is inadequate and misleading in at least two ways.

First, the historical and paleoclimatic records both suggest that the projected changes in the climate could well occur in jumps and shifts rather than gradually. As mentioned, the Greenland and West Antarctic ice sheets are particularly at risk from global warming, and there appear to be mechanisms that could lead to large and rapid changes in the amount of ice they store.[32] This is important because total loss of the ice now stored in both sheets would eventually raise the global sea level by about 12 meters. Some analyses indicate that this process would proceed slowly in a warming world, taking as much as several millennia or more. But recent studies indicate that because these ice sheets are largely below sea level and surrounded by warming water, their deterioration could happen much faster, conceivably in only a few centuries.[33] Sharply increased melting of either or both of these ice sheets, with accompanying changes in ocean circulation, is only one of several possibilities for tipping points in the climate system of a warming world, where changes could mean passing a point of no return—one where a system will shift to a different state, causing the potential for severe environmental and societal dislocations to go up accordingly.[34]

Second, no one lives in the global average temperature. Climate change impacts will differ sharply from region to region and often will interact with other environmental stresses. For example, evaporation and precipitation are both increasing and will continue to increase globally, but as the atmospheric circulation shifts, the changes will vary regionally, with some places become wetter and some drier. Among the likely additional consequences will be shifts in storm tracks, more intense tropical cyclones and extreme rainfall events, a higher snow line leading to less spring snowpack, further shrinkage of mountain glaciers,[35] reduced coverage of winter snowfall and sea ice, faster evaporation of soil moisture leading to more frequent and more intense droughts and fires, less extensive permafrost, and more frequent air pollution episodes. Shifts in the timing and patterns of the world's monsoons and ocean-atmosphere oscillations (as in the El Niño/Southern Oscillation and the North Atlantic Oscillation) are also likely. Map FA.2 and table FA.1 show some of the possible tipping points, their location, and the temperatures that might trigger change as well as the likely impacts.

Can we aim for 2°C warming and avoid 5°C or beyond?

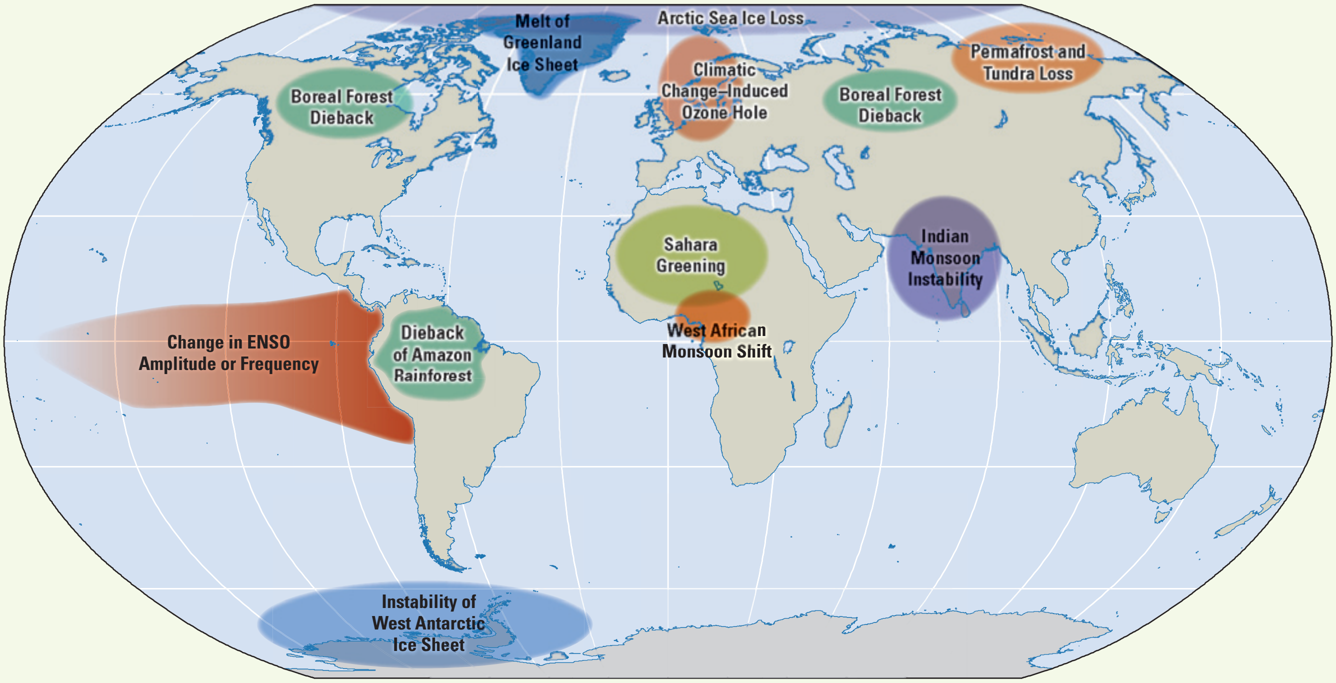
Many studies conclude that stabilizing atmospheric concentrations of greenhouse gases at 450 ppm CO_2 or its equivalent will yield only a 40–50 percent chance of limiting the global average temperature increase to 2°C above preindustrial levels.[36] Many emission paths can get us there, but all require emissions to peak in the next decade and then to decline worldwide to half of today's levels by 2050, with further emissions reductions thereafter. However, for greater confidence that a particular temperature will not be exceeded, the emissions reductions must be even steeper. As indicated in figure FA.7c, the "best guess" of a 2°C path cannot exclude the possibility of hitting 4°C.

A more robust way of thinking about the problem is in terms of an emissions budget. Keeping warming caused by CO_2 alone to 2°C will require limiting cumulative CO_2 emissions to 1 trillion tons (Tt) of carbon (3.7 Tt CO_2).[37] The world has already emitted half that amount over the previous two-and-a-half centuries. For the 21st century, a business-as-usual path would release the remaining half trillion tons in 40 years, requiring future generations to live in a world in which essentially zero carbon was emitted.

The concept of a cumulative budget provides a framework for thinking about targets for the short and long term. For example, the higher emissions are in 2020, the lower they will need to be in 2050 to stay within the same overall budget. If carbon emissions are allowed to increase another 20–40 percent before reductions begin, the rate of decline would need to be between 4 percent (the orange path in figure FA.7a) and 8 percent (blue path) each year to keep to the carbon budget. For comparison, at Kyoto the wealthy countries agreed to reduce emissions on average by 5.2 percent from 1990 levels over the 2008–12 period, whereas total global emissions would need to decline by 4–8 percent each and every year in order to limit warming to about 2°C.

Warming caused by other greenhouse gases such as methane, black carbon, and nitrous oxide—which currently contribute about 25 percent of total warming—means that an even lower limit for CO_2 will be necessary to stay near 2°C warming from human activities. These other greenhouse gases could account for about 125 billion of the remaining 500 billion tons in our emissions budget, meaning that the carbon dioxide that can be emitted—measured in carbon—is really only about 375 billion tons total.[38] Short-term measures that reduce 2020 emissions of potent, but short-lived gases, such as methane and black carbon or tropospheric ozone, slow the rate of warming. Indeed, reducing black carbon by 50 percent or ozone by 70 percent,[39] or halting deforestation would each offset about a decade of fossil-fuel emissions and would help to limit warming in concert with reductions in CO_2 emissions. To really reduce the risk of excessive warming, moving to negative emissions may also be required. Accomplishing this—that is, having no new emissions and also removing CO_2 from the atmosphere—may be possible using biomass to supply energy, followed by sequestration of the carbon (see chapter 4).

Map FA.2 Potential tipping elements in the climate system: Global distribution



Source: Adapted from Lenton and others 2008.

Note: Several regional-scale features of the climate system have tipping points, meaning that a small climate perturbation at a critical point could trigger an abrupt or irreversible shift in the system. These could be triggered this century depending on the pace and magnitude of climate change.

Table FA.1 Potential tipping elements in the climate system: Triggers, time-scale, and impacts

Tipping element	Triggering level of warming	Transition timescale	Key impacts
Disappearance of Arctic summer sea-ice	+0.5–2°C	~10 years (rapid)	Amplified warming, ecosystem change
Melting of Greenland ice sheet	+1–2°C	>300 years (slow)	Sea-level rise of 2–7 meters
Melting of West Antarctic ice sheet	+3–5°C	>300 years (slow)	Sea-level rise of 5 meters
Collapse of Atlantic thermohaline circulation	+3–5°C	~100 years (gradual)	Regional cooling in Europe
Persistence of El Niño-Southern Oscillation (ENSO)	+3–6°C	~100 years (gradual)	Drought in Southeast Asia and elsewhere
Indian summer monsoon	N/A	~1 year (rapid)	Drought
Sahara/Sahel and West African Monsoon	+3–5°C	~10 years (rapid)	Increased carrying capacity
Drying and dieback of Amazon rainforest	+3–4°C	~50 years (gradual)	Biodiversity loss, decreased rainfall
Northward shift of boreal forest	+3–5°C	~50 years (gradual)	Biome switch
Warming of Antarctic bottom water	Unclear	~100 years (gradual)	Changed ocean circulation, reduced carbon storage
Melting of tundra	Ongoing	~100 years (gradual)	Amplified warming, biome switch
Melting of permafrost	Ongoing	<100 years (gradual)	Amplified warming from release of methane and carbon dioxide
Release of marine methane hydrates	Unclear	1,000 to 100,000 years	Amplified warming from release of methane

Source: Adapted from Lenton and others 2008.

Note: An expert elicitation of opinions about the probability of passing a tipping point in a subset of these systems—the melting of the West Antarctic ice sheet, melting of Greenland ice sheet, Amazon drying, and ocean circulation (Kriegler and others 2009)—estimated at least a 16 percent probability of one of these events for a warming of 2–4°C. The probability would rise to greater than 50 percent for a global mean temperature change above 4°C relative to year 2000 levels. In many cases, these numbers are considerably higher than the probability allocated to catastrophic events in current climate-damage assessments; for example, Stern (2007) assumed a 5–20 percent loss of the ice sheets with a 10 percent probability for a warming of 5°C.

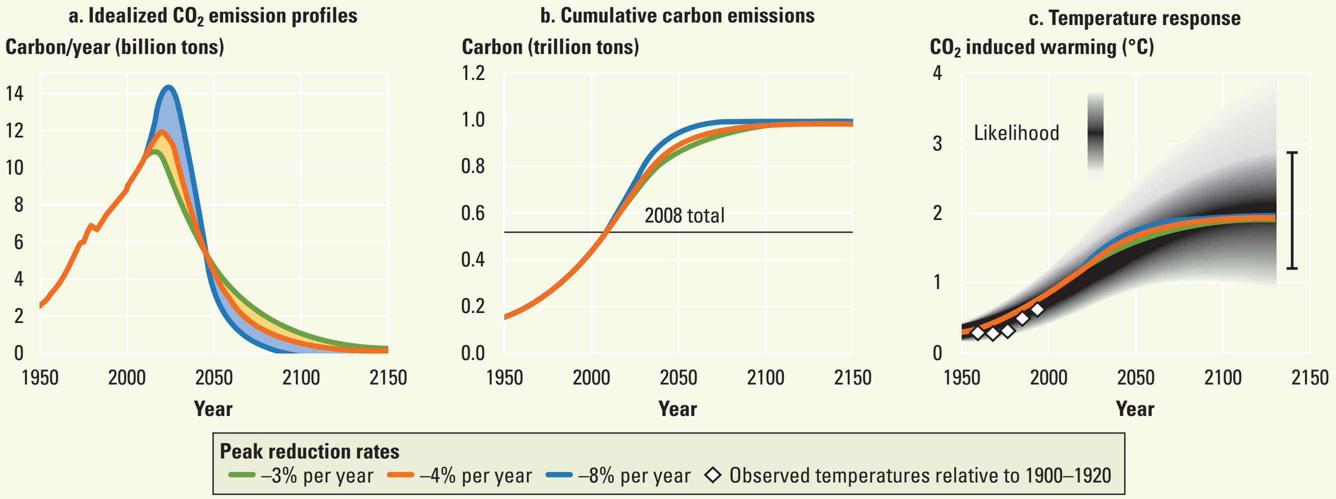


Figure FA.7 Ways to limit warming to 2°C above preindustrial levels

a. Idealized CO_2 emission profiles

b. Cumulative carbon emissions

c. Temperature response

Source: Allen and others 2009a.

Note: Three idealized CO_2 emission paths (FA.7a) each consistent with total cumulative emissions (b) of 1 trillion tonnes of carbon. Each of the paths yields the same range of projected temperature increase (c) relative to uncertainty in the climate system's response (grey shading and red error bar), provided the cumulative total is unaffected. The blue, green, and red curves in FA.7a are all consistent with the 1 trillion tonne budget, but the higher and later the emissions peak, the faster the emissions have to decline to stay within the same cumulative emissions budget. Diamonds in FA.7c indicate observed temperatures relative to 1900–1920. While 2°C is the most likely outcome, temperature increases as high as 4°degrees above preindustrial levels cannot be ruled out.

Notes

1. IPCC 2007b. The Intergovernmental Panel on Climate Change (IPCC) was organized in 1988 as a joint effort of the World Meteorological Organization and the UN Environment Programme to summarize the state of scientific knowledge about climate change in a periodic series of major assessments. The first of these was completed in 1990, the second in 1995, the third in 2001, and the fourth in 2007.

2. Raupach and others 2007.

3. http://unfccc.int/essential_background/convention/background/items/1353.php (accessed August 30, 2009).

4. Smith and others 2009.

5. Parry and others 2007.

6. Temperature increases at the poles will be about double the global average.

7. Schneider von Deimling and others 2006.

8. The observed increases have averaged about 0.2°C per decade since 1990, which give us confidence in the future projections. See IPCC 2007a, table 3.1, which gives a range of 0.1–0.6°C a decade across all scenarios.

9. According to the latest estimates from the World Meteorological Organization, the average CO_2 concentration in 2008 was 387 parts per million (ppm). Methane and nitrous oxide concentrations have also increased, reaching new highs of 1,789 and 321 parts per billion (ppb), respectively. The carbon dioxide equivalent concentration (CO_2e) is a quantity that describes, for a given mixture and amount of greenhouse gases, the amount of CO_2 that would have the same potential to contribute to global warming measured over a specified period. For example, for the same mass of gas, the Global Warming Potential (GWP) for methane over a 100-year period is 25, and for nitrous oxide, 298. This means that emissions of 1 metric ton of methane and nitrous oxide, respectively, would cause the same warming influence as emissions of 25 and 298 metric tons of carbon dioxide. Fortunately, the mass of the emissions of these gases is not as great as for CO_2, so their effective warming influence is less. Note, however, that over different periods, the GWPs can vary; for example, the near-term (20-year) GWP for methane is 75, indicating that over short periods of time, methane emissions are very important and controlling them can slow the pace of climate change.

10. Halocarbon compounds are chemicals containing carbon atoms bonded to halogen atoms (fluorine, chlorine, bromine, or iodine). These compounds tend to be very persistent and nonreactive. Until they were banned to protect the ozone layer, many were commonly used as refrigerants and to form insulating materials. Because these compounds also lead to global warming, the banning of them under the Montreal Protocol and subsequent amendments has helped to limit global warming (in fact, even more so than the Kyoto Protocol). While the replacement compounds that have been introduced do contribute less to global warming and ozone depletion, greatly increased use of the replacements could exert a significant warming influence over time, and so emissions of such compounds should be reduced over coming decades.

11. Natural removal of the sulfate particles from the atmosphere over the few weeks following their formation is also the primary contributor to acidification of precipitation (acid rain), which reduces soil fertility, damages plants and buildings, and adversely affects human health.

12. Forster and others 2007.

13. Adger and others 2008; SEG 2007.

14. Millennium Ecosystem Assessment 2005. These seemingly contradictory changes are possible because, as temperature goes up, both evaporation and the capacity of the atmosphere to hold water vapor increase. With increased atmospheric water vapor,

convective rains become more intense, more often leading to floods. At the same time, higher temperatures lead to faster evaporation from land areas, causing faster depletion of soil moisture and faster onset of droughts. As a result a particular region can, at different times, face both heavier floods and more serious droughts.

15. Webster and others 2005.

16. Melting of snow and ice in high latitudes leads to "polar amplification" of the temperature increase by replacing reflective surfaces with dark soil or open water, both of which absorb heat and create a positive feedback of further warming or melting.

17. Allison and others 2005.

18. Parry and others 2007.

19. IPCC 1995.

20. IPCC 2001.

21. IPCC 2007a. "Very likely" is used by the IPCC to denote greater than 90 percent certainty.

22. Füssel 2008; Ramanathan and Feng 2008.

23. Brewer and Peltzer 2009; McNeil and Matear 2008; Silverman and others 2009.

24. Parry and others 2007.

25. Parry and others 2007, table TS3.

26. Battisti and Naylor 2009; Lobell and Field 2007.

27. Global Forest Expert Panel on Adaptation of Forests to Climate Change 2009.

28. US National Snow and Ice Data Center, http://nsidc.org (accessed August 2009); Füssel 2008; Rahmstorf 2007.

29. Shanahan and others 2009.

30. Phillips and others 2009.

31. Allan and Soden 2008.

32. Rignot and Kanagaratnam 2006; Steffensen and others 2008.

33. Füssel 2008.

34. Lenton and others 2008.

35. UNEP-WGMS 2008.

36. See also discussions in the overview and in chapter 4.

37. Allen and others 2009b.

38. Meinshausen and others 2009.

39. Wallack and Ramanathan 2009.

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