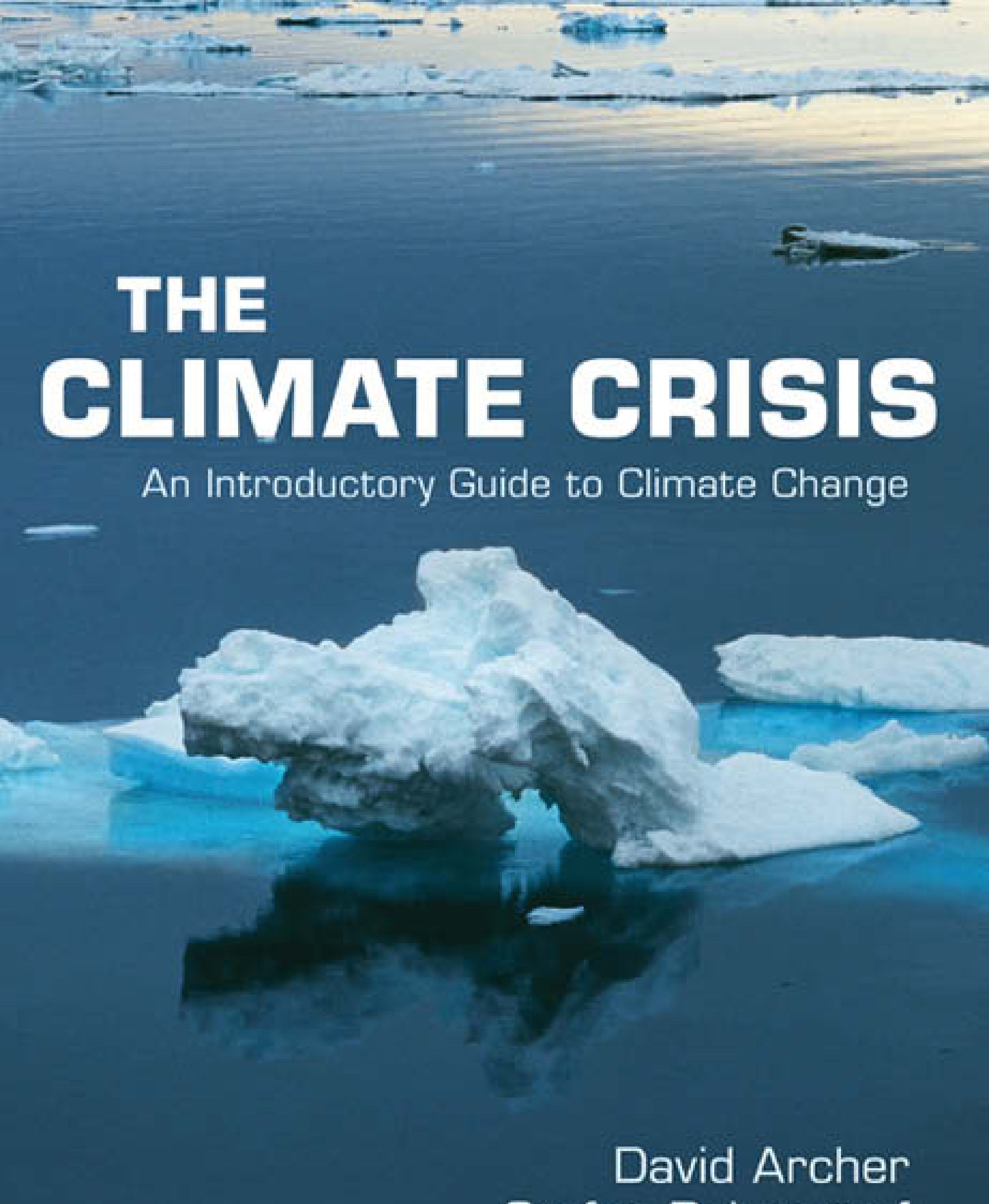

THE CLIMATE CRISIS

An Introductory Guide to Climate Change

David Archer
Stefan Rahmstorf

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The Climate Crisis

An Introductory Guide to Climate Change

DAVID ARCHER AND STEFAN RAHMSTORF

Most climate scientists wholeheartedly agree with the above statement by the US president. An incredible wealth of scientific data on global warming has been collected in the last few decades. The history of the Earth's climate has been probed by drilling into the polar ice sheets and the sediment layers of the oceans' vast depths. Great advances have been made in computer modeling of our climate. Each year, over 10,000 scientific papers are published with the key word "climate." This book provides a concise and accessible overview of what we know about ongoing climate change and its impacts, and what we can do to confront the climate crisis. It gives a readable account of the treasure trove of information contained in the Intergovernmental Panel on Climate Change reports, and also brings the subject completely up-to-date with current science and policy.

The Climate Crisis: An Introductory Guide to Climate Change makes essential scientific information on climate change accessible to a broad audience. Obtaining sound information is the first step in preventing a serious, long-lasting degradation of our planet's climate, helping to ensure our future survival.

David Archer is a professor of Geophysical Sciences at the University of Chicago. Dr. Archer has published over 70 scientific papers on a wide range of topics on the carbon cycle and its relation to global climate. He teaches classes on global warming, environmental chemistry, and geochemistry. His previous books include *Global Warming: Understanding the Forecast* (2006) and *The Long Thaw: How Humans are Changing the Next 100,000 Years of Earth's Climate* (2008). He is a regular contributor to the website realclimate.org.

Stefan Rahmstorf is professor of Physics of the Oceans, and head of department at the Potsdam Institute for Climate Impact Research. Dr. Rahmstorf is a member of the Academia Europaea and of the German Advisory Council on Global Change (WBGU). He is also one of the lead authors of the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change. In 2007 he became an Honorary Fellow of the University of Wales. He has published over 50 scientific papers (14 of which in *Nature* and *Science*) and co-authored two previous books: *Der Klimawandel* (2006) and *Wie bedroht sind die Ozeane?* (2007), published in English as *Our Threatened Oceans* (2009). He is a co-founder and regular contributor to the website realclimate.org.

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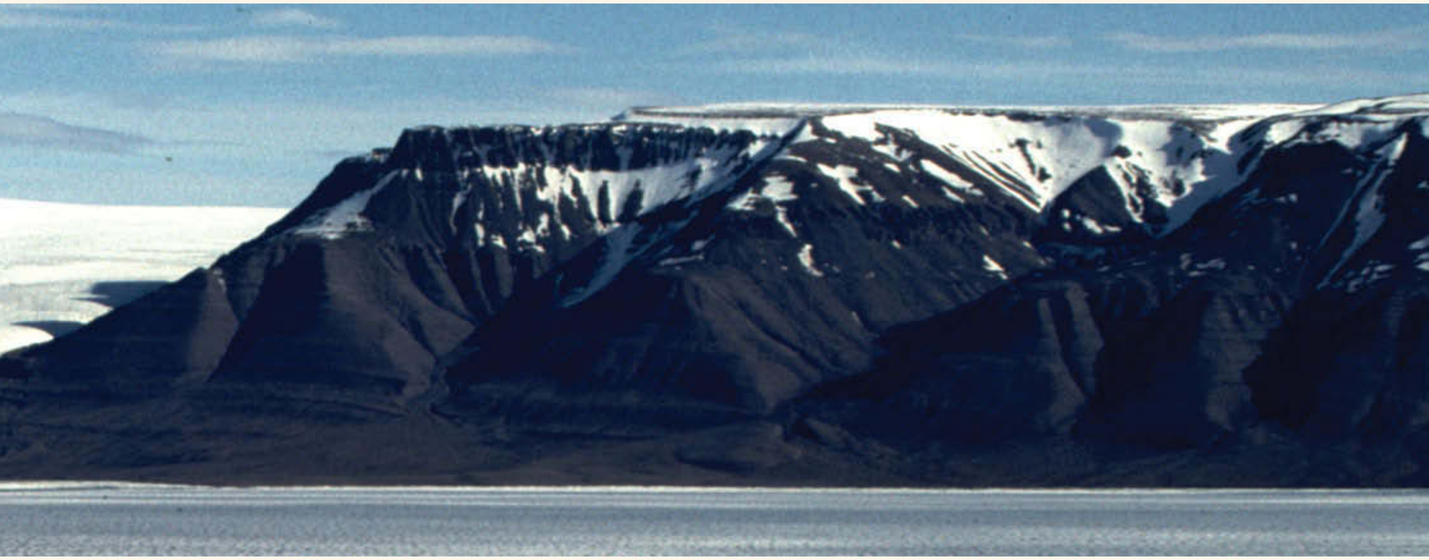
THE CLIMATE CRISIS



An Introductory Guide to Climate Change

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Contents

Few challenges facing the world are more urgent than combating climate change. The science is beyond dispute and the facts are clear.

Barack Obama
(November 18, 2008)

Preface

Most climate scientists would wholeheartedly agree with this statement by the newly elected US president, indeed would have agreed with it twenty years ago. The US National Academy of Sciences first warned of impending global warming in a historic report in 1979, and the head of the NASA climate research division, James Hansen, famously declared, “global warming is here,” in a congressional hearing in 1988. That same year, the World Meteorological Organization founded the Intergovernmental Panel on Climate Change (IPCC).

Since then an incredible wealth of scientific data on global warming has been collected. The history of the Earth’s climate has been probed by drilling into the Greenland and Antarctic ice sheets and the sediment layers of the oceans’ vast depths. Great advances in computer modeling of our climate have been made. Each year, over 10,000 scientific papers are published with a key word “climate.”

In this book we aim to provide an overview of what we know about the ongoing climate change and its impacts, and what we can do to confront the climate crisis. We base this account closely on the *Fourth Assessment Report* of the IPCC – a three-year effort of hundreds of scientists from around the world to assess and summarize the scientific literature.

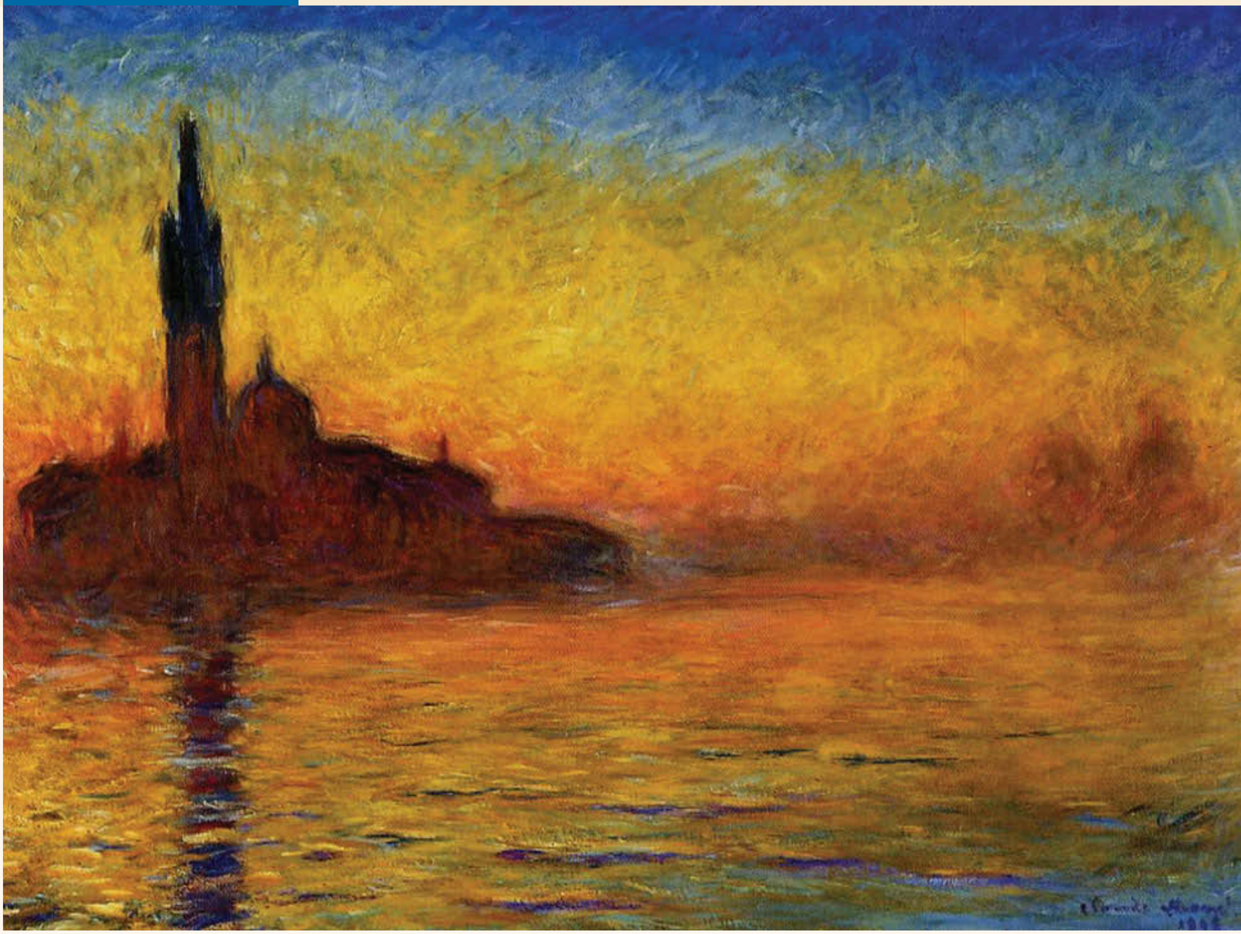
The IPCC has issued four major reports on the state of our climate since it was founded: the first in 1991, the most recent one in 2007. It has earned a reputation as the by far most authoritative, comprehensive and impartial source of scientific information on climate change, earning a Nobel Peace Prize in 2007 for its efforts. The first IPCC report provided the scientific basis for the Global Environment Summit in Rio de Janeiro in 1992, where the United Nations Framework Convention on Climate Change was passed. In this treaty, unique in the history of humanity, nations of the world pledged to stabilize greenhouse gas concentrations in the atmosphere at a level that prevents a "dangerous interference with the climate system."

IPCC reports are heavy documents (the three volumes of the most recent one total over 2,500 pages) written in carefully couched scientific language. Few non-experts would ever want to read the entire report, and it is not surprising that media accounts are mostly based only on the official report *Summaries for Policy Makers.* These summaries are terse documents with wording carefully negotiated between government representatives from around the world, examined and discussed and agreed upon line by line. Much of what scientists really think – and write in the full report – is not found in these summaries.

We see a need for a more accessible and readable account of the treasure trove of information contained in the IPCC reports, and we attempt to provide it in this book. Although we both contributed to the latest IPCC report, our account is by no means an "official" view of the IPCC. To the contrary, where we see weaknesses with the report we provide a critical and candid perspective. We also include more recent information, given that the cut-off date for scientific papers considered by IPCC was between spring and autumn 2006. Important new findings have been published in scientific journals since then. We do make it transparent to our readers which information comes from the IPCC report, which from more recent papers, and where we add our own perspective.

We hope that this book will make essential scientific information on climate change more accessible to a broad audience, since obtaining sound information is the first step in preventing a serious, long-lasting degradation of our planet's climate.

1 Retrospective: what we knew and when we knew it



The science of climate change has a long history, but progress has accelerated amazingly in the last few years. The theory of the greenhouse effect is almost two centuries old, discovered by mathematician Joseph Fourier in 1827. Later, in 1896, Svante Arrhenius estimated how sensitive the climate would be to changes in the concentration of the greenhouse gas carbon dioxide (CO_2) in the atmosphere. Arrhenius' answer of 4 to 6 °C of warming from doubling CO_2 was not far off from our current estimate of 2 to 4.5 °C.

Progress and contributions to climate change science have accelerated because science itself is growing exponentially, and also because of the importance of the topic to human well being and planning. Stanhill (2001) assessed the number of scientific papers on the topic of climate change, and found that the number of papers per year has been doubling every 11 years since the 1950s. He estimated that, globally, 3 billion US dollars were spent annually on climate change research as of about the year 2000. For scale, the net income of the Exxon Mobil Company was $40 billion in 2007.

The massive task of synthesis and summary of this exploding research effort falls to the Intergovernmental Panel on Climate Change, or IPCC. This organization was founded in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), and charged with assessing the scientific, technical, and socio-economic information relevant for understanding the risk of human-induced climate change. Most of the work of IPCC is done by thousands of research scientists at universities and national laboratories around the world.

The participants are divided into Working Groups. Working Group I is in charge of scientific assessment of global climate science. Working Group II deals with the potential impacts of climate change to socio-economic and natural systems. Working Group III deals with options for avoiding (what they call mitigating) the effects of global warming. The working groups are divided into teams of people who essentially read the peer-reviewed published scientific literature and summarize the results in individual chapters.

IPCC does not fund new scientific work, but it stimulates new research by highlighting existing uncertainties in climate change research, and also by proposing future scenarios of the drivers of climate change (greenhouse gas concentrations, aerosol emissions, etc.), which climate modelers are requested to run through their models, so that the models can be compared on a level playing field. Twenty-three models from groups around the world participated in the intercomparison exercise, running a variety of different scenarios for the drivers of climate change in the coming century.

The IPCC publishes reports called Scientific Assessments summarizing the state of the field every five years or so. The first IPCC report was in 1990, called the *First Assessment Report* or FAR. Subsequent updates were released in 1996 (the *Second Assessment Report* or SAR), 2001 (the TAR), and now the current, *Fourth Assessment Report*, called AR4, released in 2007, is the topic of this book. Most of our discussion will focus on the results of the Working Group I report on global climate science. Chapter 8 will briefly review the products of Working Group II (impacts of climate change), and Chapter 9 will address Working Group III (avoiding climate change).

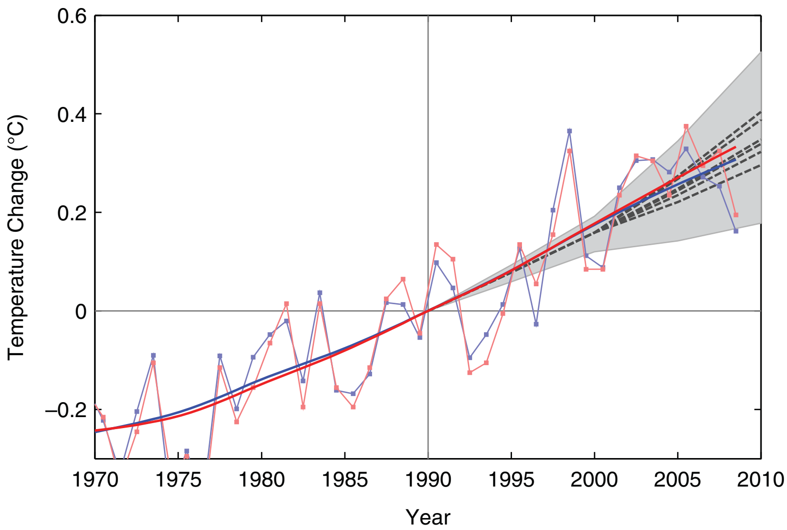


Figure 1.1 Climate projections published in the third IPCC report of 2001 compared to the actual global temperature change since 1970. The measured values are shown in red (NASA) and blue (Hadley Centre), with dots showing annual values up to 2008, while the thick curves show the trend line. The IPCC scenarios start in 1990 and are shown as black dashed lines; the broader gray band is the uncertainty range.

The short *Summaries for Policy Makers* (SPM) capture most of the public attention – not surprisingly, since the full reports are hefty and not easy to read. The summaries also go through an interesting process of line-by-line consensus approval with government representatives from around the world, who gather with IPCC scientists for a week-long meeting for this purpose. In this way, governments are involved and get a chance to raise their concerns about particular phrases in the summary. Of course, they cannot alter the science, since the summary must always reflect what is in the main report, but in some cases government representatives have weakened some of the language used by the scientists who drafted the summaries. More often, however, government representatives are concerned about the scientists' language being too technical: "My minister will not understand this sentence" was a repeated intervention during the approval process for the Working Group I summary in Paris in February 2007. Since both the draft and the final versions of the SPMs are accessible on the Internet, the influence of the government approval process is transparent and can be tracked.

The *First Assessment Report* in 1990 did not find evidence for human-induced warming sufficient to rise above the noise of natural climate variability. However, they predicted that global warming should be detectable by the year 2000. Detection of global warming came early, in 1995, as the *Second Assessment Report* concluded, “the balance of evidence suggests a discernible human influence on global climate.” This conclusion was strengthened in the 2001 *Third Assessment Report*, to read: “There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.”

All of the reports predicted rising, record-breaking heat, and all of the reports have been correct in this prediction. The *Fourth Assessment Report*, AR4, concludes that it is 90–99% likely that global warming since 1950 has been driven mainly by the buildup of carbon dioxide and other heat-trapping greenhouse gases, and that more warming and rising sea levels are on the way.

Awareness of the past

Mankind has been aware of the potential for changes in climate for over a century. Louis Agassiz (1837) proposed that the mountains of his native Switzerland had once been covered with large ice sheets like those in Greenland or Antarctica. His hypothesis explained the presence of rocks called exotics, different from the local bedrock but apparently transported from different bedrock far away. Agassiz also noted scratch and etch marks that seemed similar to marks a large sheet of flowing ice would make.

It must have been rather frightening to imagine the countryside as he knew it crushed and wiped out beneath a giant ice sheet. His proposal met resistance from the prevailing view, supported by religious doctrine, that the biblical flood was responsible for shaping the landscape. Eventually the ice age hypothesis was accepted.

Changes in atmospheric CO_2 were considered a possible cause of the ice ages, for example by Svante Arrhenius in 1896, but another potential driver for ice ages was and still is considered to be wobbles in the Earth’s orbit around the sun. The first orbital theory of climate dates to James Croll in 1864, who proposed that variations in the intensity of sunlight reaching the ground in the Northern Hemisphere winter are responsible for the waxing and waning of ice sheets. Milutin Milankovich modified the theory in 1914, while he was a prisoner in the First World War, to its current form by proposing that it is sunlight intensity in the Northern Hemisphere summer, in particular, which drives the ice age cycles.

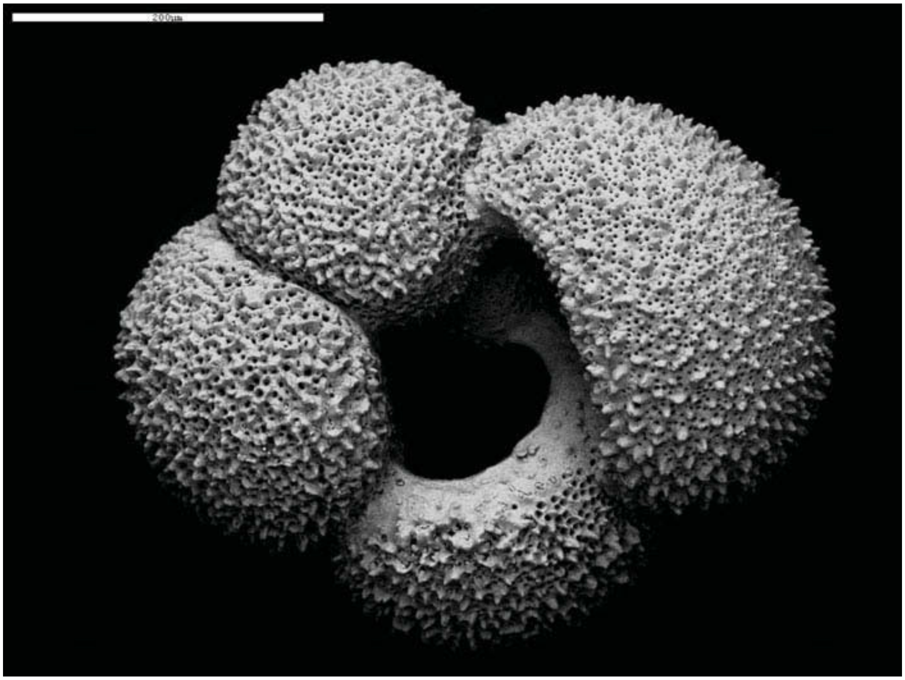


Figure 1.2 The microscopic shell of a planktonic foraminfera, *G. bulloides*.

The comings and goings of the ice ages are recorded in deep sea sediments and in ice sheets. The first sediment climate records were developed in the 1950s, based on measurements of the isotopes of oxygen in shells composed of limestone (calcium carbonate), $CaCO_3$ (Figure 1.2). Oxygen has several different isotopes, different types of atoms which all behave chemically as oxygen but they differ somewhat in how heavy they are. An ice sheet grows from water that evaporates from the ocean, the atmosphere acting like a giant still. The distilled water that makes it to the ice sheet has fewer of the heavy oxygen isotopes relative to the light ones; it is what is called "isotopically light." When the ice sheets grow large, the water left behind in the oceans tends to be isotopically heavy. The oxygen in $CaCO_3$ shells that deposit on the sea floor contains a record of the oxygen isotopic variations of the ocean, like tape in a tape recorder. In the 1970s it was found that the growth and decay of the ice sheets correlate in time with Milankovich's orbital variations, providing strong support for a role of orbital variations in determining Earth's climate.

Ice cores also contain time-detailed records of past climate variations, including notably an archive of actual samples of the ancient atmosphere, in which the concentrations of gases like CO_2 and methane (CH_4) can be measured. In the 1980s it was discovered that ice core atmospheric CO_2 and methane concentrations both rise and fall in concert with the amount of ice in the ice sheets, amplifying the climate extremes of the ice ages. The correlation between local temperature in Antarctica, and atmospheric CO_2, now extended back 650,000 years through seven glacial cycles (Figure 6.6), is compelling evidence for a role for CO_2 in global climate. The cause of the CO_2 changes is not well understood even today. The whole caboodle still marches in time with Milankovich's orbital variations, suggesting that somehow the natural carbon cycle amplifies the orbit's primary driving of the ice sheets.

It has become increasingly apparent in recent decades that climate does not respond linearly to wobbles in the Earth's orbit. It's not as simple as that. Through the past million years or so, the volume of ice through time has a much stronger 100,000 year cycle than is found in Milankovich's orbital forcing. This and other quirks of the history of ice sheets in the last two million years can be explained if we suppose that ice sheets have a tendency to grow to a certain size and then collapse quickly.

In the 1990s the Greenland ice cores revealed that the climate of the glacial world was much less stable than the warm climate of the past ten thousand years. The climate of the high northern latitudes in particular seemed to flip between different states, in what are known as "abrupt climate changes." These observations are described in Chapter 6. The abrupt climate transitions typically took less than a few decades, while the climate states before and after may have lasted for a thousand years. One could argue that the IPCC forecast for a generally smooth climate transition may be a best-case scenario, because of the lack of any abrupt surprise climate flips such as these.

The data for reconstructing the climates of the deep past have grown more comprehensive and diverse in recent years. The original core from which the glacial CO_2 cycles were discovered, from a site called Vostok in Antarctica, was extended back to 650,000 years ago in 2004 (Figure 6.6). Another new data archive comes from a site called Dome C, providing a very detailed CO_2 record of the last 2,000 years (Figure 6.7). There are also many new reconstructions of the last 1–2 thousand years from tree rings and boreholes that have been published just in the last few years (Chapter 6).

New ocean sedimentary climate records have been developed that have the time resolution to show abrupt climate changes. Ocean sediments tend to be smoothed by the actions of burrowing animals mixing up the sediment, but this problem can be avoided by finding sediments from places with no oxygen dissolved in the water, where animals cannot live, or sediments that accumulate very quickly. Sedimentary records, and also ice core records in mountain glaciers, document the abrupt onsets of regional drought events

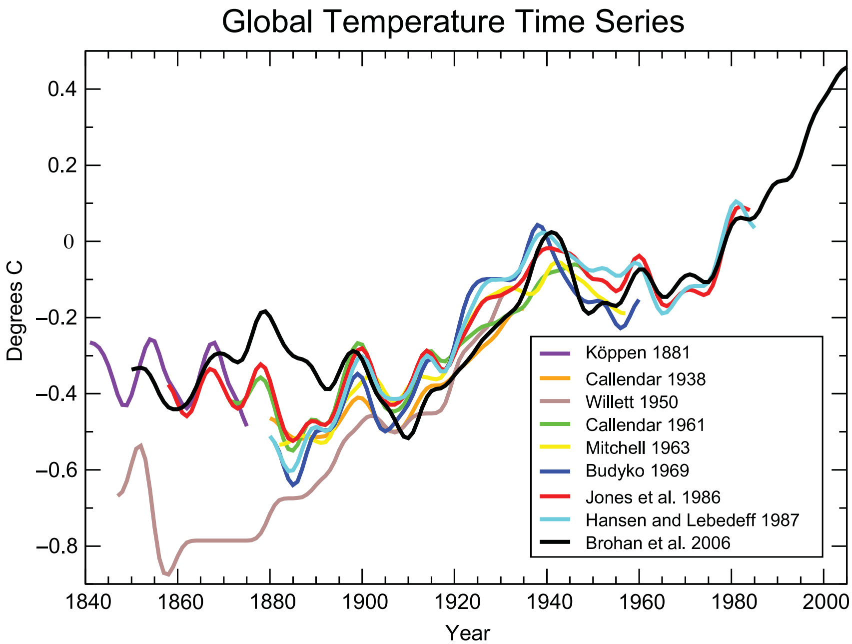


Figure 1.3 A comparison of different reconstructions of the global average temperature of the Earth.

through the Holocene, which had previously appeared to be a time of stable climate, based on ice core data.

Turning our focus back to historic times, Figure 1.3 shows reconstructions of the Earth's temperature that have been attempted in the last century. Weather observations date back several centuries, but it has been a big, ongoing job to collect, check, and then average the temperature data. Urban data are excluded to avoid bias from the urban heat island effect, although the corrections are small (Chapter 3). Sea surface temperatures need to be corrected for the method of measuring temperature, which changed from the traditional method, using cloth buckets to collect surface seawater, to automatically measuring the temperature at the intake of an engine cooling system. In spite of these differences, the various records of global average surface temperature changes, created over the past decades, show a remarkable uniformity.

Understanding climate

Scientific understanding of the basic physics of the greenhouse effect, and the potential for global warming as a result of CO_2 emission, has been building for over two centuries. The idea of the greenhouse effect, and its name, was invented by Joseph Fourier, a mathematician in Napoleon's army, in 1827. The discovery that energy can be transported by invisible infrared radiation had only been discovered in 1800 by Sir William Herschel, an astronomer. Fourier reasoned that if the outgoing infrared energy is blocked by gases in the atmosphere, analogous to a pane of glass in a greenhouse, the temperature of the surface of the planet would rise. The glass warms the interior by absorbing the light from the ground, and by shining its own light back down to the ground.

We should note that greenhouses also warm up by preventing warm air inside from rising and carrying away their heat. For this reason the greenhouse effect is perhaps not ideally named, but the idea behind it is essential for explaining the natural temperature of the Earth, which would be frozen all the way to the equator if it were not for Fourier's greenhouse effect. Venus and Mars are also warmed by their CO_2 atmospheres. The theory of the greenhouse effect is undisputed in scientific circles.

Carbon dioxide, methane, and water vapor were identified as greenhouse gases in 1859 by John Tyndall. A gas acts as a greenhouse agent if it interacts with infrared light, absorbing the light energy and converting it to heat, and in the opposite direction, radiating heat away as infrared light. The atmosphere is mostly made up of nitrogen and oxygen gases, N_2 and O_2, which are transparent to infrared light and therefore not greenhouse gases. Only the more complex molecules, containing three or more atoms, or two dissimilar atoms, act as greenhouse gases.

Svante Arrhenius in 1896 calculated that doubling CO_2 in the atmosphere would increase the temperature of the Earth by on average 4–6 °C. Data to base a calculation upon were scarce and crude. It wasn't known at that time how much infrared radiation the greenhouse gases would absorb, for example. Arrhenius used measurements of the infrared brightness of moonlight to figure out how much infrared radiation the gases in the atmosphere absorb. When the moon is directly overhead its light shines through a thinner layer of air than when the moonlight comes in obliquely. In spite of the crudeness of the data available and a few questionable assumptions, Arrhenius got the answer basically correct. The equilibrium warming from doubled CO_2 is a quantity now called the climate sensitivity. Guy Stewart Callendar estimated the climate sensitivity again, in 1938, to be 2 °C. The current most likely range for it is 2–4.5 °C, with a best estimate of 3 °C (Chapter 7).

Both Arrhenius and Callendar predicted correctly an important phenomenon called the water vapor feedback. Water vapor is a greenhouse gas; in fact it is a stronger greenhouse gas in our present atmosphere than

CO_2 is. If the water vapor concentration gets too high for a particular temperature, in other words, if what we call the relative humidity exceeds 100%, water tends to condense and it will rain or snow. In contrast to CO_2, which accumulates in the atmosphere from human emissions, the amount of water vapor in the air is regulated quickly by the water cycle, so that lawn sprinklers and swimming pools do not have a strong impact on the water vapor content of the atmosphere as a whole.

The water vapor feedback effect arises because the amount of water vapor that air can hold depends very sensitively on the temperature. A warming of the atmosphere, caused by rising CO_2 concentrations for example, allows the atmosphere to hold more water vapor. Because water vapor is a greenhouse gas, the additional vapor leads to further warming. The strength of the feedback is hard to predict precisely, because the relative humidity of the atmosphere is not always exactly 100%. As air rises, it cools and the water vapor is wrung out, leading to clouds and rain. When the air sinks again it has a very low relative humidity. The water vapor concentration in a parcel of air therefore depends on the recent history of the air, in other words the weather.

Because the air might circulate differently in a different climate, there is a possibility that the relative humidity of the atmosphere might change a bit, in either direction, making the water vapor feedback stronger or weaker. The earliest studies made the assumption that the relative humidity of the atmosphere remains about the same as the air warms. This assumption has since been corroborated by more recent numerical models (in which the humidities are determined by the models' own water cycles) and by meteorological data. The water vapor feedback more than doubles the amount of warming we'd get from CO_2 in a totally dry atmosphere.

Ice plays many roles in Earth's climate. Ice and snow tend to reflect sunlight, and therefore act to cool the Earth. When ice melts, more of the sunlight is absorbed by the darker ground or ocean underneath the ice. Melting ice therefore acts to amplify an initial warming, in a process called the ice albedo feedback. The word albedo refers to the reflected fraction of sunlight. The planet Venus is very reflective because of its clouds: we say it has a high albedo.

The ice albedo feedback was predicted by Arrhenius in 1896. Climate records from the past few decades show the effect of the ice albedo feedback already, in that warming is more intense in the Arctic than it is on the planet as a whole. The Arctic Ocean is projected in some models to be seasonally ice-free in the coming decades, representing one of the clearest examples of a "tipping point" in the near-term future. Sea ice in the Southern Hemisphere has not been melting the way it has in the North, so there has not been much change in albedo in the Southern Hemisphere. The observed cooling in the

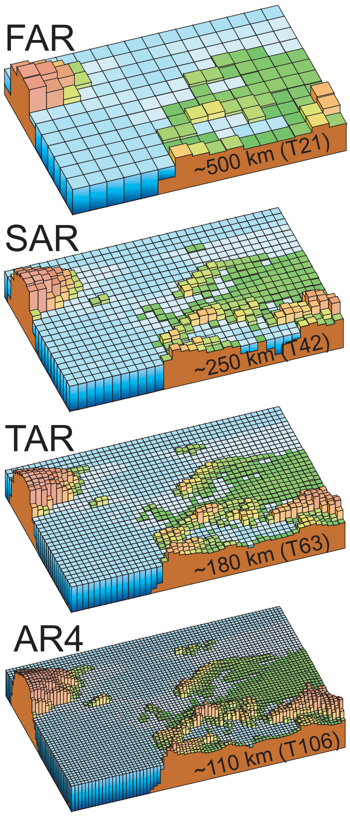


Figure 1.4 The climate models used in the sequence of Assessment Reports have become more detailed with the growth of computer power. These levels of detail are used for short-term climate projections. Century time scale climate simulations are typically done using the resolution at the previous level.

interior of the Antarctic may be caused by changes in atmospheric circulation resulting from the ozone hole, which is most intense in that region.

The specifics of the climate change forecast, the regional climate changes, and the impacts on the water cycle, for example, are derived from numerical models of the atmosphere, ocean, ice, and biosphere coupled systems. Atmosphere and ocean flows are turbulent, and the amount of heat and other properties that they carry depends on the details of this flow. The models used to forecast climate change are cousins to the models used to forecast the near-term weather. Weather forecasts have become demonstrably better since the 1990s, an indication of the growing sophistication of the climate models as well.

In general, the fidelity of the forecast, and the characteristics of the simulation, improve with increasing detail in the model. However, increasing the amount of detail in a computer climate model slows it down dramatically. Doubling the number of grid points in all three dimensions slows the code down by more than a factor of ten. Working in our favor however is the explosion in computer power since the 1990s, enabling the resolution of climate models to expand as shown in Figure 1.4.

In spite of increasing computer power, many processes within the climate system are impossible to predict from first principles, as would be ideal. Clouds, for example, depend on meter-scale gusts of wind, and on micrometer-scale interactions between cloud droplets. These processes will not be explicitly resolved on even the fastest computers within the foreseeable future, and so the end result, the clouds, must be based on larger-scale observations of cloudiness, rather than the true microscopic mechanisms that really control the evolution of the cloud. The cloud parameterizations are tuned until they reproduce the observed distribution of clouds. Unfortunately, changes from one apparently reasonable cloud parameterization to another are sufficient to make a large difference in the climate sensitivity predicted by the model.

Given the imprecise and subjective nature of climate models, significant progress has been made by the process of model intercomparison. Independent models written by separate teams of researchers incorporate different assumptions and parameterizations. Running the different models through the same scenarios of CO_2 rise, etc. allows them to be directly compared, with each other and with observational data. This helps identify aspects of the forecasts that are sensitive to the model details, versus aspects that are robust.

Formal climate model intercomparison efforts progressed through the Atmosphere Model Intercomparison Project (AMIP), to coupled models (CMIP), to paleoclimate simulations (PMIP). The IPCC solicits model simulations of various standard scenarios for the future of atmospheric CO_2 concentration, for presentation and analysis in the Assessment Reports. Twenty-three models are shown in the most recent AR4 report, as shown in Figure 6.14. The latest models are not radically different from previous generations in their global response to rising CO_2, but the models are getting better at simulating the regional details of Earth's changing climate.

Finding the smoking gun

The human impact on atmospheric CO_2 was first measured in the 1950s (Figure 2.3). The longest-standing measurement time series was instigated by David Keeling on the top of the remote marine volcano Mauna Loa on the Big Island of Hawaii (Figure 1.5). This location was chosen to sample the large-scale average marine troposphere, avoiding contamination by local uptake and release of CO_2 by the land biosphere, which would tend to obscure the global trend.

There is a strong seasonal cycle of atmospheric CO_2 concentration in the entire troposphere, driven by the life cycle of deciduous trees, which take up CO_2 to manufacture leaves in spring and release the carbon again as the leaves decompose after they've dropped to the ground in winter (Figure 1.6). It took a few years of measurements before the upward trend in the atmospheric CO_2 concentration was clearly apparent above all of this natural variability.

Carbon dioxide concentrations are now monitored from a variety of locations around the world. The CO_2 concentration in the atmosphere is mostly well mixed, although there are subtle variations from place to place. The concentration in the boundary layer near the ground may be higher or lower than the atmosphere at large, especially when the Earth's surface is giving off or taking up CO_2, as near a city or a forest. Above the boundary layer there are subtler variations in CO_2 concentration driven by these sources and sinks of CO_2. Atmospheric modelers use these CO_2 concentration measurements to deduce the rates of CO_2 uptake and release by the oceans and the land.

Figure 1.5 Mauna Loa observatory on the volcano, on the Big Island of Hawaii.

The climate impact from human release of other greenhouse gases methane (CH_4), chlorofluorocarbons (Freons), and nitrous oxide (N_2O) was discovered in the 1970s. A property of the greenhouse effect is that a single molecule of a very rare gas, such as methane or a Freon, has a much stronger effect on climate than a single molecule of an abundant gas such as CO_2. The human-caused energy imbalance from these secondary greenhouse gases, added together, begins to rival the imbalance from CO_2, even though the trace gases are being emitted at a much lower rate than CO_2 (Chapter 2).

It became apparent in the 1970s that sulfate aerosols have the potential to scatter sunlight back to space, cooling the Earth by increasing its albedo. The aerosols may also alter the size distribution of cloud droplets, increasing scattering and albedo still further. The cooling effect of aerosols offsets somewhat the warming impact of greenhouse gases.

An important difference between aerosols and CO_2 is that the lifetime of aerosols in the lower atmosphere is just a few weeks, while CO_2 accumulates. The cooling impact of aerosols is therefore much stronger in the Northern Hemisphere where they are emitted. In contrast, because CO_2 and many

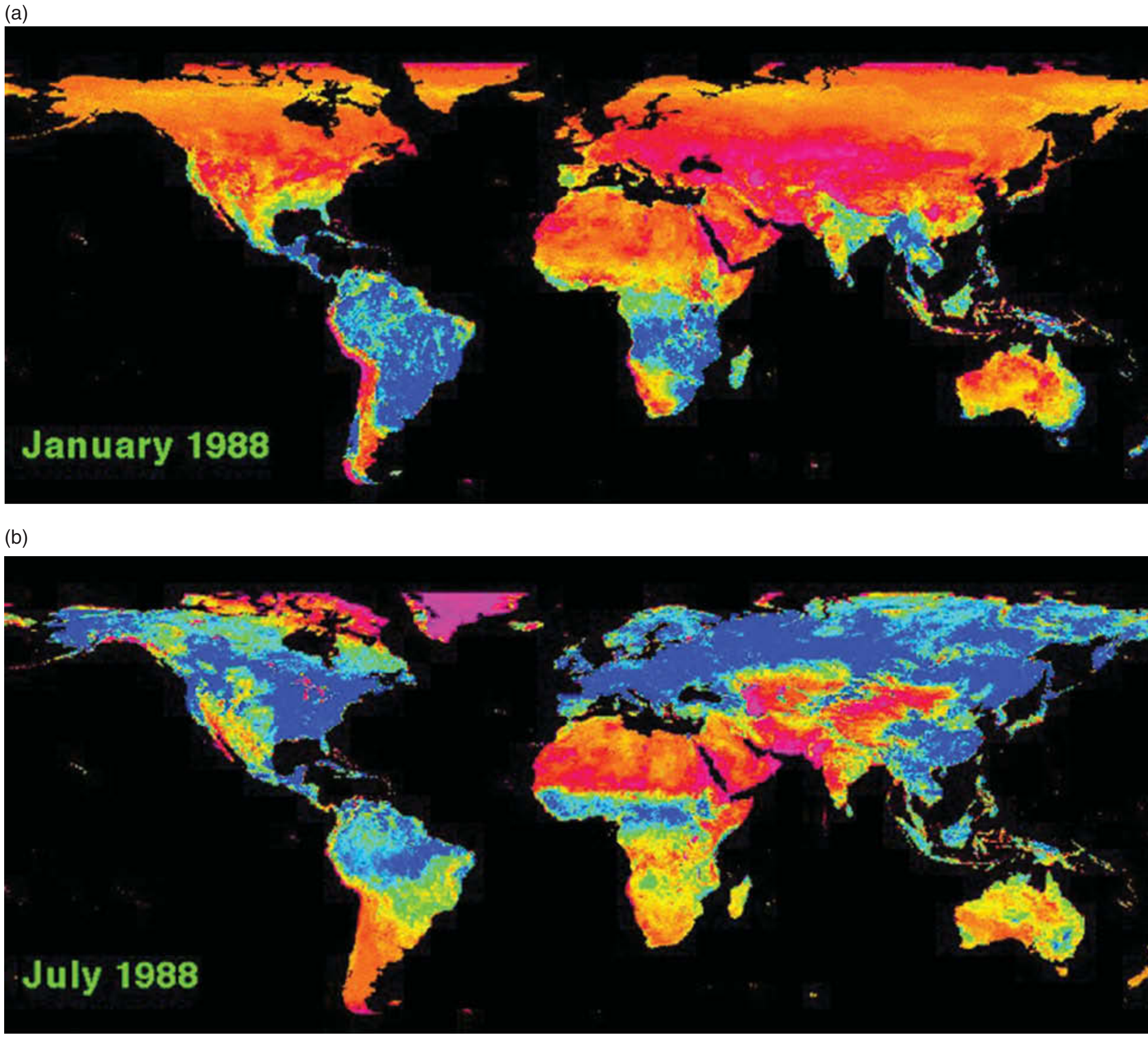


Figure 1.6 The extent of vegetation on the land surface, blue colors indicate green terrain. This vegetation index, called NDVI, is from satellite data.

other greenhouse gases are generally fairly well mixed in the atmosphere, the imbalance in radiative energy caused by their rising concentration is more global in impact. The precise total climate impact of aerosols is still less certain than is the impact of the greenhouse gases (Chapter 2).

Variations in the intensity of the sun could also have an impact on climate. Solar intensity has been measured accurately since the launch of the Nimbus-7 satellite in 1978. The brightness of the sun varies somewhat with the number of sunspots, following a sunspot cycle of about 11 years. Detailed sunspot observations date back to the 1600s with the invention of Galileo's telescope. There have been times when the sun had fewer spots than it has had in the past few decades, and even times when the spots disappear altogether for several decades, such as the Maunder minimum, from 1645 to 1715, the middle of the Little Ice Age. The climate forcing from the sun, measured in watts per square meter (W/m^2) and called its radiative forcing, is somewhat warmer now than it was in 1750, but greenhouse gases have increased their radiative forcing by 30 times as much (Chapter 2). There has been no increase in solar intensity in the "global warming decades" from the 1970s to the present.

The most direct way to look for global warming is in the global average temperature of the Earth. Natural variability in the climate system tends to rearrange heat around the surface of the Earth, rather than warming or cooling the entire Earth. Some natural climate variations, such as El Niño or variations in solar output, do affect the global mean temperature. In 1980 the signal of global warming was still indistinguishable from natural variability, but it was predicted that the human impact on climate would become evident within the decade (i.e. by 1990). The First IPCC Scientific Assessment in 1990 didn't find it, but the 1995 IPCC Scientific Assessment (SAR) declared "a discernable human impact on global climate." The conclusion has stood, and got stronger, in subsequent IPCC reports. The *Fourth Assessment Report*, AR4, assigns a probability of more than 90% that rising greenhouse gases are the dominant factor in the current warming.

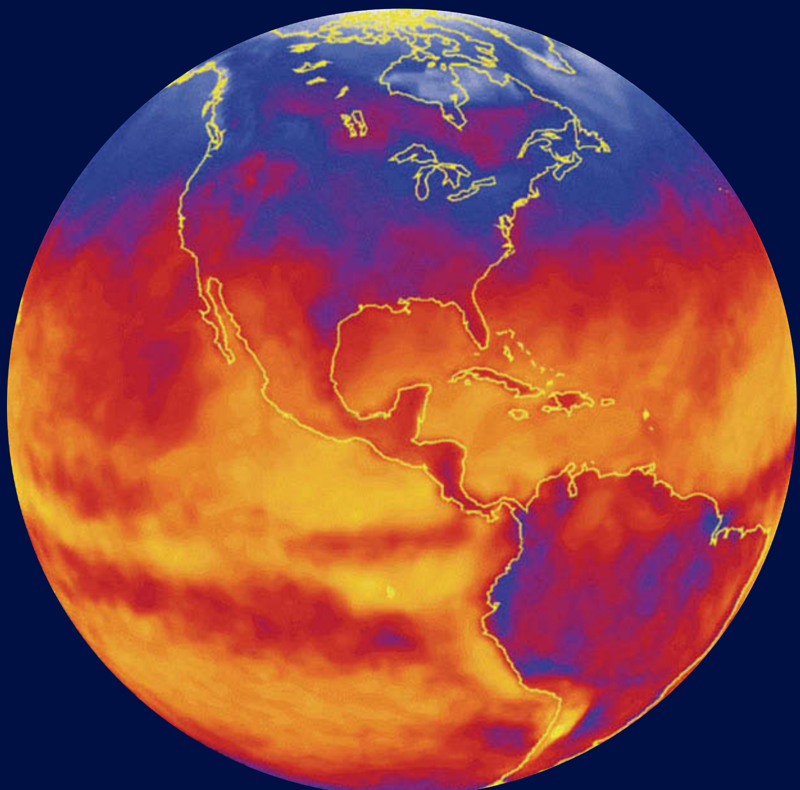
The point is illustrated dramatically by the output of 23 independent climate models that participated in the IPCC model comparison exercise. For one set of model runs, the models were told only about changes in the natural forcings of climate over the past century. Then the models were run again including the human impacts from greenhouse gases and aerosols. The results are shown in Figure 6.14 in Chapter 6. The model runs that include the effects of human impacts are able to reproduce the observed warming of the Earth since about 1970, while the ones that only know about the natural forcings don't have a clue about the warming.

In addition to the detection of global warming in the global average temperature, the effects of greenhouse gases can be seen in changes in the temperature cycles between day and night, or summer and winter, or the temperature trends with altitude above the Earth's surface. These patterns, called "fingerprints," can be used to distinguish warming due to changing solar intensity, for example, with warming due to CO_2 and other greenhouse gases. This topic is discussed in Chapter 6.

Summary

The basic concepts of the greenhouse effect and its role in global climate have been in place for over a century. Science is a self-correcting enterprise, in which concepts and hypotheses such as the role of atmospheric CO_2 concentration on the temperature of the Earth are subjected to testing and verification against observations. The importance of the global warming forecast to human interest has stimulated considerable research using a variety of approaches, especially in the most recent years. This work has refined but not really changed the evolving conclusions from the IPCC assessment process. Other theories for climate variability, such as a theory that solar irradiance is responsible for temperature trends, do not survive the same verification process. There is currently no competing theory or model for climate that explains the observed evolution of climate in the past, and that forecasts a substantially different future than the global warming forecast presented in the IPCC reports.

2 Earth's energy budget



This chapter explains the greenhouse effect, and the various changes to the greenhouse effect that can affect Earth's energy budget, and therefore its climate. Greenhouse gases are the obvious change that we read about in newspapers, but other factors include changes in the amount of small particles in the air, called aerosols, and changes in the intensity of the sun. Knowing something about the causes of climate change so far will enable us to decide whether global warming has already started, or whether the warming that has been observed on Earth in the last decades could have natural causes. This chapter is based on IPCC Chapter 2, "Changes in Atmospheric Constituents and in Radiative Forcing" and Chapter 7, "Couplings between Changes in the Climate System and Biogeochemistry."

The concept of radiative forcing

The climate of the Earth is governed by the very fundamental First Law of Thermodynamics. This is the law of energy conservation: energy cannot appear from nowhere, nor can it vanish into nothingness. Earth's climate is ruled by a very simple and fundamental principle: "energy coming in must go out." Energy comes in by way of sunlight, mostly in the form of visible and ultraviolet (UV) light. Energy travels back out to space via infrared light shining up from the Earth's surface and atmosphere.

The Earth's energy fluxes in and out can be wildly out of balance at any given instant or location, but on average for the entire planet and over a long time, the energy fluxes must balance. If the global energy fluxes are out of balance, the temperature of the Earth's surface rises or falls, seeking a new equilibrium. Heat energy on Earth is like a bank account; if more money comes in than goes out, the balance will increase with time.

A change in Earth's temperature affects the outgoing energy flux according to a fundamental law of physics called the Stefan–Boltzmann relation, which says that the outgoing energy flux from an object increases as the object gets warmer. According to this relation, an object radiates energy at a rate equal to $\varepsilon\sigma T^4$, where the energy flux is in units of W/m^2, epsilon (ε) is the emissivity, reflecting the efficiency with which the material radiates energy, sigma (σ) is the Stefan–Boltzmann constant which has the value of 5.67×10^{-8} $W/(m^2\,K^4)$, and T is the temperature in kelvin. The Stefan–Boltzmann relation says that an ordinary object emits light all the time as long as its temperature is greater than absolute zero (–459 °F or −273 °C). For example, an electric burner on a stove glows visibly with red light when it is hot to the touch. But at room temperature, the burner still emits radiation, but in infrared frequencies that our eyes cannot see.

Because global mean temperature is governed by such a simple and fundamental physical law, it is far easier to calculate than other aspects of climate such as regional temperatures, rainfall, sea level, or winds and ocean currents. There is not much wiggle room in the Stefan–Boltzmann relation; the energy flux as a function of temperature is known very well.

The average temperature of the Earth can still change, however, if we monkey with the pathways by which energy enters and leaves the Earth. The sun could get brighter, for example, increasing the energy coming in to the Earth, which would drive the Earth to warm up. Initially, immediately after the sun brightens, there would be more energy coming in to the Earth than leaving it. The excess energy would warm the Earth, which would then shine more brightly in the infrared according to the Stefan–Boltzmann relation. Eventually, the Earth warms enough for outgoing IR to balance the incoming solar energy again.

The Earth would warm up much more quickly if it were a dry planet like Mars. The Martian climate would respond completely to added CO_2 within a few years. But the Earth is kept cool by the large thermal inertia of the oceans. The CO_2 we emit today commits the Earth to temperatures that will continue to warm for centuries. The Earth is roughly 0.7 °C warmer today than it was in 1950, and it has been estimated that, given the amount of CO_2 already emitted, the Earth will warm further to about 1.0 °C.

The energy balance of the Earth is also affected by reflective stuff like snow, ice, and clouds. When visible light is reflected or scattered back to space, it does not deposit any heat energy on the Earth the way absorbed light does. As far as Earth's climate is concerned, it is as if the reflected beam of sunlight never even reached the Earth at all. The fraction of the incoming sunlight that is reflected is called the Earth's albedo. Clouds are very reflective and therefore have a high albedo; they are responsible for most of the reflected sunlight from the Earth. Sea ice is also very reflective. Overall, the Earth reflects about 30% of the sunlight that hits it. Both of these factors, clouds and ice, may be changing with time, perhaps in response to changes in climate. The albedo of the Earth acts as a feedback, potentially amplifying the climate response to human activity.

The pathway for heat energy leaving the Earth to space can also be altered, in particular by greenhouse gases and clouds. Earth sheds energy in the form of infrared radiation emitted at the ground. A greenhouse gas in the atmosphere can absorb that energy, and the gas re-emits infrared radiation itself. If the gas is colder than the ground, then the infrared from the gas will be less intense than the infrared from the ground. Looking down on the Earth with infrared eyes, one would see the cold, dim gas in the atmosphere rather than the bright warm surface. The effect of the greenhouse gas on the energy budget is to decrease the energy flow from Earth to space. Earth's response to adding greenhouse gas to the atmosphere is to use that energy imbalance to warm up, until it gets warm enough to balance the energy budget again.

The average temperature of the Earth can be altered by changing the intensity of the sun, the reflection of incoming sunlight by clouds or ice, or by changing the intensity of outgoing infrared light. We will compare all these different ways of changing climate according to the impact they have on the energy budget of the Earth, measured in units of watts of energy flow per square meter of the Earth's surface, or W/m^2. The various factors that can

Table 2.1. **Radiative forcing values, in W/m^2, for the year 2005 from the *Fourth Assessment Report*. Uncertainty represents 90% confidence intervals.**

Forcing agent	2005 (W/m^2)	Uncertainty
CO_2	1.66	±0.17
CH_4	0.48	±0.05
Halocarbons	0.34	±0.03
N_2O	0.16	±0.02
Total direct aerosol	–0.50	±0.40
Aerosol indirect effect	–0.70	–1.1, +0.4
Land surface albedo	–0.10	±0.30
Air transport effects	+0.01	–0.007, +0.02
Solar irradiance 1750 to present	+0.12	–0.06, +0.18

change the Earth's temperature are called *climate forcing agents*, and the strength of the forcing in W/m^2 is called the *radiative forcing*.

The point of this chapter in *The Climate Crisis*, and of Chapter 2 in the *Fourth IPCC Assessment Report* (AR4), is to compare all of the various climate forcings, say CO_2 versus contrails, using an apples-to-apples comparison of their radiative forcing values.

One complication is that one W/m^2 of radiative forcing from one forcing agent may not cause exactly the same climate change as would one W/m^2 from a different forcing agent. The two responses would be similar, but not exactly the same. This is because different radiative forcings have different patterns as a function of latitude and of time of year. For example, aerosols affect the energy budget by reflecting sunlight, which they can only do in daylight, not at night. Aerosols also only affect climate in polluted air where they are found. Greenhouse gas concentrations, in contrast, change the energy budget of the whole Earth surface, all the time. The radiative forcing, expressed in W/m^2 of energy, is not a perfect and foolproof way to compare the different climate forcings such as CO_2, methane, and volcanoes, but it is pretty good. The radiative forcing can be used to figure out which gases will have the largest impact on climate, which ones are growing in importance most quickly, and which ones are most harmful to emit. The bottom line of this chapter is a list of radiative forcing values for different greenhouse gases and other climate forcings in Table 2.1, Figure 2.1, and Figure 2.2.

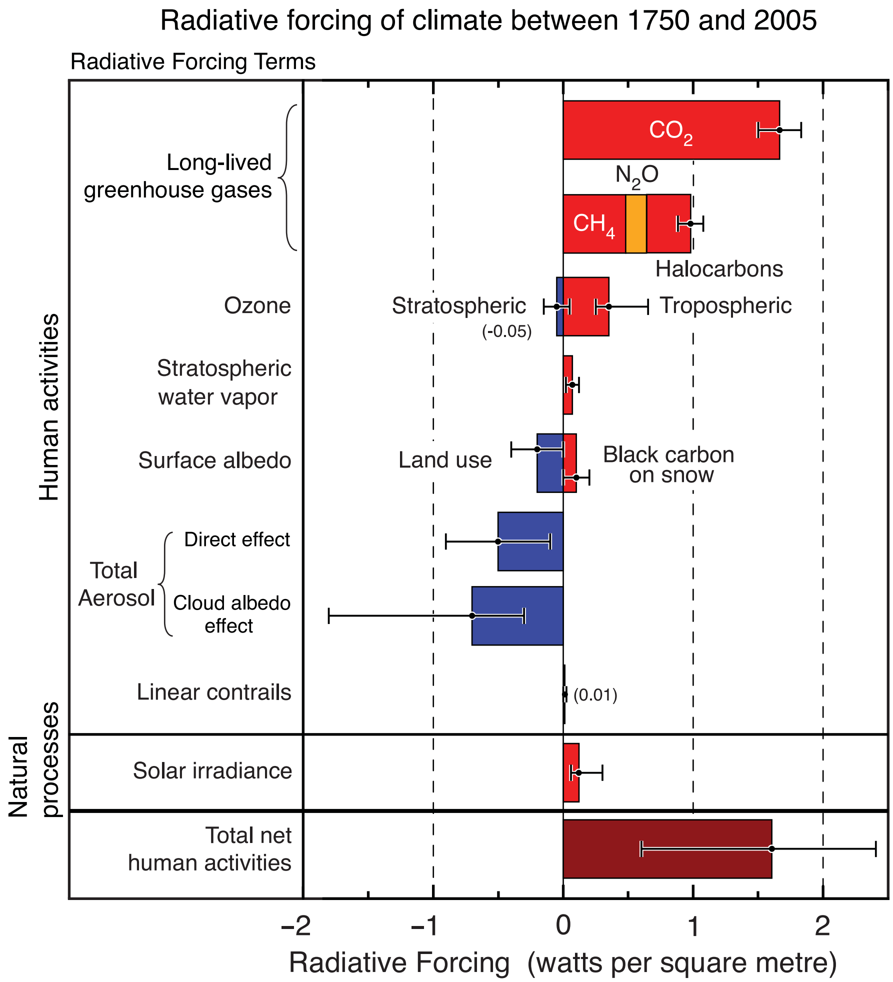


Figure 2.1 Changes in the energy budget of the Earth, between 1750 and 2005, arising from various natural and human causes.

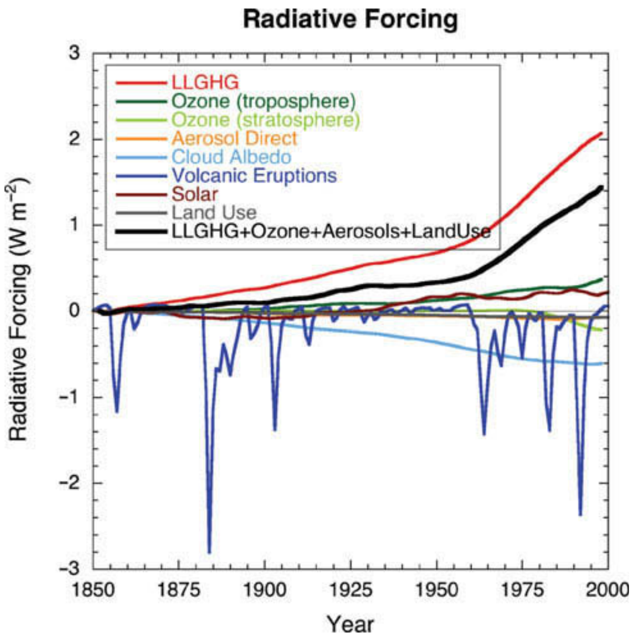


Figure 2.2 Changes in radiative forcing through time.

Greenhouse gases

Radiative forcings of greenhouse gases are based on measurements of the IR absorption characteristics of greenhouse gases. The absorption of infrared light by a gas depends crucially on the exact wavelength of the light; the spectra are remarkably complex and spikey. The absorption spectra depend on the pressure and on the molecular velocity, a function of temperature. The best estimates of the total radiative forcing of the gas comes from what are called line-by-line models of infrared radiation in the atmosphere. These models divide the light into thousands of different wavelengths, and treat each band separately. The model then takes the complicated absorption and emission spectrum of a greenhouse gas and predicts what the effect of the gas would be in terms of the total rate of energy flow to space.

Clouds would complicate this calculation, because they block the infrared light coming from the ground and from the greenhouse gases below the altitude of the cloud. For the sake of consistency, the radiative forcing of a greenhouse gas is defined to be the value under clear-sky conditions.

One important issue to understand is called the band saturation effect. Each molecule of greenhouse gas added to the atmosphere has some impact on the energy budget of the Earth. The first few molecules of a greenhouse gas in an atmosphere absorb a tremendous amount of the infrared light from the ground, but as the concentration of the gas increases, further additions of the gas have a weaker impact on the radiative forcing. This is because, at high concentrations, much of the light most easily absorbed by the gas will have already been absorbed even before you add the new slug of gas.

The radiative forcing becomes less sensitive as the concentration of the gas rises, but it never becomes completely insensitive to further increases in the concentration. For CO_2, the radiative forcing is the same for any doubling of the CO_2 concentration. Changing CO_2 from 10 to 20 ppm will have about the same impact on the energy budget of the Earth in W/m^2 as changing CO_2 from 1000 to 2000 ppm, or any other doubling. For this reason, it is convenient to talk about the temperature change of the Earth for doubling CO_2: a benchmark called the climate sensitivity.

Trace gases like Freons, which didn't exist before we produced them, have a much stronger impact as greenhouse gases, molecule per molecule, than CO_2 does, because the Freons are absorbing IR wavelengths that no other greenhouse gas could touch. The Freon absorption bands are unsaturated; they are virgin territory. For this reason, a single molecule of Freon could have the same radiative impact as 10,000 molecules of CO_2. The methane absorption bands are also relatively unsaturated, so that a molecule of methane is about 30 times more effective at greenhouse forcing than a molecule of CO_2.

The radiative forcing from long-lived greenhouse gases (excluding ozone and water vapor) has risen by 7% since the *Third Assessment Report* in 2001 (Figure 2.1 and Table 2.1).

Carbon dioxide is the dominant greenhouse gas responsible for our concern about global warming. It has a longer lifetime in the atmosphere than many of the other human-released greenhouse gases. The actual strongest greenhouse gas in the atmosphere is water vapor, but the concentration of water vapor is controlled by the fact that, if the air gets too humid, it rains. The response is part of the water vapor feedback (Chapter 6), which amplifies the climate change caused by other climate forcings, and which is therefore

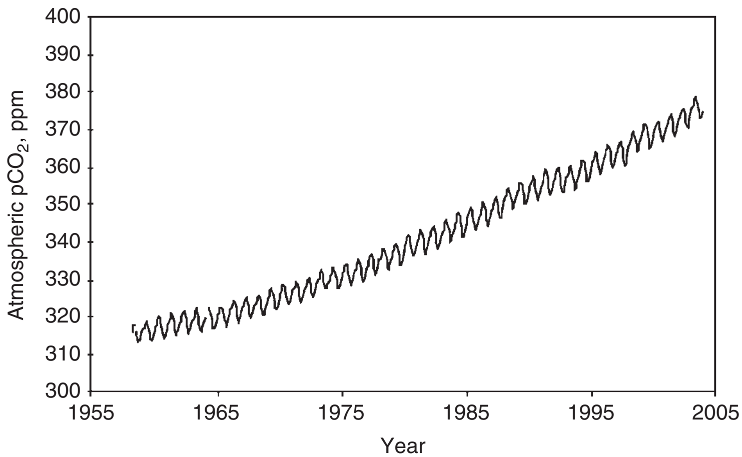


Figure 2.3 Atmospheric concentration of CO_2 as measured at Mauna Loa on the Big Island of Hawaii.

treated as a climate response rather than an initial forcing. The bottom line is that avoiding climate change means limiting the emission of CO_2.

The concentration of CO_2 in the atmosphere has been systematically measured since the middle 1950s (Figure 2.3). In 1996 the concentration was 361 ppm and it rose to 379 ppm by 2006. The rate of atmospheric CO_2 rise is accelerating, growing 20% faster in the period 2000–2004 than the growth rate was in the 1990s (Table 2.1). Carbon dioxide exerts a stronger radiative forcing than any other human-released greenhouse gas, and the largest change in radiative forcing from any greenhouse gas since the *Third Assessment Report*.

The rise in concentration is due to the human release of CO_2, from fossil fuel combustion, deforestation, and cement manufacture (Figure 2.4). Deforestation contributes a significant amount of CO_2 to the atmosphere in the form of burning or decomposing trees and soil carbon, and cement manufacture releases CO_2 from the source $CaCO_3$ rocks as an intrinsic part of the process. The rate of emission has accelerated in the past decades, up 37% since the 1980s (Table 2.1).

There is natural uptake of excess CO_2 from the atmosphere into the ocean and into the land biosphere. Ocean uptake is relatively easy to measure, because the concentration of dissolved carbon in the ocean is more uniform than it is on land. A wide variety of techniques have provided broadly consistent results, suggesting that the ocean uptake of CO_2 has increased somewhat since the 1980s (Figure 2.5).

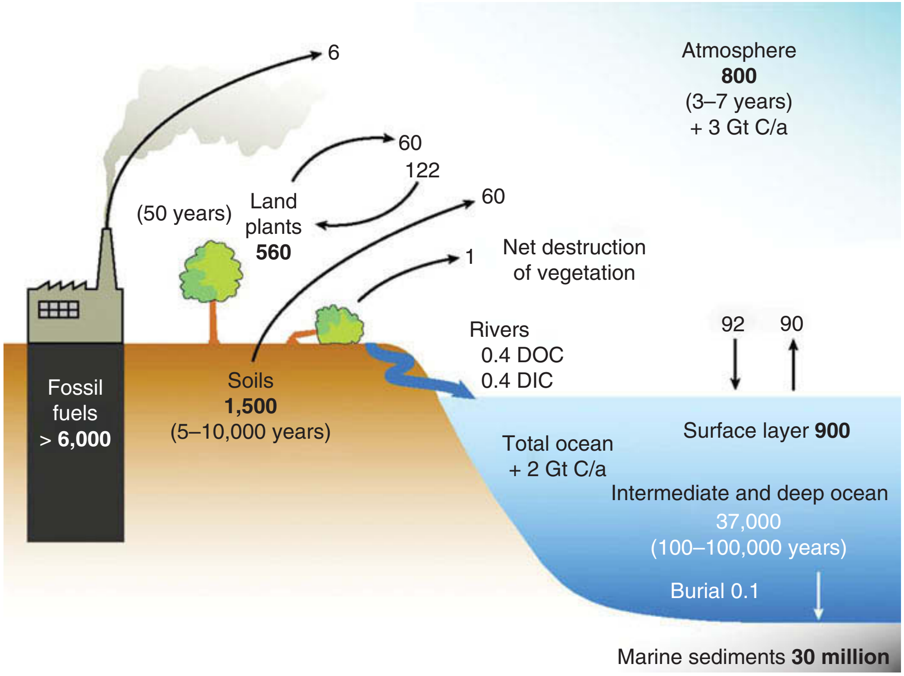


Figure 2.4 A cartoon of the global carbon cycle in the 1990s. Values for carbon reservoirs (bold type) are given in gigatons of carbon. Values for average carbon exchanges (normal type) are given in gigatons of carbon per year.

The other place for CO_2 to go is the land biosphere. Unfortunately, the rate of carbon uptake and release by the land surface is a difficult quantity to measure. Estimates of how much carbon is released to the atmosphere every year by deforestation disagree wildly (Table 2.2). Carbon is also apparently taken up into other places on land, going to ground in what has been referred to as the "missing sink." The most precise way to estimate the total rate of CO_2 uptake by the land surface is to combine the other pieces of the CO_2 budget, and assume that land makes up the difference. The spatial pattern of the mysterious CO_2 uptake can be inferred from subtle differences in the CO_2 concentration in the atmosphere around the world.

The best guess is that overall the rate of the natural CO_2 uptake on the land surface is probably roughly comparable to the rate of CO_2 dissolution into the ocean, roughly 2 Gton C per year. For comparison, the combined mass of humanity, not just our carbon but our entire combined body weights, adds up to less than a Gton. More carbon than all the people on Earth is disappearing into the land someplace every year, but it's not clear where it's hiding. One possibility is that the longer growing season from warming temperatures has

Table 2.2. **CO_2 fluxes in units of Gton C per year.**

	1980s	1990s	2000–2005
Atmospheric increase	3.3 ± 0.1	3.2 ± 0.1	4.1 ± 0.1
Emissions (fossil fuel + cement)	5.4 ± 0.3	6.4 ± 0.3	7.2 ± 0.3
Ocean–atmosphere	–1.8 ± 0.8	–2.2 ± 0.4	–2.2 ± 0.5
Land–atmosphere	–0.3 ± 0.9	–1.0 ± 0.5	–0.9 ± 0.6
Land use	1.4	1.6	NA
Greening	–1.7	–2.6	NA

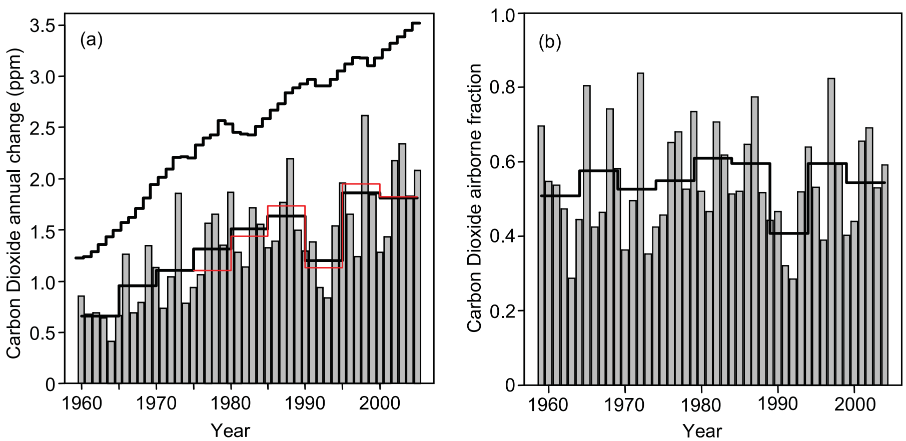


Figure 2.5 Fate of fossil fuel CO_2 in the atmosphere. (a) The atmospheric increase, including the potential increase (stepped line) if all the CO_2 remained in the atmosphere. Blocked lines are 5-year averages. (b) The fraction of each year's emissions that remains in the atmosphere each year.

stimulated forests to grow more lushly, or tundras to be replaced by forests. The rising CO_2 concentration in the air could be stimulating plant growth. Or it could be that nitrogen compounds from smokestacks act as fertilizer when they rain out on the land surface in the chemical form of nitrate. Unfortunately, until we know more clearly why the land surface is absorbing CO_2, it will be impossible to predict whether the CO_2 absorption will continue.

It is convenient to think about the fate of fossil fuel CO_2 in terms of its airborne fraction – the fraction of carbon released from fossil fuels that can still be found in the atmosphere. This quantity makes it possible to relate emissions to atmospheric CO_2 concentrations and therefore climate impacts. For the last 50 years, the airborne fraction has fluctuated around a value of

50 to 60%, with no obvious trends. A caveat to this way of looking at the carbon budget is that carbon sources from deforestation are not included as emissions. Perhaps by chance the land surface overall has remained nearly neutral as a CO_2 source or sink, with natural uptake balancing deforestation. The airborne fraction as it is presented here therefore largely tells us about ocean uptake.

Models of the global carbon cycle predict that, by the year 2100, rising temperatures and CO_2 concentrations will tend to reduce the natural world's ability to absorb CO_2. As atmospheric CO_2 rises, the chemistry of the ocean loses its ability to store more CO_2. Forests grow better with more CO_2 in the air, but this effect usually seems temporary in field studies. Soil respiration rates increase with temperature, resulting in low organic carbon concentrations in warm parts of the Earth, and perhaps in the release of CO_2 from soils in the future.

The factors driving human-related CO_2 emission will be discussed in Chapter 9.

Methane

Methane, CH_4, is the second strongest human-released greenhouse gas. The methane concentration in the atmosphere is currently about double its natural concentration in the year 1750 as recorded in ice cores. The radiative forcing from a molecule of methane is about 30 times stronger than that from a molecule of CO_2. This is because the concentration of methane is lower than that of CO_2, and so the methane doesn't currently absorb all of the infrared light in the frequencies that methane absorbs most strongly. This phenomenon, called band saturation, was described earlier in this chapter. Methane is less band saturated than CO_2 is.

Methane differs from CO_2 in that methane is a relatively short-lived gas in the atmosphere, while CO_2 accumulates. The methane concentration in the atmosphere depends on how much methane is being released each year, and how long each molecule survives, which is currently about 8 years. The carbon from the methane eventually reacts with oxygen to wind up as CO_2, the same product as from a combustion reaction. The CO_2 accumulates in the atmosphere just the same as fossil fuel CO_2 does.

Swamps (Figure 2.6), termites (Figure 2.7) and oil wells all release methane, but the rates for each process are not known very well. The largest source of methane to the atmosphere is natural wetlands. Rice farming produces artificial wetlands that also release methane. Ruminant animals and the fossil fuel industry are approximately co-equals with rice farming, and landfills and

Figure 2.6 Swamps on the shore of Lake Neuchâtel, Switzerland.

biomass burning also contribute significantly. Methane sources from wetlands are extremely sensitive to the depth of the water table, and therefore to changes in rainfall and climate. Methane sources are generally projected to increase with rising temperature, especially in regions of thawing permafrost.

Methane decomposes gradually in a slow stew of chemical reactions in the atmosphere, driven by ultraviolet light from the sun. The ultraviolet light breaks up certain gas molecules (ozone and nitrogen-oxygen compounds mostly) into very reactive fragments called radicals. A flame burns by generating similar radical compounds. Methane decomposes by reacting with a radical called hydroxyl, OH. Without sunlight and radicals, methane would be stable in the air for thousands of years, the way it is in the gas bubbles in ice cores. Similarly, a candle would be stable in air indefinitely if it is not lit, or it can burn quickly if it is.

The concentration of methane, as measured in bubbles from ice cores, was steady through time for thousands of years until the industrial era when it

Figure 2.7 Termite mounds from Litchfield National Park, Australia.

began to rise, driven by an increase in human-released methane from agricultural and industrial sources (Figure 2.8). Then beginning about 1993 the concentration stopped increasing. One possible explanation is that the emission rate stopped growing, unlike other greenhouse gases such as CO_2 and N_2O. Or it could be that the chemical lifetime for methane is shorter than it used to be.

The lifetime of methane in the atmosphere seems like it could quite easily be altered by human activity, but there is no clear indication that any change in methane lifetime has occurred. The fate of methane is to react with OH radicals, so one way to estimate the lifetime of methane would be to measure how much OH radical there is. More OH in the air would be like a larger flame on a candle, burning more quickly.

Unfortunately the concentration of OH is extremely low, and extremely variable (there is no OH at night, for example), making it extremely difficult to tell if there is more or less OH radical in the air than there used to be. There are indirect measurements of the atmosphere's combustion rate, such as the disappearance with time of the industrial compound methyl chloroform,

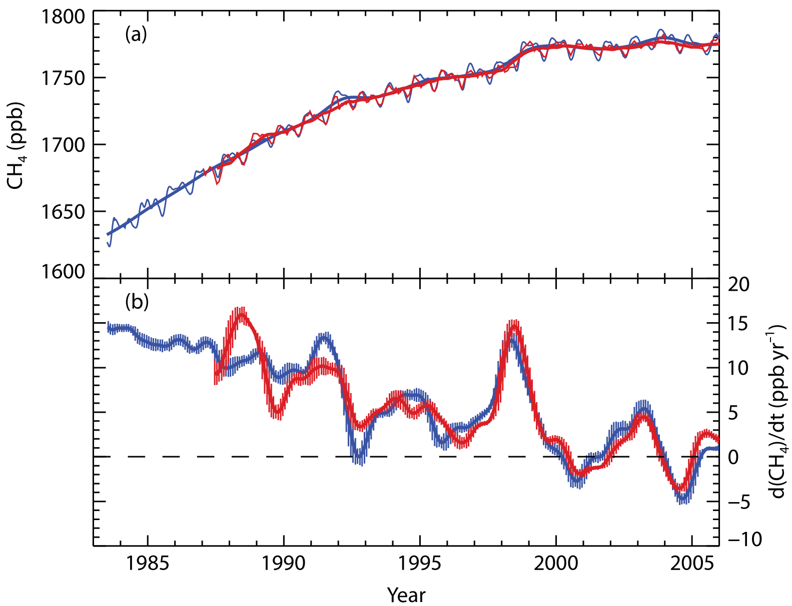


Figure 2.8 Recent changes in atmospheric methane concentration (top), and rate of change (bottom).

CH_3CCl_3, or the concentration of the cosmic ray product carbon-14 in carbon monoxide, ^{14}CO. The details of the results differ from study to study, but in general there is no evidence for a change in the OH concentration of the atmosphere by more than $\pm 10\%$ or so. The lifetime of CH_4 therefore seems to be more-or-less constant.

The conclusion that these observations bring us to is that the human-related sources of methane to the atmosphere have reached a steady plateau, and the atmospheric concentration has therefore also reached a plateau. However, given the uncertainties in the present-day methane budget, it is difficult to forecast the future evolution of the methane concentration in the atmosphere.

Halocarbons

Halocarbons are strictly man-made gases used in refrigerators and air conditioners, composed of carbon, chlorine, fluorine, and in some cases hydrogen. Halocarbons collectively make up the third most important greenhouse gas radiative forcing after CO_2 and methane. The halocarbons with the highest concentration in the atmosphere, and currently the fastest

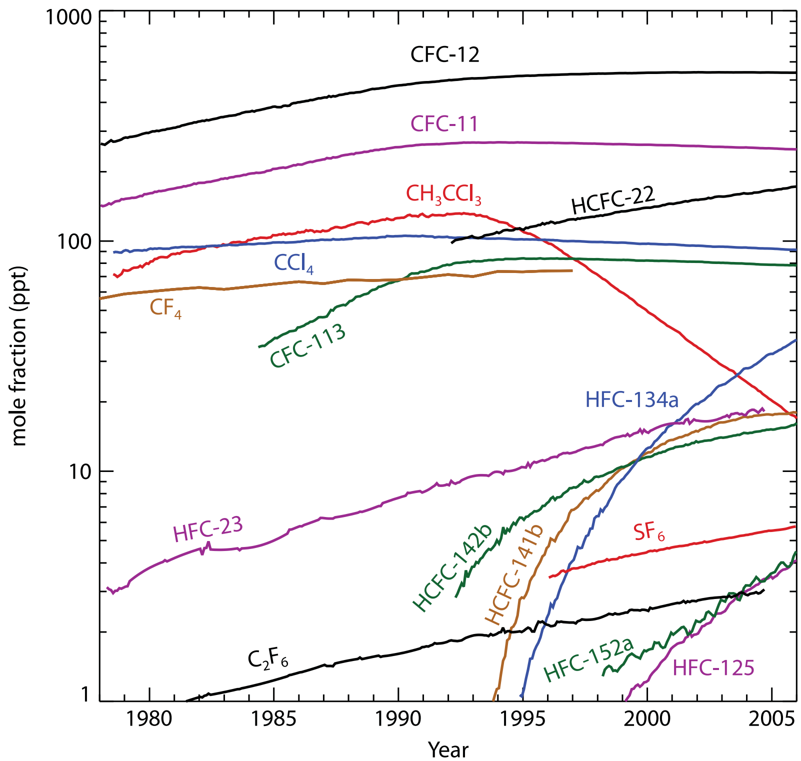


Figure 2.9 Concentrations of various halocarbon compounds in the atmosphere.

release rate, are the Freons, such as CFC-11 ($CFCl_3$) and CFC-12 (CCl_2F_2) (Figure 2.9). The very low concentrations of these gases give them a strong radiative forcing for each molecule of gas, twenty thousand times more effective per molecule than CO_2.

When halocarbons decompose in the stratosphere, they release the element chlorine, which acts as a catalyst to destroy the three-oxygen molecule ozone, O_3. Emission of halocarbons is regulated by the Montreal Protocol agreement, and as a result, the concentrations of the halocarbons are declining, but only slowly because of their long lifetimes of 50 to 100 years. As the concentrations decline, so do their radiative forcing values. Although the aim of the Montreal Protocol is to protect the ozone layer, rather than to prevent global climate change, the Montreal Protocol has arguably done more to reduce global warming than the Kyoto Protocol has! New compounds called hydrofluorocarbons were developed to replace the halocarbons, but with reduced impact on stratospheric ozone. These are also strong greenhouse gases, and their concentrations are rising in the atmosphere, but they as yet only contribute about 5% of the radiative forcing from halocarbons.

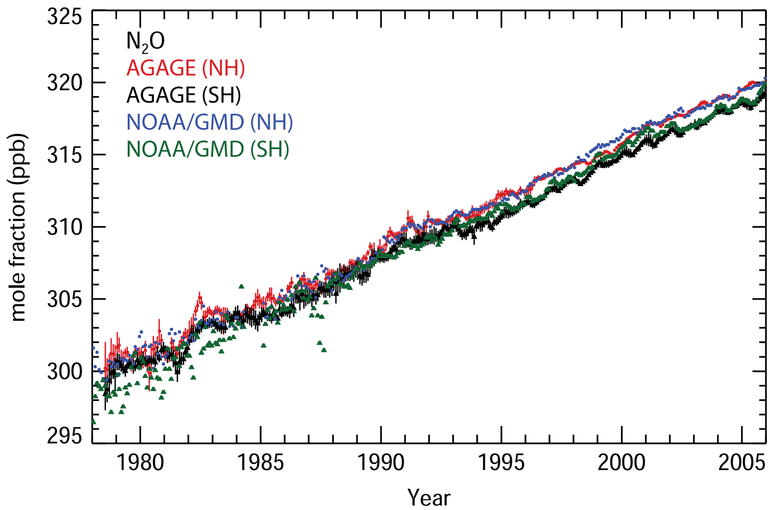


Figure 2.10 Concentration of N_2O in the atmosphere.

Nitrous oxide

Nitrous oxide, N_2O, also known as laughing gas, is a relatively long-lived greenhouse gas that existed in the natural world but is growing more abundant because of human activity. The lifetime of N_2O in the atmosphere is about 150 years. Most of the rise in atmospheric N_2O concentration (Figure 2.10) is thought to be due to agricultural processes. Nitrogen in the forms of nitrate (NO_3^-) and ammonia (NH_4^+) are used as agricultural fertilizers. Bacteria, particularly in tropical soils, convert a small fraction of this nitrogen into the form of N_2O. Internal combustion engines also produce N_2O from nitrogen and oxygen molecules in the air inside the combustion cylinders. The ultimate fate of the N_2O is to be blasted apart by ultraviolet light in the upper atmosphere. Like methane and CO_2, the concentration of N_2O measured in ice cores was steady in time for thousands of years, but has been increasing in the past decades, in response to the increased human-related emission. As the concentration of the halocarbons declines, N_2O will move to third place in the radiative forcing ranking of greenhouse gases.

Ozone

Atmospheric ozone is found at its highest concentration in the stratosphere. The ozone is produced when ultraviolet light from the sun splits oxygen molecules (O_2) into the two separate oxygen atoms. Instead of recombining, the oxygen atoms each find intact oxygen molecules and join them, forming O_3 or ozone.

Ozone molecules are less stable chemically than O_2, so the concentration of ozone depends on how easy it is for the ozone to decompose into O_2. Chlorine carried to the stratosphere in halocarbons, and nitrogen compounds produced from N_2O, are able to catalyse the decomposition of ozone into O_2. Because ozone today has a shorter lifetime than it did in the natural atmosphere, its concentration is about 4% lower than it was naturally. Since ozone is a greenhouse gas, its absence leads to a small net cooling of the Earth.

In the troposphere, ozone is produced by a combination of pollutants, in particular hydrocarbons and nitrogen oxide compounds (a chemical family consisting of NO and NO_2, and abbreviated as NOx). Concentrations of ozone vary seasonally and from place to place. The climate impact of human-related tropospheric ozone is relatively small on a global average, although its concentration is much higher above cities and downwind of them than it is in remote areas.

Other human-related climate forcings

Aerosols

Aerosols are small particles or droplets suspended in the atmosphere. These can affect Earth's energy balance by scattering visible light from the sun, cooling the Earth by increasing its albedo. Aerosols can also potentially absorb and re-emit IR light coming upward from the ground, acting as a greenhouse agent. The estimates of the radiative forcing impacts from various types of aerosols are given in Table 2.1. The most important type of aerosol radiative forcing agent is the sulfate aerosols, which are produced by combustion of coal. In total, sulfate aerosols are estimated to have a direct radiative forcing of about $-0.5\ W/m^2$, cooling the Earth.

There is another potential impact of aerosols on the energy budget of the Earth, very uncertain but very important, called the indirect effect. Sulfate aerosols act as nucleation sites, or "seeds," for making cloud droplets. Where aerosols or other condensation nuclei are abundant, clouds tend to form with more abundant but smaller cloud droplets. The smaller drops are more efficient at scattering light back to space, rather than absorbing the light as larger drops tend to do. Smaller droplets therefore have a higher albedo than larger droplets. Smaller drops may also persist longer in the atmosphere before raining out. The indirect effect of the aerosols is the change in radiative forcing due to the change in the cloud droplet size, and the increased cloudiness we expect in a dirtier atmosphere.

Previous IPCC reports presented a range of possible values for the aerosol indirect effect, but with no indication of what they think the most likely value is within that range. For the first time in the *Fourth Assessment Report*, the indirect effect has a best guess estimate as well as an uncertainty. The indirect effect of aerosols is estimated to cool the planet even more than the direct effect, but the uncertainties are still very large.

A strong cooling effect of sulfate aerosols is bad news for the future evolution of climate, because as societies become wealthy enough to clean up the sulfur from their coal plant effluent, the aerosols fall out of the atmosphere very quickly, while the CO_2 emitted from that same power plant tends to accumulate in the atmosphere. If aerosols are strong Earth coolers, then when they are cleaned up, they will leave the Earth under the unmitigated warming effect of the greenhouse gases.

Land surface albedo

The albedo of the surface of the Earth is changing due to human activity, in several ways. Land use change, in particular deforestation in temperate regions, has increased the albedo, leading to a small cooling radiative forcing, while deposition of black carbon on new-fallen snow decreases the albedo, leading to an even smaller warming tendency. The total land surface albedo radiative forcing is thought to be cooling; the radiative forcing is minor compared with the greenhouse gases (Table 2.1). The Earth's surface is getting shinier, as viewed from space, but the impact on climate is pretty small compared to the impacts of greenhouse gases and aerosols.

Contrails and other airplane effects

The most obvious human fingerprints in the sky are the contrails, long wispy clouds left in the wake of airplanes (Figure 2.11). Airplane contrails are judged in the *Fourth Assessment Report* to have a very small impact on the radiation budget, less than 1% of the climate impact of greenhouse gases. The 2007 estimate in the Fourth Assessment Report is three to four times smaller than the estimate from the Third Assessment Report in 2001, based on new observations of contrail area and optical depth. This radiative forcing applies to the contrails themselves, the long white lines across the sky, but it is possible that the contrails dissipate as the ice particles that form them smear out across the sky, rather than dissipating by evaporation of the ice particles back to water vapor. In this case, the particles might continue to affect the climate even after the line in the sky is no longer visible. The *Fourth Assessment Report*

Figure 2.11 Contrails.

estimates that the total radiative forcing from contrail particles is 2–10 times greater than the effect of the linear contrails themselves. This is a wide range of uncertainty, but since the overall radiative forcing from contrails is small in any case, it doesn't matter as much as for example the uncertainty in aerosol radiative forcing.

Climate forcings that are not our fault

Solar intensity

The brightness of the sun varies naturally over time. The clearest variation in solar intensity, and the easiest to measure, seems to be a part of the roughly 11-year sunspot cycle. In recent decades, the maximum in the sunspot cycle brings maybe 100 dark spots on the surface of the sun. In the low part of the cycle, there may be no sunspots at all. Visual records of the number of sunspots go back to the year 1610 (Figure 2.12).

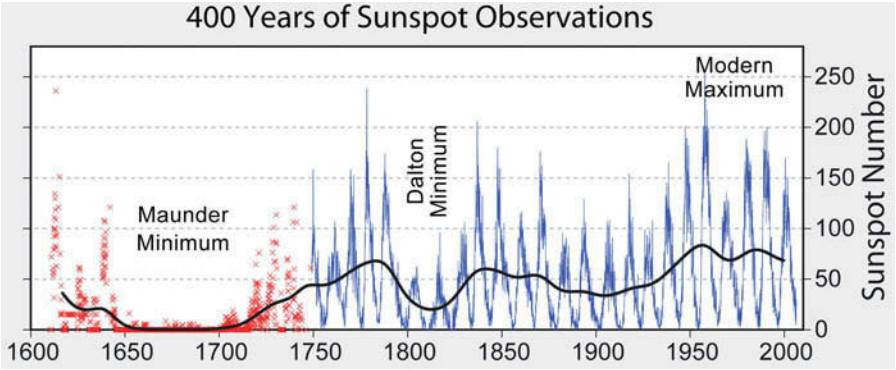


Figure 2.12 Sunspot observations for the past 400 years. Sunspot numbers follow an 11-year cycle, the Schwabe cycle (see blue curve). Beyond that they also show longer-term variations, see the smoothed black curve. Sunspot numbers correlate with the intensity of solar radiation: when there are lots of sunspots, radiative forcing is strong. Solar activity increased in the first half of the twentieth century, but it has been steady since, even showing some decline over the past 20 years.

Although each individual sunspot is a cool region, overall the sun shines more brightly when there are lots of sunspots. Accurate measurements of the solar intensity go back about three decades, and they reveal that the sunspot cycle alters the intensity of the sun by about 0.08% (Figure 2.13). When this intensity is averaged over the entire surface of the Earth and corrected for the Earth's albedo, it results in radiative forcing variations of about 0.2 W/m^2.

Going back even further in time, the sunspot cycle was more variable than it has been in the past 30 years, when measurements of solar intensity were being made. There were many fewer sunspots during the Little Ice Age, which ended about 1750. In particular, there was a time period called the Maunder minimum, 1645 to 1750, when no sunspots were seen at all. The lack of sunspots implies a cooler sun at that time, driven by a radiative forcing decrease of about 0.12 W/m^2, much smaller than the increased radiative forcing from greenhouse gases of about 3.6 W/m^2.

It could be that the climate impact of solar intensity is stronger than the radiative forcing value (in units of W/m^2) would suggest. The extra boost comes from ultraviolet light. When the sun is brighter, the ultraviolet rays intensify more strongly than visible light does. Ultraviolet light packs a punch to the climate system above and beyond its energy content in W/m^2. Ultraviolet light is powerful enough to break apart molecules in the atmosphere, creating the ultra-reactive radical compounds that were discussed above with regard to methane and ozone. More ultraviolet light would lead to

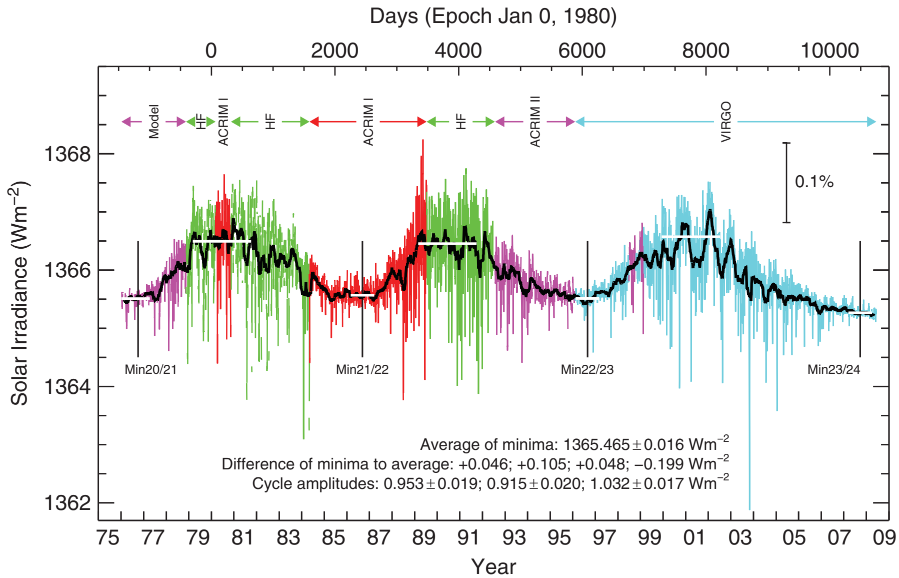


Figure 2.13 Measurements of solar irradiance from satellite from 1975 to mid 2008. The variations are dominated by the three last 11-year solar cycles. That these do not have a marked effect on global temperatures shows how weak the influence of solar variations is on our climate. Currently the intensity of the sun is at an all-time low since these measurements began.

more ozone, a greenhouse gas. Ozone also absorbs so much ultraviolet light that it changes the temperature of the upper atmosphere, changing also the large-scale atmospheric circulation, leading potentially to a more intense climate impact than you would get from the radiative forcing alone.

In the past few decades, when the global average temperature of the Earth has been rising, the intensity of the sun has varied according to the solar cycle, but there has been no overall trend in the solar cycle (Figure 2.13). So even if the solar radiative forcing is amplified by some unknown feedback, no trend multiplied by an amplification factor is still no trend. Greenhouse gases are the only positive (warming) radiative forcing agent on our list for the global warming decades.

Volcanos

Volcanic eruptions such as El Chichon (Mexico, 1982) and Pinatubo (Philippines, 1991, Figure 2.14) inject sulfate aerosols into the stratosphere, resulting in strong but short-term cooling radiative forcings. Prehistoric volcanic eruptions can be documented by measuring the concentration of

Figure 2.14 The June 12, 1991 eruption of Mount Pinatubo, Philippines.

sulfate in ice cores. Pinatubo acted to cool the planet for a few years, but there has not been much climate impact from volcanic activity since then.

Summary

The radiative forcings of the various different agents of climate change are summarized in Figure 2.1 and Table 2.1. Radiative forcing values, in W/m^2, for the year 2005 are from the *Fourth Assessment Report*. Uncertainty represents 90% confidence intervals, one of the most important figures in the *Fourth Assessment Report*. The dominant balance is between warming from greenhouse gases, more than half of which comes from CO_2, versus cooling by sulfate aerosols.

One conclusion worth noting is that the climate change agents that last a long time are all on the warming side. The lifetimes of halocarbons and N_2O are measured in centuries, while the lifetime of CO_2 runs from centuries to hundreds of millennia. Aerosols, on the other hand, persist for only a few weeks in the troposphere. If the sources of aerosol emission were cleaned up, say by reducing sulfur emission from coal plants to improve local air quality and fight acid rain, then the aerosol concentration in the atmosphere would decrease quickly, leaving behind the undiluted, strong, warming influence of the greenhouse gases.

Another conclusion is that the climate forcings that cause warming are known rather well, while the strengths of the cooling climate forcings are poorly constrained, mostly because the climate impact of aerosols is difficult to pin down. The radiative forcing from aerosols is important to know, because the aerosols have been keeping the planet cool to some lesser or greater extent, counteracting some of the warming impact from greenhouse gases. If we ultimately find that aerosols have been having a strong cooling effect, then we will see a strong warming if we clean up the aerosols.

The third point to notice is that none of the natural forcings have a recent upturn that could explain the warming of the past five decades (Figure 2.2). Solar irradiance clearly has an impact on climate, as demonstrated by the Little Ice Age and Medieval warm climate intervals. But the intensity of the sun has not increased in the past decades, ruling out the sun as an explanation of the observed warming trend, leaving only greenhouse gases with a positive (warming) radiative forcing through these “global warming decades.”

3 Climate change so far

When people think of climate change, they usually think of the atmosphere first. They think of the kind of things they hear about in the weather forecast: air temperature, rainfall, winds. Professional climatologists usually have a more encompassing view of the climate system, which includes things like the oceans, the ice sheets and mountain glaciers. But let's go step by step and start with the atmosphere, and let's start by taking stock of what is actually happening there. Many people feel that significant changes are underway – that winters are not what they used to be in their childhood, or perhaps that summers never used to be so hot and dry in their region. While these are often valid observations, any single person's experience is necessarily rather limited to the region where they live and to what they can remember. So what do measurements from around the world show? That is what we will discuss in this chapter.

With each IPCC report, the picture is getting ever more clear. There is an obvious reason for this: since the first report in 1990, we have accumulated 17 more years of measurements. But in addition to that, a lot of work has been done on the quality control and a comprehensive analysis of errors in past measurement data sets, on filling gaps and on recovering data archives that had not yet been included, for example because they existed only on paper and not yet in digital format.

Temperature changes

As was explained in Chapter 2, the global mean surface temperature is ruled by a simple energy balance which involves the effect of greenhouse gases. It is therefore the best number to look at if one wants to see whether the increase in greenhouse gas concentrations is actually having the effect that is predicted by the physics of the greenhouse effect. The global mean temperature has the additional advantage that its natural variations are much smaller than the variations on a regional or local scale; this makes it easier to detect any long-term trend. The reason is simply that many natural climate variations cancel out when averaged over the globe. At any moment in time, some parts of the planet will be warmer than normal while others will be colder. As an example, the monthly temperature anomalies in Boulder, Colorado, have a range of 7 °C (meaning that in 90% of cases the average temperature of a particular June, say, is within a 7 °C wide interval). For the USA as a whole, this range of monthly anomalies is 3.9 °C, while for the globe it is only 0.8 °C. Annual anomalies are much smaller again than these monthly anomalies: if June was rather hot, there is still a chance that September or December (say) were colder than average, and such anomalies would partly cancel out.

The global mean surface temperature is computed by combining measurements of air temperatures over land and measurements of sea surface temperatures in the oceans. Air temperatures are measured at thousands of weather stations around the globe, while sea surface temperatures are measured from thousands of ships and buoys. These measurements are combined on a regular grid, so that every square kilometer of Earth's surface counts equally towards the global average, regardless of how densely the measurements are spaced.

The urban heat island effect

Errors in the computed global mean temperature arise mostly where the data coverage is thin – this is a problem in the tropics and the Southern

Hemisphere, especially around Antarctica, in the earlier times, particularly the nineteenth century but to a lesser extent still up to 1950. Another potential error source is the "urban heat island effect", which can affect weather stations in cities. For various reasons cities usually have a warmer microclimate than their surroundings; this can lead to a spurious warming trend at an urban weather station as the city grows. This warming is of course very real in the city concerned, but it is spurious in the sense that it is a highly localized effect not representative for a wider area. Most stations affected by the "urban heat island effect" are therefore excluded from the global records; they can be filtered out by comparison with nearby rural stations. Several studies have shown that the urban heat island effect causes only a tiny error in the computation of global temperature trends. For example, it was found that no differences exist in the warming trend computed for very windy days versus that for calm days. If the urban heat island effect did play a role, then clearly it should have a much larger impact on calm days. Also, studies for the USA and for China showed that the temperature trends computed using only rural stations were practically indistinguishable from those that included urban stations.

How global temperatures changed

After all these preliminaries about temperature measurements you may be curious what they actually show. This is seen in Figure 3.1. From the level in the second half of the nineteenth century, temperatures increased in two phases: first from the 1910s to the 1940s, and then more strongly from the 1970s to the present. Around 1950 (let's use the average 1946–1955), it was 0.2 °C warmer than at the beginning of the century (1896–1905). Global temperature remained near this level until the 1970s, after which it started a steady rise at a rate of 0.17 °C per decade until today. The decade 1996–2005 was 0.6 °C warmer than 1946–1955. The overall rise since 1900 is 0.7 °C when expressed as a linear trend, which understates somewhat the actual, non-linear increase. This warming trend is greater than any experienced since at least the Middle Ages (the eleventh century – see Chapter 6). Table 3.1 shows how the warming trend has accelerated over time, from 0.05 °C per decade for the past 150 years to 0.18 °C per decade over the past 25 years.

This time history is due to a combination of factors. First, there are *forced* temperature changes, that is changes driven by the kind of forcings discussed in Chapter 2 (see Figure 2.1). Superimposed on this are unforced, internal variations – you can think of them simply as random jitters. The latter mostly

Table 3.1. **Linear trend in global mean temperature over the past 25, 50, 100 and 150 years. Note that the trend is accelerating. The error bars reflect the fact that trends over shorter time periods can only be determined with less accuracy, due to the random variability also seen in Figure 3.1.**

	Period Years	Rate °C per decade
	25	0.177 ± 0.052
	50	0.128 ± 0.026
	100	0.074 ± 0.018
	150	0.045 ± 0.012

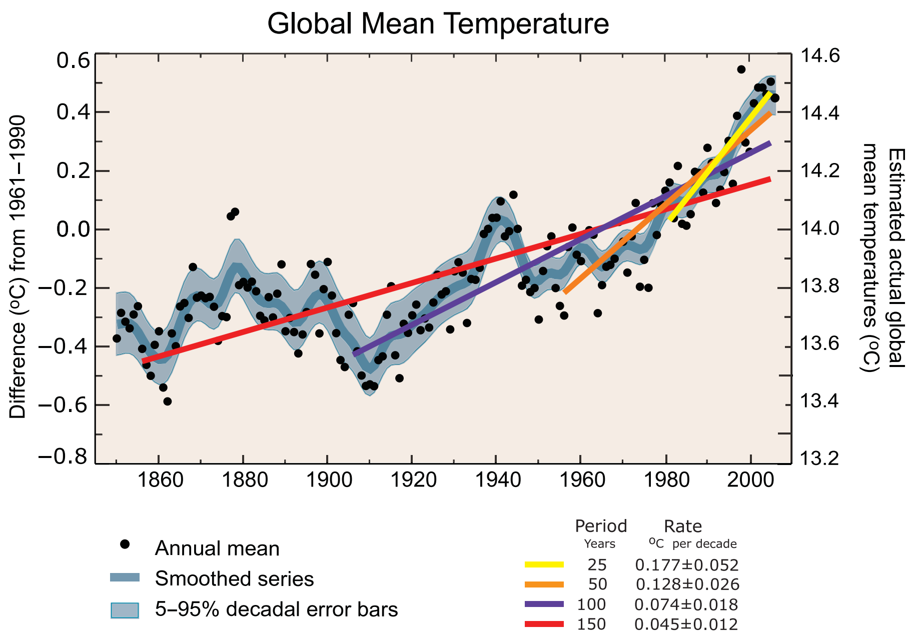


Figure 3.1 Global average surface temperature from 1850 to 2006. Dots show individual years, and the black line with its blue uncertainty range shows decadal averages. The temperature changes on the left scale are given with respect to the average over the years 1961–90.

cause the random variations from year to year. As the graph shows, these typically have an amplitude of about 0.1–0.2 °C. If one looks at just a short time interval – less than 10 years or so – such random jitters dominate temperatures, since the forced trend over such a short time is small. The table shows this: the error margin to which the trend can be determined gets ever larger when the time period gets shorter, and around 10 years or so the uncertainty is as big as the trend itself. It is thus pointless to look at such a short time period for answers on whether global warming has slowed or accelerated, as some recent newspaper articles have done.

Most of the longer-term variations are due to forced change, namely the human-caused changes in greenhouse gas concentrations and aerosol pollution, as well as the natural changes in solar activity and volcanic particles. For the first warming phase (1910s to 1940s), the dominant factors were probably the joint increase in both solar activity and greenhouse gas concentration. During the stagnant phase (1940s to 1970s), solar activity remained almost constant, while the warming due to increasing greenhouse gas concentrations was mostly cancelled by the cooling effect of increasing aerosol pollution. After that, sulfur filters on power station smoke stacks cleaned up this aerosol pollution in many parts of the world, so that from the 1970s the accelerating rise in greenhouse gas concentrations dominates the temperature record.

Record years

About record warm years, the IPCC report has the following to say:

The warmest years in the instrumental record of global surface temperatures are 1998 and 2005, with 1998 ranking first in one estimate, but with 2005 slightly higher in the other two estimates. 2002 to 2004 are the 3rd, 4th and 5th warmest years in the series since 1850. Eleven of the last 12 years (1995 to 2006) – the exception being 1996 – rank among the 12 warmest years on record since 1850. Surface temperatures in 1998 were enhanced by the major 1997–1998 El Niño but no such strong anomaly was present in 2005. Temperatures in 2006 were similar to the average of the past 5 years.

At the time of writing, the latest data show that 2007 and 2008 also ranked amongst the top 10 warmest years on record. January and February 2008 turned out to be relatively cool (causing a flurry of misguided newspaper reports calling off global warming) due to exceptionally widespread snow cover in parts of Asia and cool ocean temperatures in the tropical Pacific (La Niña conditions, see Chapter 5). This brief cold snap was one of those "random jitters" mentioned above. It was gone again by March 2008, which ranked the second or third warmest March, depending on the data set used. Above the global land masses, it even was the warmest March since records began in the nineteenth century.

Land and sea temperatures

It is interesting to see where temperatures have increased most: over land or sea, in the north or south? The partitioning in land and ocean is shown in Figure 3.2. Since the 1970s, temperatures over land have increased much faster than over the oceans. This is to be expected for several reasons. The oceans are wet, so a large part of the incoming energy goes into evaporation rather than heating. On land, evaporation is limited by the available moisture – when the soil is dry, heating is greater. The oceans also act as a big heat buffer: they store heat and therefore respond with a delay. That's a boon and a curse. It reduces the warming we have experienced so far, so that's good. But it also could lull us into complacency by hiding some of the warming we are committed to from the greenhouse gases we've put already into the atmosphere. Since we live on land, it is important to realize that land areas are and will be warming more rapidly than the global average numbers most often cited.

If we compare the northern and southern halves of our planet, we find that the temperature rise has been more steady since the 1950s in the Southern Hemisphere. The stagnant phase until the 1970s was mostly a northern phenomenon – this is consistent with the idea that it is due to aerosol cooling, as most of the smog pollution happened in the north. Overall, the Southern Hemisphere has warmed slightly less than the Northern Hemisphere – that

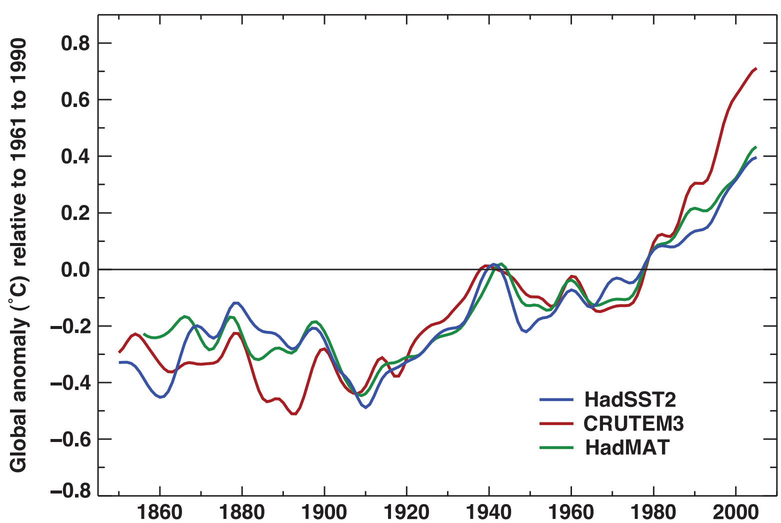


Figure 3.2 Warming over land and sea: the blue curve shows global sea surface temperatures, the green curve the air temperatures over the oceans, and the red curve the air temperatures over land.

is likely due to the fact that most of the land areas, which warm faster, are in the north, while the Southern Hemisphere is mostly ocean.

The map of warming

A map of the warming trend since 1900 is shown in Figure 3.3. We see that warming is evident almost everywhere on the planet, with the largest warming over the northern continents, where in a few places it already exceeds 2 °C. Thus, the overall warming trend is already so strong that it has overwhelmed most of the internal regional climate fluctuations, which would be equally likely to be warming or cooling during any given time period.

The most prominent patch that shows cooling is an area of the northern Atlantic south-east of Greenland – exactly the same spot where models show a minimum of warming, some even a cooling, in simulations forced by greenhouse gases (see Figure 7.1). The IPCC report does not discuss this further, but in our view the cooling in this area is likely a systematic response to greenhouse gases, rather than this being an area where natural variability has happened to cause some cooling that bucks the global warming trend. In the models, a cooling or reduced warming in this particular area is usually a response to a slowdown in the Atlantic ocean circulation. This cooling patch may thus be an indication that this circulation has slowed down during the past century – whether it has or not is an area of intense scientific debate (see Chapter 5), as conclusive data are missing and further analysis of this issue is required. The report concludes on this question that we simply don't know, as yet.

Over the past 50 years, the night-time temperatures have increased more than daytime temperatures. That is, the daily minimum has increased by 1.0 °C, the maximum only by 0.7 °C. This could be due to aerosol and cloud cover changes (smog and clouds tend to make the day cooler but the night warmer; on clear nights more heat escapes into space).

Surface, troposphere and stratosphere

We've so far talked about surface measurements taken at weather stations near the ground. But temperatures are also measured higher up in the troposphere (the lowest 10–15 km of the atmosphere), by weather balloons and satellites. For years and until quite recently, "climate skeptics" claimed on their websites that there is no global warming, as the satellites don't show any. This claim was wrong, but it was based on a real discrepancy between the surface measurements and those from satellites. Satellites cannot tell what the surface temperature is, but they measure the temperature of the bulk of the

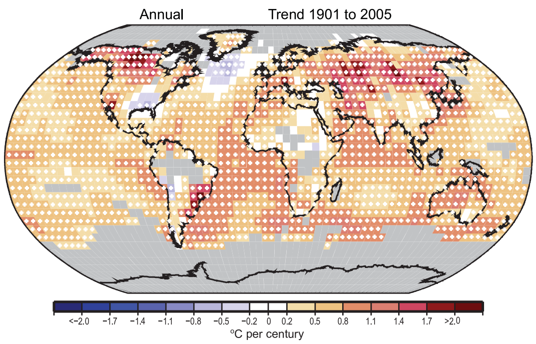


Figure 3.3 Map of the temperature change over the twentieth century. Shown is the linear trend of temperatures taken from 1902 to 2005. Gray regions lack sufficient data to determine the trend. In boxes marked by a white "+", the trend is statistically significant.

troposphere by measuring radiation from the troposphere that arrives at the satellite. This initially indicated considerably less warming than the surface records, a somewhat puzzling result. This discrepancy has now finally been resolved: it was mainly due to errors in the satellite analysis (which involves a number of complex corrections for changes in the orbit and instrument calibration issues). After several errors were discovered and fixed, surface measurements, balloons, and satellites now give a consistent picture of our warming Earth, with the troposphere warming slightly more and a lot more uniformly than the surface climate, as predicted by models (see Figure 3.4).

The stratosphere (the layer above the troposphere), on the other hand, *is* cooling. Balloon and satellite data show 1.5 °C cooling since 1950. This is expected for two reasons. The first is the increase in greenhouse gases, which traps heat in lower layers of the atmosphere, while it helps to radiate heat away from the stratosphere (this difference in the vertical is one way

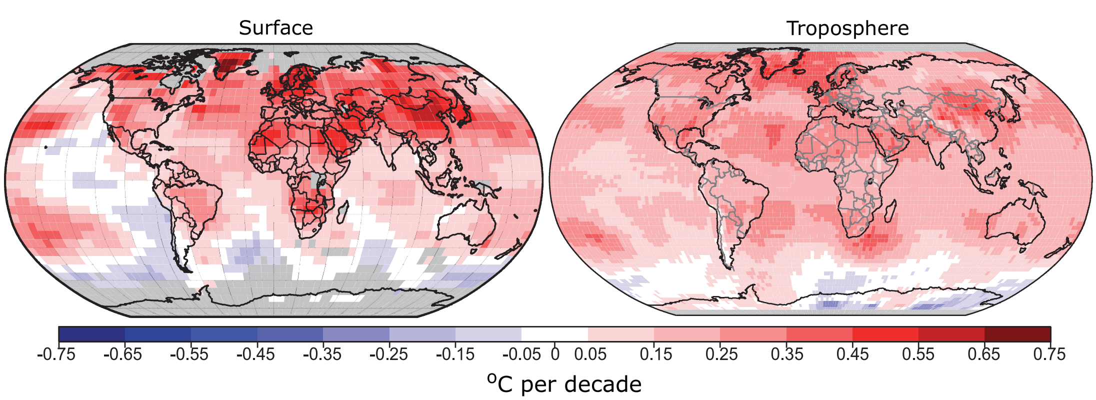


Figure 3.4 Map of temperature changes (linear trends) from 1979 to 2005. Left shows surface data, right shows data for the troposphere as measured from satellites.

to tell apart the effect of greenhouse gases and the effect of solar activity variations). The second is the ozone loss in the stratosphere. Ozone is a major absorber of solar UV radiation and therefore a major heat source in the stratosphere.

Rain and snow

Climate is not just temperature. For land ecosystems and agriculture, precipitation (rain, hail, snow) is at least as important. So how has precipitation changed? This is far more difficult to measure than temperature, not just because precipitation measurements are less precise in themselves, but also because precipitation is a lot more variable in time and space. We start with a little physics to understand some of the key features of precipitation.

A little physics

Precipitation arises when moisture condenses in the atmosphere, usually as the air rises. Air cools as it rises since the pressure drops as you go up. Since colder air can contain less water, the water falls out on the way. Air rises when it has to cross mountains, or when it slides over colder air (in a warm front), or when cold heavy air pushes underneath it (in a cold front), or when it is heated from below. The spotty nature of precipitation and the many physical processes that play a role make for complex patterns of change, quite different from those for temperature.

Nevertheless, two simple physical principles give us some guidance as to what we may expect. The first is that *evaporation increases* in a warmer climate (as long as there is water available, as is always the case over the oceans). What goes up must come down. Hence precipitation, on average, also must increase in a warmer world. Moisture on average only stays about five days in the atmosphere until it rains out again.

The second, not directly related principle is that *warmer air can contain more moisture*. An established law of nineteenth-century physics, the Clausius–Clapeyron relation, states that the amount of water vapor that fits into a given volume increases by 7% for each °C warming: that's how much water vapor you can evaporate into a parcel of air until it can take no more. This law will tend to increase extreme rainfall events, which typically arise when moisture-loaded air is forced up (say, over a mountain range) and is thereby "squeezed out like a sponge," as happened during the Elbe River flooding disaster in Europe in 2002. In a warming climate, the sponge is getting ever larger according to the Clausius–Clapeyron relation.

The "relative humidity" measure familiar to all of us simply states how close to saturation an air parcel is. A humidity of 90% means that the air contains 90% of the maximum moisture that it can hold – add 10% more and it will be saturated. The average relative humidity in the atmosphere remains almost constant during climate change. Even if evaporation increases, the extra water just rains out of the atmosphere when on average a certain percentage of the saturation level is reached, and this is what ultimately determines how much water is in the atmosphere. Because of this, as the water-holding capacity goes up, the *average* water vapor content also goes up – not just the water content of saturated air parcels discussed in the previous paragraph. The data support this; they show that, over the oceans, vapor content in the atmosphere has increased in line with the Clausius–Clapeyron relation. It is estimated that water vapor content has increased by about 5% in the atmosphere over the oceans during the past hundred years. Over land the increase is found to be a bit smaller. Again that's expected, as moisture supply is limited over land. Since water vapor is a greenhouse gas, the increase in water vapor content (caused by the warming) in turn enhances the warming. This is one of the amplifying feedbacks that make the climate system so sensitive to perturbations.

A final and very simple physical consideration: as temperatures rise, we may expect that a larger fraction of precipitation falls in the form of rain, rather than snow, which has implications for example for water storage in the snow pack and for glaciers.

Observed rainfall changes

A global map of measured precipitation changes over the past century is shown in Figure 3.5. We warned you it would be rather patchy – and it is. Unlike temperature, which has increased almost everywhere on the planet (see Figure 3.3 – "global warming" is thus an appropriate term), precipitation increases in some parts of the world and decreases in others. The gray areas (or blue over the ocean) are regions where the data coverage does not suffice to compute reliable trends, while white regions have enough data, but no trend. The remaining, colored parts of the map show that in some large regions precipitation has indeed increased, for example in the eastern parts of North and South America, in the northern parts of Europe and in central and northern Asia. In other regions, rainfall has significantly decreased: in the Mediterranean region, in the Sahel, in southern Africa and in some parts

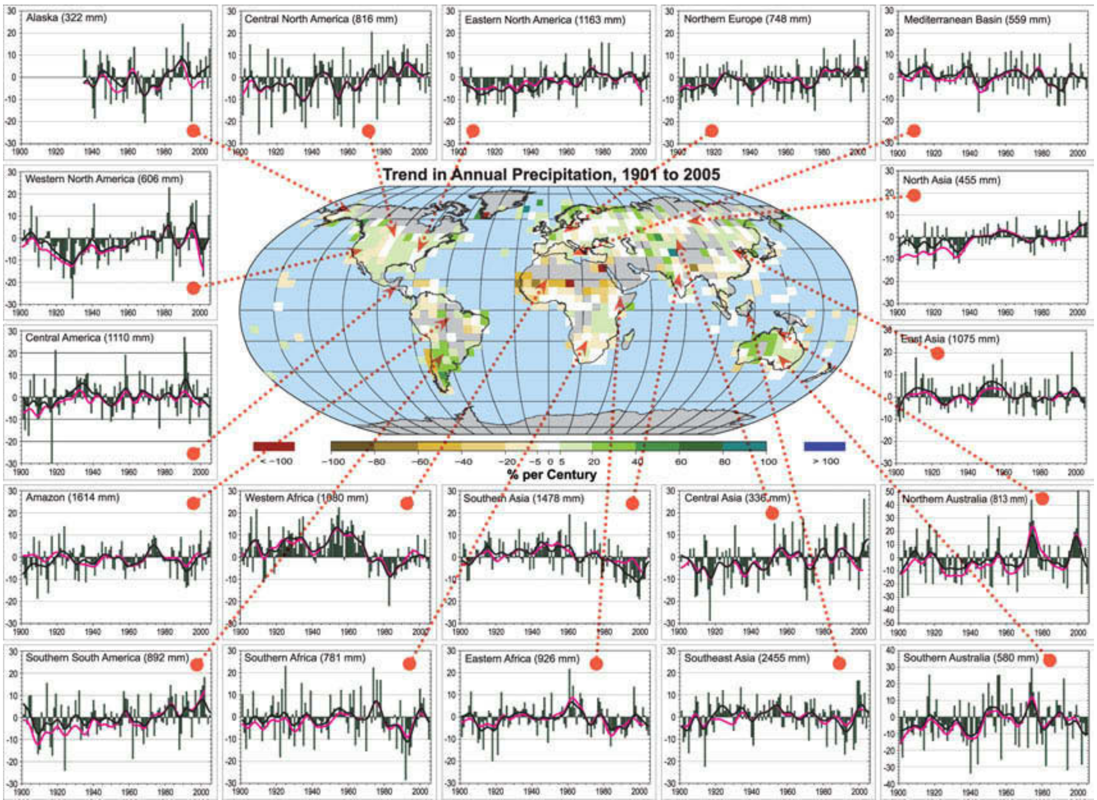


Figure 3.5 Precipitation changes around the world. The map shows the linear trends from 1900 to 2005 over land (gray areas lack sufficient data), and the time series show individual regions. Precipitation is given as a percentage of the mean, where the mean is given at the top of the panels for the period 1961–90. In contrast to temperature trends, precipitation trends are far more "patchy" and can point in either direction: up in some regions, down in others.

of southern Asia. Behind many of these 100-year trends lies a more complex time evolution with ups and downs, which are not yet fully understood.

People, and particularly farmers of course, care not only about the average amount of rain or snow that falls each year. They also care about seasonality, namely about how much rain falls in winter, summer or spring. In some parts of the world, rainfall has gone down in summer but is on the rise in winter, causing little change in the annual total – but increased flood risk in winter and drought problems in summer. In other regions, where precipitation mostly falls in winter, a larger fraction is now falling as rain. This reduces the snow pack in the mountains, which is an important source of runoff in summer when water is most needed, as well as the basis of much winter tourism.

Figure 3.6 The "flood of the century" in June 1999 of Lake Constance, central Europe's third largest lake, situated between Germany, Switzerland, and Austria.

And people care about the extremes: about the number of heavy rainfall events that cause flooding, or about long stretches without rain that can cause drought and water shortages. One important observation is that heavy rainfall events are on the rise: in many parts of the world, the fraction of the total annual rainfall that comes down on just a few very wet days has increased (Figure 3.6). A likely explanation is the physical effect mentioned above, namely that warmer air can hold more water, so more can come down during extremely wet days. This is found to be happening even in regions where the overall rainfall has not increased.

The flip side of flooding is drought. Drought can be defined in various ways, since the amount of rainfall is just one part of the issue. The amount of water that is evaporated and the amount stored in the soil are equally important. The most commonly used measure for drought is the Palmer Drought Severity Index (PDSI), which combines monthly precipitation totals and temperatures. This accounts for the fact that in warmer temperatures more rainfall is required to maintain soil moisture and healthy vegetation. The data to compute the PDSI are readily available, and a map of changes in this index is shown in Figure 3.7. These data show that drought severity has increased over the past hundred years in many parts of the world, for example in the larger Mediterranean region, the Sahel, southern Africa, the Amazon region, India and parts of China, the Caribbean and the eastern half of

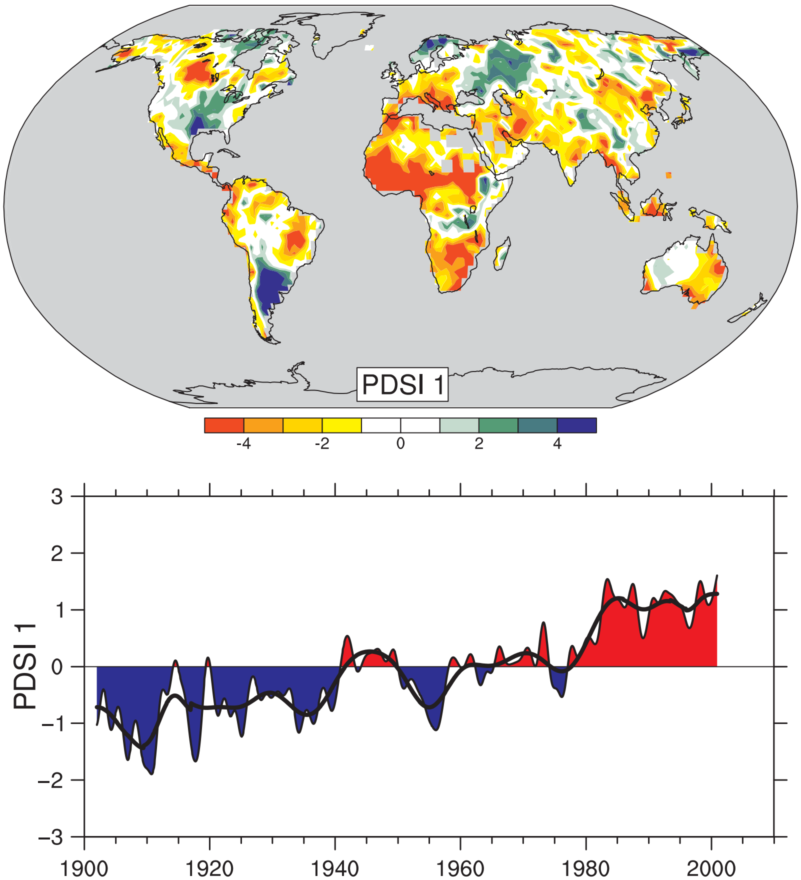


Figure 3.7 Change in drought severity as measured by the Palmer Drought Severity Index. The map shows a global map of the main pattern of change, while the lower panel shows the corresponding time evolution. Drought severity has increased in many parts of the world, including most of Africa, the Mediterranean region, Central America, and the eastern half of Australia (see also Chapter 8).

Australia. Only a smaller part of the planet has seen a reduction in the drought risk, despite the fact that global rainfall has increased. Based on this drought index, very dry areas (defined as land areas with a PDSI of less than –3.0) have more than doubled in extent since the 1970s. As we will see in Chapter 7 on future changes, the already worsening drought situation is expected to get a lot worse.

Clouds and radiation

As we saw in Chapter 2, the way humans affect the climate system is not by producing heat, but by interfering with radiation – either with the

Figure 3.8 Women busy drawing water for their animals and families at one of the few wells in Darfur in 2005. Increasing drought problems in the Sahel have contributed to the violent conflict in Darfur.

incoming solar radiation, or with the outgoing longwave radiation. Hence it is important to monitor changes in the radiation budget directly. Clouds have a big impact on both types of radiation, as everyone knows from personal experience. When clouds hide the sun during the day, it gets a lot colder, while a blanket of clouds at night keeps the longwave radiation in and makes for a mild night. This (and the fact they are difficult to model) makes cloud cover changes the prime reason for the uncertainty we still have about how sensitively the climate system will respond to human interference (see the discussion of climate sensitivity in Chapter 7).

Clouds can be monitored either from the Earth's surface or from satellite, but only with some difficulties. If there are several layers of cloud, observers at the surface tend to see only the lower, while satellites only see the upper layer. Observations from the surface go far back in time, but are available only

Figure 3.9 Image of the sky taken at the Arctic Facility for Atmospheric Remote Sensing, a permanent cloud monitoring station in Alaska.

from a limited number of stations, while satellite observations have a global coverage and frequent sampling, but they start only in the 1970s and are affected by biases that arise from the frequent changes of satellite and other problems.

Surface observations suggest that, since 1950, cloudiness has increased in many large continental regions, including the USA, the former USSR and Western Europe. This is consistent with an increase in precipitation and a decrease in the difference between day- and night-time temperatures. However, trends since the 1970s are small and less coherent, and not fully consistent between surface and satellite observations. Hence, the IPCC report comes to the scientifically rather unsatisfying conclusion: "at present there is no clear consensus on changes in total cloudiness over decadal time scales."

Radiation at the top of the atmosphere can be monitored from satellites (most notably, the Earth Radiation Budget Satellite, ERBS). This provides global cover but poor time sampling. The satellite data show some changes between the 1980s and 1990s, but measurements are not fully consistent between different systems and the time period is too short to establish meaningful trends.

In addition there is a limited number of high-quality ground-based stations, which provide excellent time coverage. The Swiss radiation monitoring network showed an increase in longwave radiation reaching the surface over the past 20 years related to an enhanced greenhouse effect, but the conclusions that can be drawn from one small region are naturally very limited since the local near-surface energy balance is complex and includes many contributing factors.

Surface measurements of radiation from land stations showed a widespread decrease of solar radiation by about 7 W/m^2 between 1970 and 1990, which has been dubbed "global dimming." This trend has turned out to be mostly in urban areas, not global, and probably caused by aerosol pollution – in other words, by smog and associated changes in cloud cover. Since then, this trend has reversed, and surface radiation has recovered by about 6 W/m^2.

Overall, the measurements of clouds and radiation from satellites still have some teething problems to sort out and need to continue for longer to provide robust trends, while ground-based observations are too localized to draw firm conclusions about global changes. At this stage, these measurements thus neither provide proof nor a reason to question the idea that the anthropogenic rise in greenhouse gases is responsible for the observed global warming.

Patterns of atmospheric circulation

Winds in the atmosphere are organized in a few distinct large-scale patterns, such as the trade winds, the "westerlies," the monsoons, and the jet streams. These are called atmospheric circulation patterns. They include large overturning cells such as the Hadley cells and Walker cells in the tropics and subtropics. In addition, there are particular patterns of circulation variability: patterns of irregular, large-scale oscillations such as the El Niño/Southern Oscillation (ENSO) phenomenon. The IPCC report finds that these circulation and variability patterns of our atmosphere are changing to some extent.

On the westerly winds that dominate the mid-latitude air flow, the report concludes that they have generally increased in both hemispheres over the past 50 years. The storm tracks – the main routes that low pressure systems follow in mid-latitudes – have moved polewards, meaning for example that in Europe, Scandinavia is now getting more westerly storms while Spain is getting

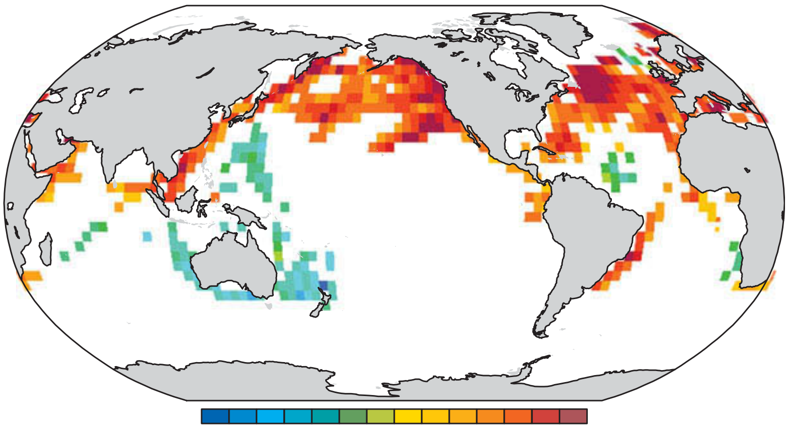


Figure 3.10 Trends in wave heights in the ocean from 1950 to 2002. White regions denote lack of data to determine trends; good data are available mainly near major shipping routes. In the northern Atlantic and Pacific, waves have become significantly higher.

fewer. The intensity of storms has increased, but the total number of storms appears to have decreased. There are, however, still significant uncertainties in these wind data, and not all studies reach consistent conclusions. The apparent increase in westerly winds is, however, supported by a trend towards increased wave heights observed in the northern Atlantic and Pacific (Figure 3.10).

On time scales of a few years, the dominant variability pattern of the atmosphere is the irregular oscillation between El Niño conditions (characterized mainly by exceptionally warm conditions in the eastern tropical Pacific) and the opposite extreme, called La Niña. This is a natural ocean–atmosphere oscillation that appears to have gone on for centuries, probably even for many millennia (with some interruptions). Although centered on the tropical Pacific, it has repercussions around the world. For example, El Niño conditions tend to cause flooding in Peru and California (Figure 3.11) but drought in Indonesia, Australia, the Amazon, and parts of Africa. There are different ways to measure the ups and downs of this oscillation. One common measure is the air pressure in Darwin (north Australia), which goes down during El Niño conditions and up during La Niña (see Figure 3.12). The record since 1865 shows that since the late 1970s, a tendency towards stronger and longer El Niño events is evident. Whether and how this is physically linked to global warming is not yet clear.

El Niño events tend to cause a warm anomaly in the global mean temperature, since a large amount of heat is released during these events

Figure 3.11 Flooded area in Lakeport, California, as a result of the 1998 El Niño event.

from the tropical Pacific Ocean into the atmosphere. The strongest El Niño event on record, in terms of the warmest sea surface temperatures reached in the eastern tropical Pacific, was that of 1997/8. This is probably the reason why 1998 was globally the warmest year on record (at least until 2005, which rivaled 1998 even without the help of an El Niño event, see Figure 3.1).

The report further discusses changes in a number of other patterns of circulation, such as the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), the Southern Annular Mode (SAM), and others. These all show interesting variations that are too complex to summarize here in a few sentences. Current research efforts are making good progress towards a better understanding of these patterns, which will in future allow us to better predict regional climate variations and their link to global changes. These efforts are spurred on by the successes in El Niño prediction, which are already saving society billions of dollars in avoided damages to agriculture.

A particularly important pattern of winds and seasonal rainfall is the monsoon, upon which the food production for a large fraction of the world's population depends, especially in southern and eastern Asia. Monsoon winds and rainfall are driven by seasonal temperature differences between land and sea: in summer the land is usually warmer than the ocean, in winter it

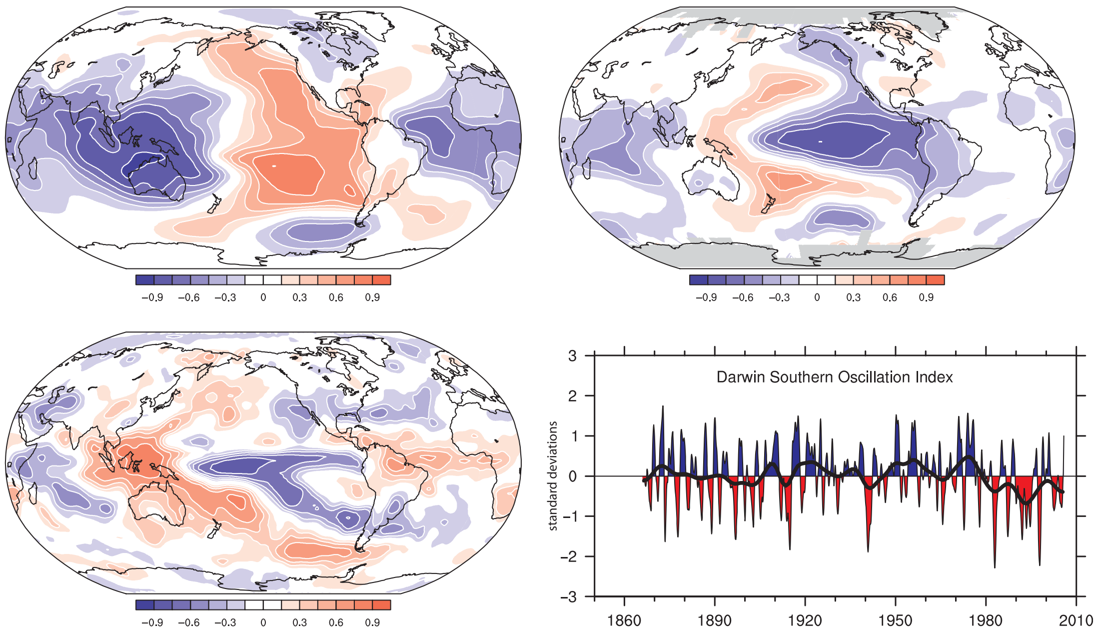


Figure 3.12 The three maps show the effects of the Southern Oscillation around the world. Top left shows the sea level pressure, top right the surface temperature and bottom left precipitation. An index of the Southern Oscillation is shown at bottom right, where the negative excursions of this index show El Niño events (e.g., in 1982/83, 1998). The maps measure the correlation with this index at each point on Earth; e.g., the map shows that a positive SOI (La Niña conditions) correlates with cold conditions in the western tropical Pacific and high rainfall over Indonesia. The reverse applies to El Niño conditions.

is the opposite. Changes in monsoon rainfall observed between two periods before and after 1975 (when a shift in atmospheric circulation was observed) are depicted in Figure 3.14. The African and south Asian monsoons have decreased, while the seasonal rainfall has increased in parts of South America and Australia. Studies show that the monsoon is influenced by a number of factors, particularly regional changes in sea surface temperatures (as occur, for example, with the El Niño phenomenon discussed above) and air pollution. This smog (e.g. the "Asian haze") shades the incoming solar radiation that drives the monsoon by heating the land masses in summer, and it has therefore been linked to monsoon weakening.

Tropical storms

Tropical cyclones are highly structured, rotating storm systems that occur in the tropical region, but not right on the equator since the influence of the

Figure 3.13 Agricultural production in Asia is strongly dependent on regular, predictable monsoon rains. The image shows children celebrating the arrival of the monsoon in a street of Chittagong, Bangladesh.

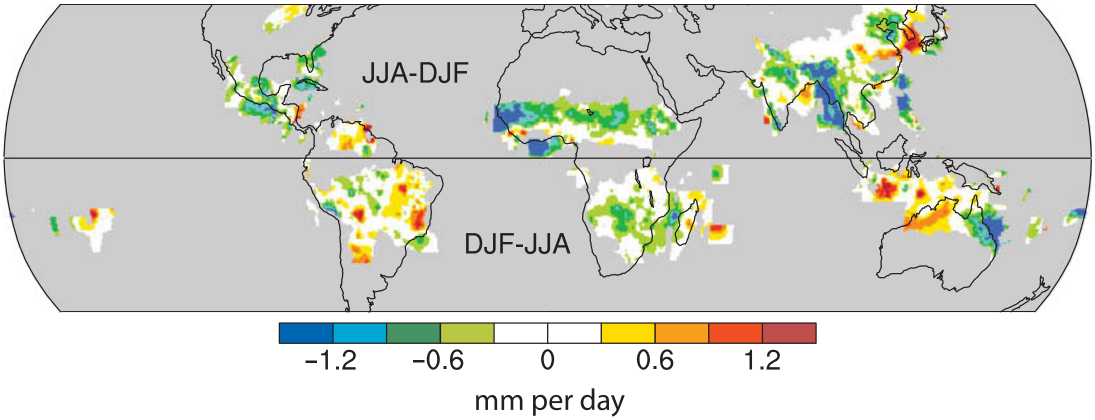


Figure 3.14 This map shows how the annual range in precipitation has changed since the middle of the twentieth century. This range is the difference between summer and winter rainfall, which in these latitudes is indicative of the monsoon. In the blue/green regions the monsoon has weakened.

Figure 3.15 Haze over mountains in Japan.

Earth's rotation on the winds vanishes there. Above a certain wind speed they have traditionally been called hurricanes in the Atlantic and eastern Pacific, and typhoons in the western Pacific. These storms are fueled by sapping energy from the warm ocean waters below – this is why they occur only in the tropics in the warm season over waters exceeding about 26 °C, and why they quickly die over land. In fact, tropical cyclones are a kind of valve through which the heat of the tropical summer sun is vented from the oceans.

Figure 3.16 People sheltering in Burma in the aftermath of typhoon Nargis, which caused over 100,000 casualties and made over one million people homeless. Nargis was a category 4 tropical cyclone. The number of strong cyclones (categories 4 and 5) has increased over the past 30 years in the Indian Ocean.

Public interest in tropical storms has increased strongly as a consequence of the extreme Atlantic season 2005 and the devastation of New Orleans by hurricane Katrina in August of that year. One or two extreme seasons of course cannot tell us much about long-term trends or about the important question of whether these trends are influenced by global warming. Neither can the fact that severe hurricanes also occurred over a century ago, before global warming. To establish whether any long-term changes in tropical storm activity are occurring, we need to analyze comprehensive data sets about these storms. This has been done in a number of studies by different research groups, which are reviewed and summarized in the IPCC report.

In short, the report finds trends since the 1970s towards more intense and longer-lasting tropical cyclones, but no trend in the total number that occur each year. It states:

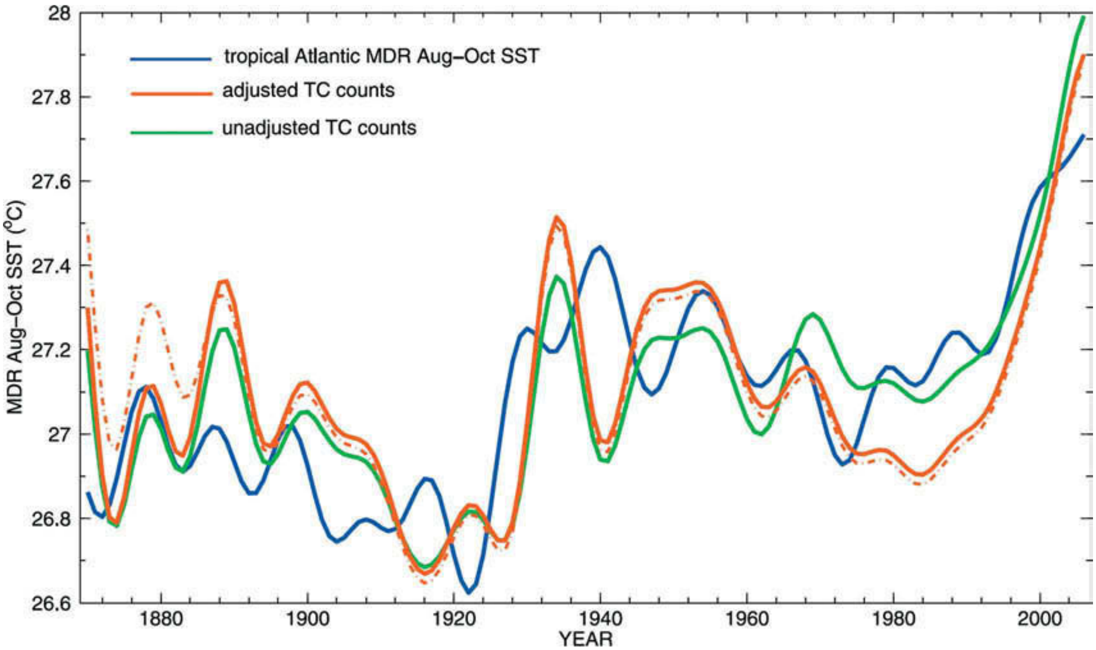


Figure 3.17 The figure shows the close link between sea surface temperatures in the main hurricane development region of the Atlantic (blue curve), and counts of North Atlantic tropical cyclones. The green curve shows the unadjusted cyclone numbers, while the orange curves show adjustments to account for possible missed cyclones in the past. All curves are smoothed over a decade.

Globally, estimates of the potential destructiveness of hurricanes show a substantial upward trend since the mid-1970s, with a trend towards longer storm duration and greater storm intensity, and the activity is strongly correlated with tropical sea surface temperature. These relationships have been reinforced by findings of a large increase in numbers and proportion of strong hurricanes globally since 1970 even as total numbers of cyclones and cyclone days decreased slightly in most basins. Specifically, the number of category 4 and 5 hurricanes increased by about 75% since 1970. The largest increases were in the North Pacific, Indian and Southwest Pacific Oceans. However, numbers of hurricanes in the North Atlantic have also been above normal in 9 of the last 11 years, culminating in the record-breaking 2005 season.

Given that warm ocean water is their energy source, it is physically plausible that a strong link between hurricane intensity and tropical sea surface temperatures (Figure 3.17) is observed, especially in the longer term. The rise in North Atlantic hurricane activity over the past 25 years occurred while tropical sea surface temperatures there rose to a record high – to a large part associated with global warming. This is why many hurricane experts are concerned about stronger hurricanes in the future, when sea surface temperatures will get even warmer.

Short-term variations in hurricane activity from year to year are large and depend strongly on a number of other factors, like the wind shear and the vertical stability of the atmosphere. For example, hurricane activity tends to be weaker in the Atlantic but stronger in the western North Pacific during El Niño events. Centers of greatest activity are shifting around, and a particularly active season in one area is often associated with a below-average season elsewhere, so that trends apparent in individual ocean basins partly cancel out in the global average. Large decadal variations and data problems in the pre-satellite era (before the 1970s) make long-term trends harder to detect.

Several studies since the IPCC report have found more evidence for an increase in hurricane activity over the past decades. A study by Carlos Hoyos and colleagues from the Georgia Institute of Technology in Atlanta found a strong global increase in the number of hurricanes of the strongest categories 4 and 5, and they identified rising sea surface temperatures as the leading cause (Hoyos *et al.* 2006). Meanwhile, scientific debate about data quality has continued, especially on the question of how many tropical cyclones may have gone undetected before satellites provided a global coverage of observations. Michael Mann and several colleagues concluded that such an undercount bias would not be large enough to question the recent rise in hurricane activity and its close connection to sea surface warming (Figure 3.17).

Causes of the observed climate changes

How can we establish the causes for these observed climate changes? This is known as the “attribution problem” in the jargon of climate science, and a great deal of effort has gone into studying this issue over the years. The IPCC *First Assessment Report* (FAR) contained little observational evidence of a detectable human influence on climate. Six years later, the IPCC *Second Assessment Report* (SAR) concluded that the balance of evidence suggested a discernible human influence on the climate of the twentith century. The *Third Report* concluded: “most of the observed warming over the last 50 years is *likely* to have been due to the increase in greenhouse gas concentrations.” Now, the *Fourth Report* says that the latter is *very likely.*

What are these conclusions based on? We need to distinguish two different kinds of reasoning here. First, there are so-called “detection and attribution” studies. This refers to a specific set of statistical techniques which allow us to “detect” climate changes in an observational data set (that means, to distinguish a real change from mere random fluctuations) and to “attribute” these changes to a set of causes. We will discuss this type of studies further below.

Second, there is the overall “balance of evidence.” That simply includes everything we know about the climate system: our understanding of the physics (e.g. of the global energy balance that rules the changes in global mean temperature), all the information about past climate variations in Earth’s history, all the data sets of recent weather and climate, and so on. Ultimately, it is of course this “balance of evidence” that determines the confidence we have in our understanding of the causes of climate change. This balance of evidence includes the results of the formal “detection and attribution” studies; they are one important piece of the puzzle but not the only one.

We can thus usually be more confident about the causes of certain climate changes than the results of “attribution” studies alone suggest. This important distinction is sometimes forgotten, even in discussions amongst climatologists. For example, scientists may find it very likely that the increase in extreme precipitation events (see above) is due to human activities, since we know that global warming is mostly due to human activities and there is a robust physical reason why a warmer climate would cause more extreme precipitation (the Clausius–Clapeyron relation mentioned earlier). Nevertheless, a formal “attribution” study may *not* find that extreme precipitation can be attributed to human effects in a statistical sense, simply because observational data are too patchy to prove a statistically significant link.

A simple analogue would be a kettle of water on a gas stove. If we light the gas and the water gets hotter, how do we know this is due to the gas flame? A formal “detection and attribution” study would require detailed temperature measurements to prove that the warming is not within the range of natural variations that could occur even without the gas flame, and that the heat spreads from below and not from above (where the sun shines through the window onto our kettle). Even in the absence of such measurements, we obviously would be quite sure that the warming is due to the gas flame, based on past experience and on understanding of the physics. We know from the past that the sun is too weak to heat the kettle so much, that the gas flame does this every time, and a physicist could easily calculate how fast the water should heat up given the amount of gas that is burned. Back to the climate system, “past experience” is the information from paleoclimate, the physics of the greenhouse effect has been well understood since the nineteenth century, and the observed rate of warming fits what is expected from a simple energy balance calculation.

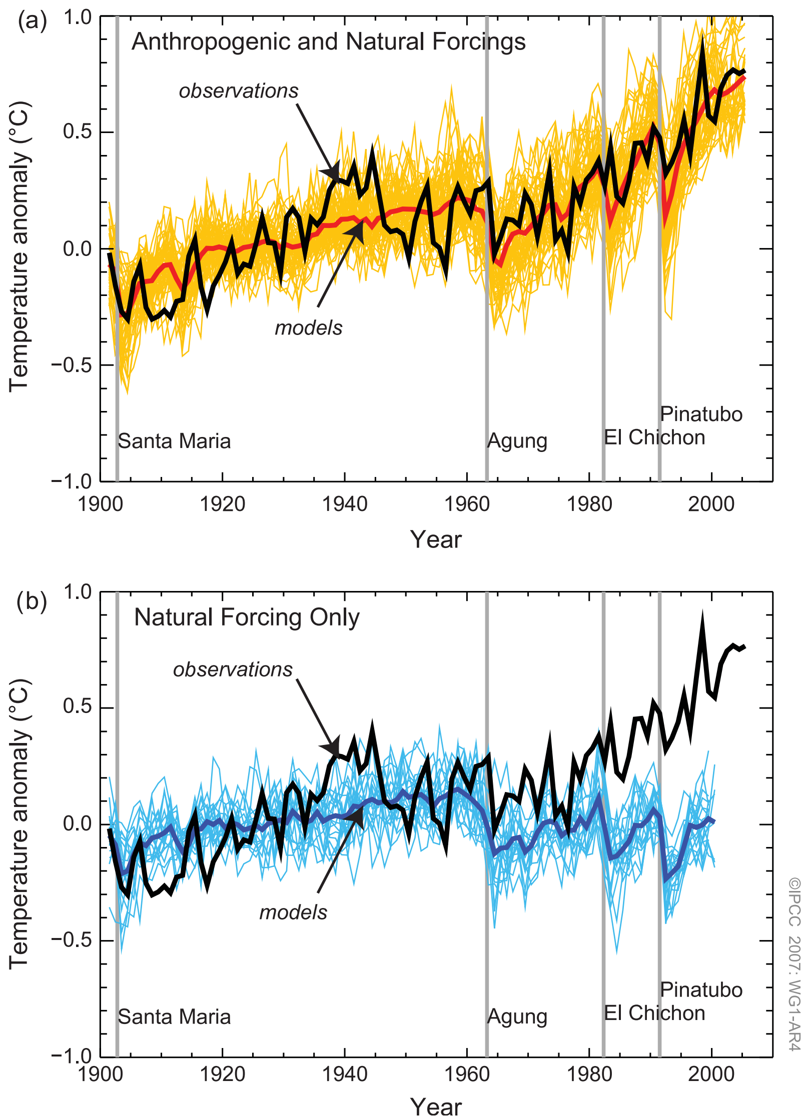


Figure 3.18 Temperature evolution since the year 1900. The black curve in both panels shows the observations, as shown earlier in Figure 3.1. The upper panel shows model simulations with natural and anthropogenic drivers of climate change, where the red curve shows the average across all models and the thin orange lines the individual model simulations. Note that the individual model runs show a random year-to-year variability in global temperature, just like the data. In the model average this is averaged out to a large extent because of its random nature. The lower panel shows model simulations driven only by natural factors, indicating that these cannot explain any warming over the past 50 years or so.

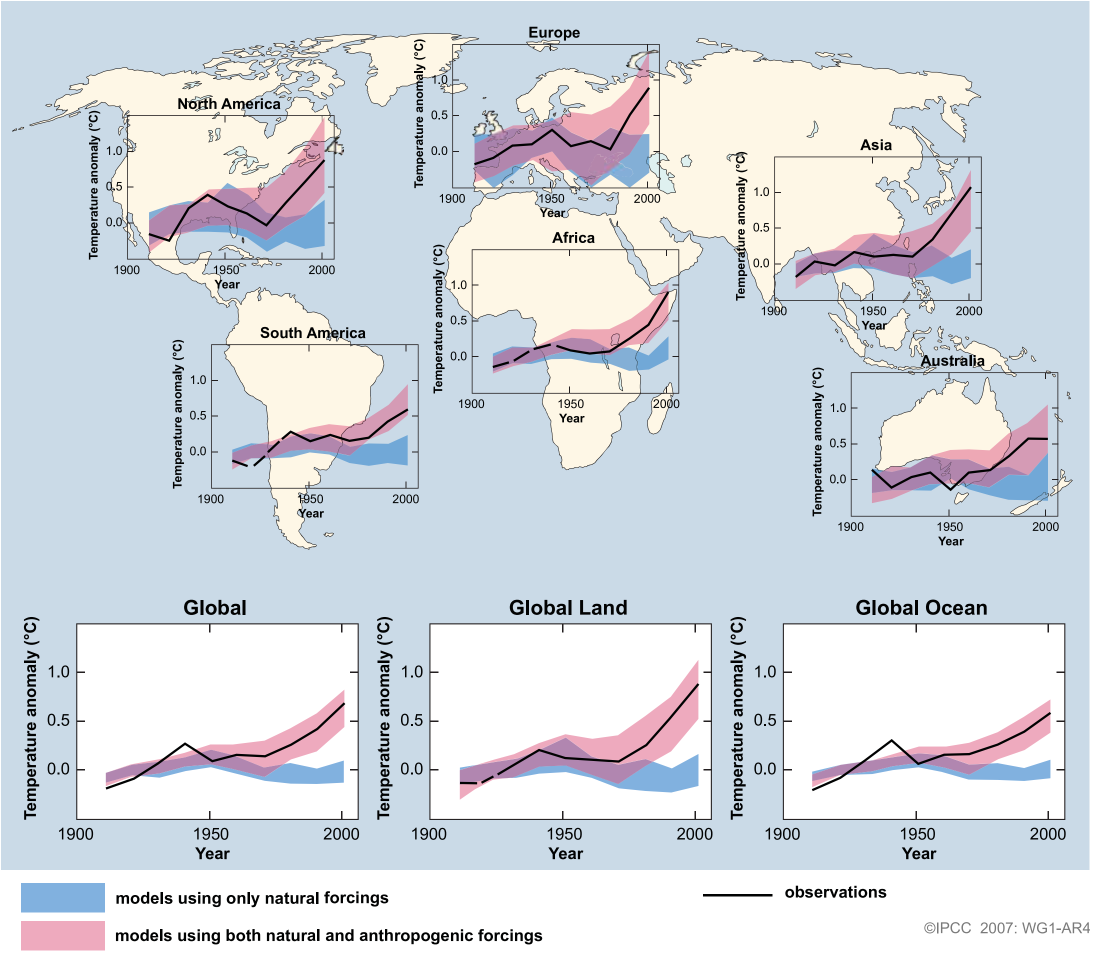


Figure 3.19 Comparison of observed and modeled surface temperature changes for different continents and the world. Black lines show observed data. The blue bands show results of a range of climate models using only natural climate forcings such as solar variability and volcanic eruptions. The pink bands show results of a range of climate models if anthropogenic forcings are used together with the natural forcings. Only in the latter case do the models agree with the data, indicating that the observed temperature changes since about the 1970s can only be explained with anthropogenic forcing.

Having said that, how are these formal "attribution" studies performed? To put it simply, observed data from the climate system are compared to what we would expect from natural internal variability (such as random weather fluctuations), from changes in solar activity, from greenhouse gases, or from possible other drivers of climate change. Different drivers of climate change cause different tell-tale patterns of change, so called "fingerprints." Hence, these studies are also known as "fingerprint studies." For example, greenhouse gases tend to trap more heat in the lower parts of the atmosphere, in contrast to a change in solar activity. The effect of greenhouse gases also equally works at night or in winter, while a change in solar activity is obviously more pronounced when the sun actually shines, namely during daytime and summer. Many of these "fingerprint studies" have been performed over the past years by different groups of researchers, using a number of different data sets and statistical approaches.

So what are the results? Those studies analysing global temperature changes have unequivocally come to the conclusion that global warming is indeed to a large part caused by human activities. Global temperatures have already risen beyond their natural range of internal variations, and the observed pattern of changes can only be explained when the effect of rising greenhouse gases is included. That is, the observed patterns are inconsistent with changes in solar activity or any other natural driver of climate change. In fact, natural factors over the past 50 years would have caused a slight cooling of climate, not a warming, due to the observed decline in solar activity (Figure 3.18). Specifically, the report concludes: "It is *very likely* that anthropogenic greenhouse gas increases caused most of the observed increase in global average temperatures since the mid-20th century." (Very likely meaning at least 90% certain.)

Beyond this basic conclusion, attribution studies have come up with a number of other important findings. Not only the surface warming, but also the warming in the free atmosphere above and in the ocean can be attributed to human activities. And not only the global changes, but even the warming in each of the individual continents (except Antarctica) can be attributed to human activities (see Figure 3.19). This is much harder, because natural regional climate variations are much larger than global ones, making it more difficult to prove human-caused changes. A statistically significant human effect has also been found in data other than average temperatures, namely in the decline in sea ice cover in the Arctic, in the rise in sea level, in extreme temperatures, in changing rainfall patterns and in some changes in atmospheric circulation. Taken together, these studies provide a strong confirmation that humans are indeed altering climate in a profound way.

Summary

Measurements unequivocally show that we are in the midst of an accelerating global warming: temperatures have increased on global average by 0.8 °C since the late nineteenth century, and by 0.6 °C since the 1970s. Almost all regions of the planet have warmed over the past century. Both ocean and land areas have warmed, although since the 1970s the land areas have been warming faster. The incidence of extremely hot days is rising, while the number of extremely cold days is declining.

Significant changes in rainfall are also observed. They show a more complex pattern, with some regions showing an increase and some a decrease. Many regions show an increase in the number of days with extreme rainfall amounts, raising the risk of flooding. On the other hand, drought problems are increasing in many parts of the world. The area suffering from drought, according to the widely used Palmer Drought Severity Index, has more than doubled since the 1970s.

In addition, some changes in atmospheric circulation patterns are starting to become apparent. Mid-latitude westerly winds appear to have increased, with storm tracks shifting somewhat towards the poles. The incidence of El Niño events has increased since the 1970s. Finally, tropical storms have shown an increase in intensity and duration since the 1970s.

Many of these observed changes have been shown to be due to human activities by using “fingerprint” analysis.

4 Snow and ice

Some of the most startling news since the 2001 TAR can be found in Chapter 4 of the IPCC *Fourth Assessment Report*: Changes in Snow, Ice, and Frozen Ground. In particular, there is a section, toward the second half of the chapter, on recent observations of the response of great ice sheets in Greenland and Antarctica to our warming climate. There you will read about all sorts of new melting tricks that ice sheets are showing us. Seismometers on the ice record more icequakes than there used to be, and more in summers than winters. Floating ice shelves are breaking up catastrophically, allowing the ice flow from the land to the sea to accelerate. The ice sheets are melting faster than the *Third Assessment Report* assumed we would see until the year 2100, and the melting appears to be accelerating.

We are concerned about the fate of the great ice sheets for the reason of sea level rise. The ice sheets have the potential to raise sea level by about 70 meters, enough to completely and catastrophically change the map of the Earth. The ice sheets are not melting too much today, but the question is how quickly and strongly they will respond to warming in the future.

Forecasts such as for ice sheet melting are based on computer models, which try to simulate the underlying mechanisms controlling what they are trying to simulate. So far, however, the models that have been developed to simulate the ways that ice sheets flow and melt are not really complete in their treatment of the underlying mechanisms. Glaciologists do not yet understand the meltdown of an ice sheet well enough to put it into a model. Ice sheet models do exist, but they do not predict the observed strong responses of ice sheets, in particular the Greenland ice sheet, to changes in climate. There are also melting events in the prehistoric past, such as the Heinrich events (Chapter 6), which are not sufficiently understood to be able to forecast them in advance.

Because of the inadequacy of current ice sheet models, the IPCC *Fourth Assessment Report* excludes changes in ice sheet flow, which they refer to as "dynamical changes" in the ice sheet, from the forecast for sea level rise. The sea level rise forecast has an asterisk. We do not feel that IPCC made a wrong call on this. But we note that a "dynamical change" in ice sheet flow has the potential to be a very large asterisk. Sea level changes associated with prehistoric climate events, such as the last deglaciation or Heinrich events, were 10–100 times faster than the forecast for the coming century.

Other topics covered in Chapter 4 include sea ice, snow cover, and permafrost soils. These may affect climate by changing the amount of sunlight reflected back to space rather than being absorbed and converted to heat by the ground. A little warming melts the ice, the ground absorbs light energy rather than reflecting it, and the Earth warms further: the ice albedo feedback. Melting sea ice is a particularly strong climate feedback, because sea ice is one of the most reflecting surfaces on the Earth, while the ocean is one of the most absorbing surfaces.

Ice sheets

Some aspects of the physics of large ice sheets (i.e. Greenland (Figure 4.1) and Antarctica) are understood quite well. The interiors of the ice sheets derive from snowfall at the surface, which can be modeled using atmospheric circulation models. The flow in the interior of the ice sheet is driven by the

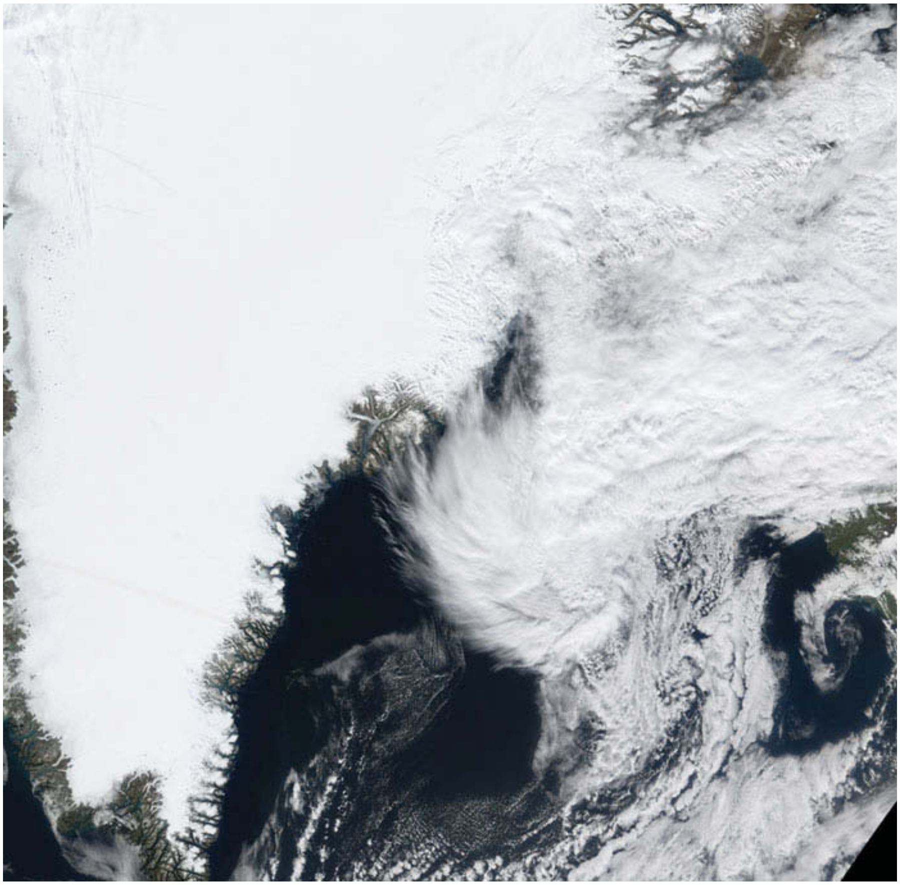


Figure 4.1 Greenland from space.

sloping surface of the ice, which generates a pressure gradient down the slope. The base of the ice is typically frozen and stuck to the bedrock in the interiors of most ice sheets, so that the flow rate decreases close to the bed.

When an ice sheet flows horizontally, it gets thinner in the vertical. In an ice core drilled through the ice sheet, the age layers toward the bottom of the ice sheet have been squeezed together as the ice is lost laterally. The relationship between depth and age in the ice cores provides a means of checking the models of ice sheet flow, by comparing their independent prediction of the amount of layer squeezing. In general the flow models work very well in the interiors of ice sheets, but the surprise since the *Third Assessment Report* in 2001 is that processes at the edges of ice sheets are not at all well simulated by the models.

When the base of an ice sheet is warm enough to sustain liquid water, or a slurry of water and deformable sand or rocks, it acts as a lubricant for the ice overhead to flow. Ice can flow like crazy in narrow rivers called ice streams, narrow rivers bounded by slow-flowing ice on both sides. In a qualitative way, the fast velocities can be understood as a result of friction from the flow melting ice, lubricating the bed, and facilitating the fast flow. But models do a poor job of reproducing the flow rates and locations of ice streams today, and are clearly inadequate for predicting their future behavior.

Ice sheet models, such as those used to forecast the ice sheet response to global warming, tend to respond very slowly to changes in the climate at the ice surface. Warming at the surface is communicated to the bed by conduction, a process which takes centuries or millennia. This sleepy picture of heat flow in the ice was shattered by a paper published by Jay Zwally in 2002, where he found that the flow rate of the Greenland ice sheet, 50 km from the edge, responds to the seasonal cycle at the surface, that is, on a time scale of months rather than a time scale of centuries. The ice flows more quickly in warm summers than cool summers.

The heat-carrying culprit is apparently meltwater, produced at the surface during warm summers. Meltwater is apparently able to flow through the ice all the way to the bed (Figure 4.2). The details of how it manages to do this without freezing are not well enough understood to include this process in ice sheet models. But glaciologists can see it going in, and see it coming out, and see the flow rate of the ice responding to the changes in water flow.

Another surprise, since the *Third Assessment Report*, has been the catastrophic breakup of several of the floating ice shelves protruding from the Antarctic Peninsula. An ice shelf is essentially the floating extension of an ice sheet that has flowed onto the ocean. An ice shelf can be hundreds of meters thick, much thicker than sea ice which is typically only a few meters thick. The Larsen B ice shelf shattered into a thick swarm of small icebergs in just a few days in March, 2002 (Figure 4.3). In March of 2008 the Wilkins ice shelf disintegrated in a similar way. Once the ice detaches from the shelf into icebergs, its days are numbered, because icebergs can flow equatorward much faster than heat can travel poleward to melt them in place. An ice shelf per se does not affect sea level when it explodes into bergs, or when the bergs are carried into warm water to melt. The impact of an ice shelf breakup on sea level is that it tends to hem in the ice streams that feed it. An ice shelf really puts on the brakes if it is attached at one side, or if it runs into some shallow rock outcrop. Ice streams feeding the former Larsen B ice shelf have accelerated by a factor of eight since the destruction of the ice shelf.

Figure 4.2 Meltwater lake and streams on the Greenland ice sheet near 68° North at 1,000 meters altitude. Such lakes form in summer and can be kilometers across.

The Jakobshavn glacier in Greenland has been shrinking, and the ice streams there have doubled their flow rate to the sea.

These observations were a surprise. Even now, in hindsight, the physics responsible for these phenomena cannot be incorporated into models of the entire ice sheets, to forecast the future response to global warming. Flow in ice streams depends on the details of the material at the bed, which can be tuned to generate an ice stream in a detailed, small-scale model, but isn't generally known over the larger scale of an entire ice sheet. The current ice sheet models also neglect lateral stresses, which allow the entire flow structure to respond to a pinned ice shelf, for example. There is an intense effort among scientists and funding agencies to improve our understanding of the behavior of melting ice, and we predict that the next IPCC report, a few years from now, will have a more concrete forecast for the future of the ice sheets.

In the meantime, it is not so easy to measure how fast a major ice sheet is growing or melting even today. The total mass of ice in the high-latitude ice sheets can be estimated from gravity measurements from the GRACE satellite

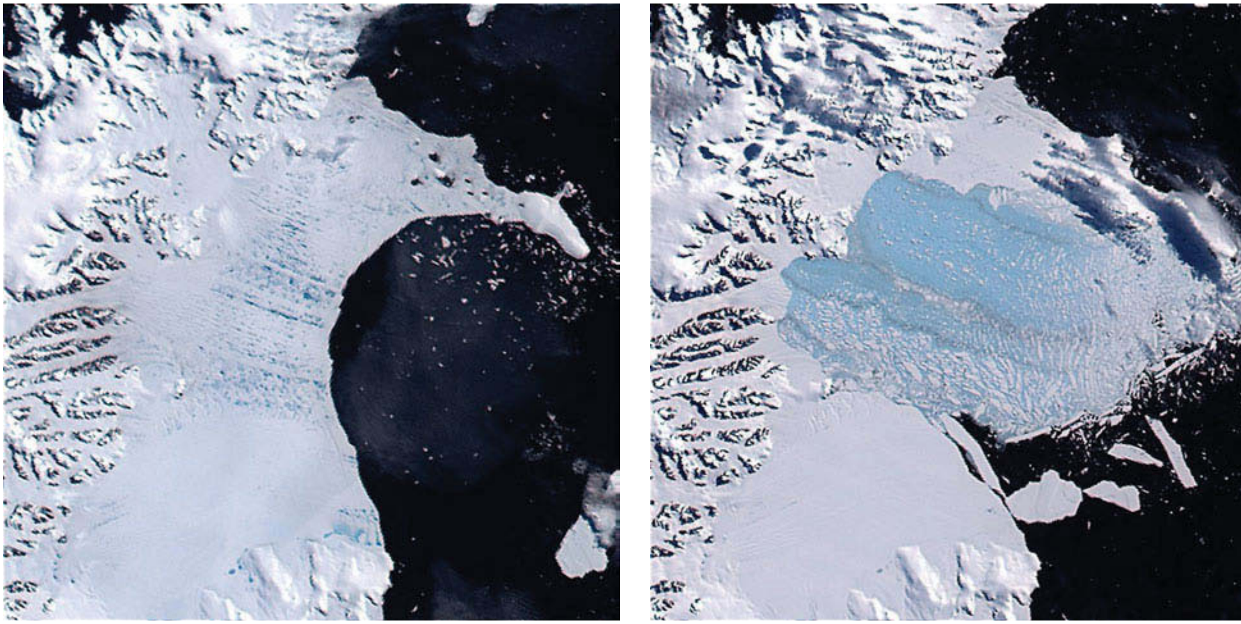


Figure 4.3 The Larsen B ice shelf viewed from space before and after its breakup in early 2002.

mission. The long-term rate of snowfall to the ice sheet can be determined from ice cores, and extrapolated to larger areas using changes in elevation from aircraft or satellite laser altimetry. Snow accumulation can also be estimated from climate models. The flow of ice to the sea can be measured by radar altimetry, an advance since the *Third Assessment Report*. One uncertainty in the altimetry measurements is the effect of the density of the ice, how much air there is in between the ice grains.

Greenland

The Greenland ice sheet contains enough water to raise sea level by about 7 meters if it were to melt entirely. The ice mass on Greenland is close to the melting point at low elevation, and meltwater ponds and streams are seen at the surface of the ice sheet, and flowing into channels in the interior of the ice, called moulins. The ice flows to the sea in rock-walled glaciers mostly (Figure 4.4), but the coast of Greenland lacks the large ice shelves of the Antarctic ice sheet. Numerous studies document accelerated flow in ice streams south of about 70 °N in Greenland. Breakup of the small ice tongue terminating the Jakobshavn glacier caused a doubling of the flow velocity of this glacier.

Figure 4.4 The Greenland ice sheet is drained by outlet glaciers like the Eqalorutsit Kitdlît Sermiat glacier shown here, flowing south into the Nordre Sermilik fjord. Many outlet glaciers have increased their flow speed over the past decades.

Greenland is located near the site of convection and overturning circulation in the North Atlantic Ocean. An influx of fresh water to the North Atlantic, such as would be generated by melting of the Greenland ice sheet in a few centuries, could serve as a stick in the spokes of the meridional overturning circulation in the North Atlantic, which carries heat into the northern high latitudes. The climate impact of stopping this "Nordic heat pump" in models is generally small, a regional cooling that is more than offset in global warming forecasts by the direct warming. However, there have been very large climate changes in the past, such as the Younger Dryas cold interval and the 8.2 k climate event that were apparently driven by fresh water influx to this particular region. According to climate models, if the Greenland ice sheet were to melt in a century or so, it would generate sufficient runoff to significantly slow the overturning circulation.

Radar measurements of the altitude of the ice sheet surface show increased accumulation of snowfall in the interior, especially in the southern interior of the ice sheet, and thinning near the sides (Figure 4.5). Budget calculations, net melting or freezing, show what appears to be a real increase in the rate of melting just in the past few years (Figure 4.6). The different estimates are

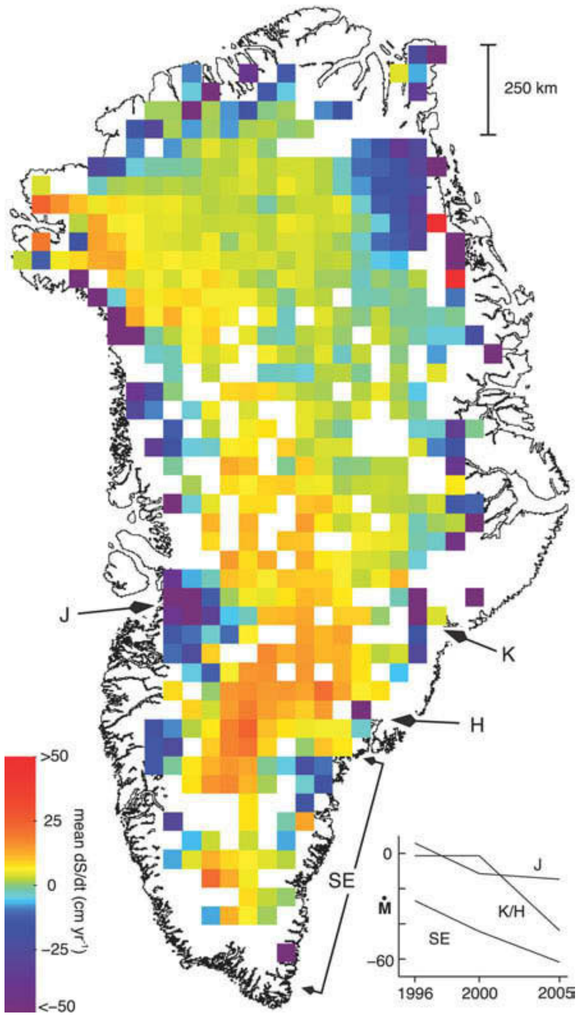


Figure 4.5 Rate of change of the elevation of the Greenland ice sheet, from laser altimetry measurements.

not in complete concordance, in that they differ by more than the stated uncertainties of the results, indicating some sources of systematic errors that have yet to be identified. However, all of the techniques that have been applied at multiple times over the past decade show an acceleration of mass loss due to increased flow and melting.

Antarctica

The Antarctic ice sheet differs from Greenland in that it is cold enough to prevent surface melting all the way to sea level. Ice loss is therefore entirely by

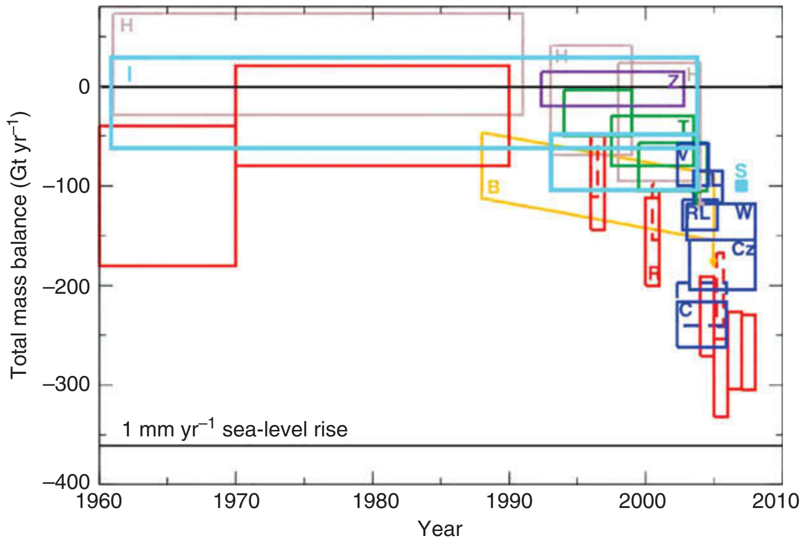


Figure 4.6 Estimates of how fast the Greenland ice sheet is losing water into the oceans, plotted as a function of the time span for which the estimates apply. (For the original citations, see the caption to Figure 4.18 in the IPCC (2007) *The Physical Science Basis*).

flow to the sea. Nearly all ice streams terminate in ice shelves, which comprise 11% of the area of the Antarctic ice sheet. The Antarctic ice sheet can be divided into three pieces. The east Antarctic ice sheet is the largest and is considered to be the most stable. Most estimates find a net increase in the mass of this ice sheet (Figure 4.7).

The west Antarctic ice sheet has the distinction of being attached to bedrock below sea level. It originally formed on the exposed west Antarctic continent, but the mass of the ice eventually submerged the bedrock surface below sea level. As a result of this history, the deepest depression of the land surface lies in the center of the ice sheet, leading to the fear of a runaway melting. The ice flow to the sea accelerates near the boundary between ice attached to bedrock and floating ice (the grounding line). As the ice is lost at the edges, the grounding line retreats deeper into the hole under the center of the ice sheet. A deeper grounding line leaves room for a taller floating column ice, thereby accelerating the volume of ice flow out to the ocean. The west Antarctic ice sheet drains to the sea in ice streams flowing into the Ross Sea, Pine Island Bay, and the Amundsen Sea. Numerous studies have documented acceleration in the ice streams draining the west Antarctic ice sheet. Thinning of the ice shelf in the Amundsen Sea allowed the ice flowing into this sea to accelerate.

Third, and smallest, is the ice on the Antarctic Peninsula. This differs from the rest in that the Antarctic Peninsula has been subjected to some of the most

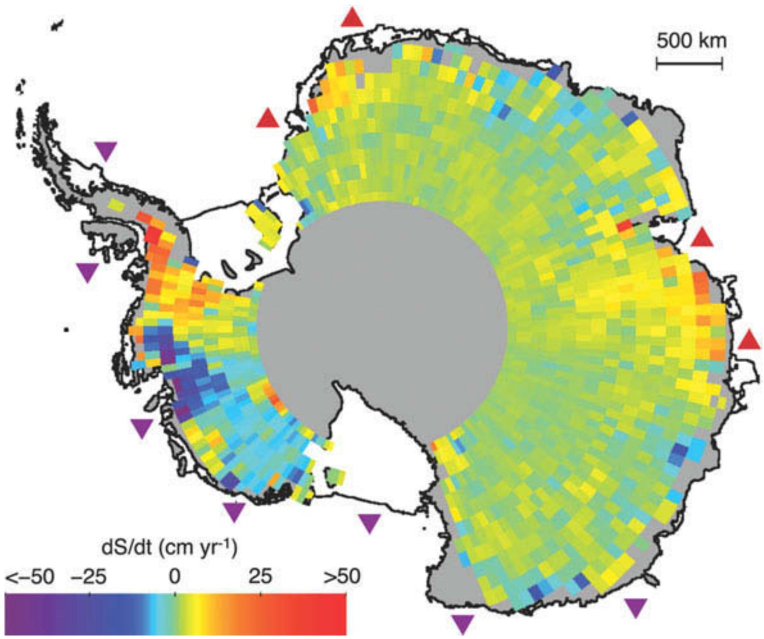


Figure 4.7 Rate of change of the elevation of the Antarctic ice sheet, from laser altimetry measurements.

intense warming trends on Earth, as opposed to the interior of Antarctica, which has generally cooled over the past decades. Ice streams and glaciers on the Antarctic Peninsula have also accelerated in the past few years. Ice shelves have broken up on the peninsula in a north-to-south progression, consistent with warming as a dominant driver for the ice shelf loss. The existence of ice shelves on the peninsula correlates with temperature; warmer than a mean annual temperature of –5 °C, ice shelves are not found, whereas colder than about –9 °C, the ice shelves have not broken up. Ice flow behind the former Larsen B ice shelf accelerated markedly after the loss of the ice shelf, while ice to either side, still buttressed by intact shelves, continues to flow as before.

Glaciers and ice caps

Mountain glaciers and ice caps (Figure 4.8) contain less water than is found in the great ice sheets, but this water has the potential to melt more quickly in response to warming. The combined volume of all of the non-ice sheet ice is thought to be a bit less than a meter of sea level equivalent, but this is known only to within a factor of two or so. Mountain glaciers have been retreating

Figure 4.8 The Mueller glacier (foreground, covered in rubble) in New Zealand is shrinking, like most mountain glaciers around the world. Clearly visible is the terminal moraine: until a century ago the glacier stood up to its upper edge. Behind the moraine, a meltwater lake has since formed.

around the world (Figure 4.9), a dramatic illustration of the effects of climate change. Mountain glaciers have a response time ranging from a few years for the smallest, to several centuries for the largest. Glaciers have been in general retreat since the end of the Little Ice Age in the eighteenth century, but there has been an acceleration in meltback since about 1970 (Figure 4.10). Small glaciers have melted relatively the most extensively, affecting places like Mt. Kilimanjaro (Figure 4.11) in Kenya and Glacier National Park in the USA.

Mountain glaciers and snow pack serve to hold winter precipitation, releasing it slowly over the summer, providing a fresh water source just when it is needed for agricultural irrigation. Melting ice today also provides a temporary stream of fresh water, until the glacier is gone (Figure 4.12).

Sea ice

Sea ice is a climate indicator that can be monitored from space. Sea ice also reflects sunlight back to space, cooling its local climate and stabilizing its

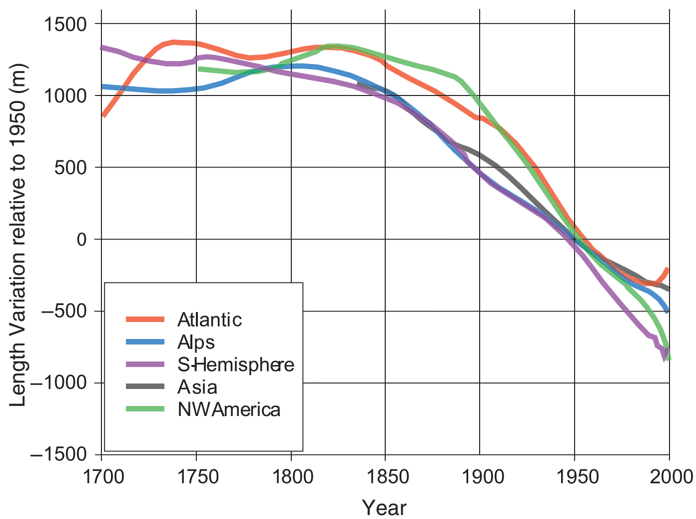


Figure 4.9 Changes in the lengths of mountain glaciers.

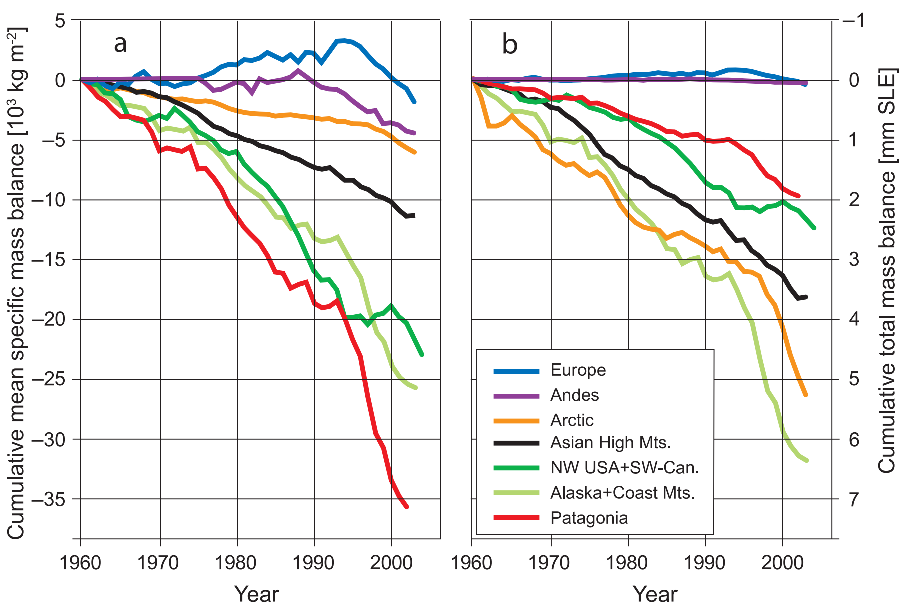


Figure 4.10 The rate of change of the amount of ice in the mountain glaciers through time.

existence. When it does melt, there is a strong warming feedback as the previously reflected light is instead absorbed in the water column of the ocean. Sea ice is one of the most reflective surfaces of the Earth, while open ocean is one of the most efficient surfaces at absorbing light. The ice albedo feedback

Figure 4.11 Mount Kilimanjaro, in 1993 and 2000.

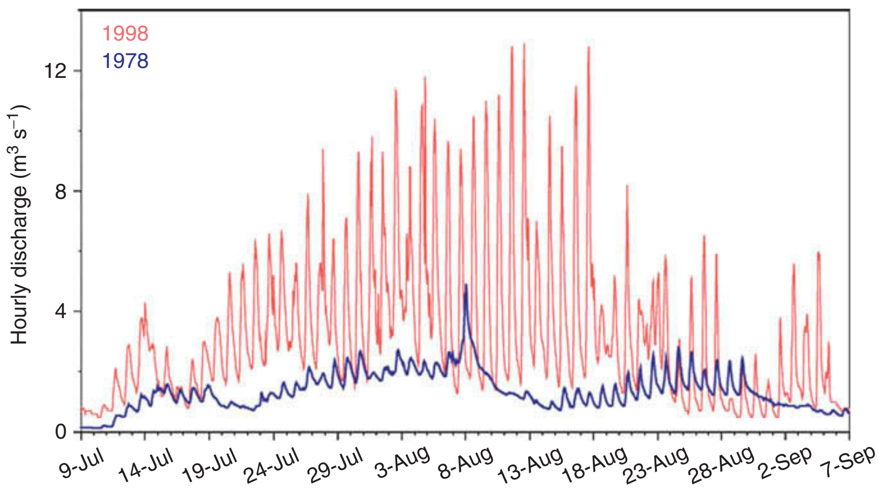


Figure 4.12 A comparison of the rates of water flow in the Vernagtferner River in Austria. The melting glacier is supplying most of the water in the warm parts of the day.

is the primary reason why climate change tends to be more intense in high latitudes. The Arctic is projected to be ice-free in the summertime by mid century. This is probably the clearest example of a "tipping point" in present-day climate change.

Trends in sea ice are shown in Figure 4.13. There has been a substantial decrease in sea ice in the Northern Hemisphere, but not around Antarctica, an observation that is not explained in the *Fourth Assessment Report*. The most dramatic change has been the decline in the summertime ice extent in the

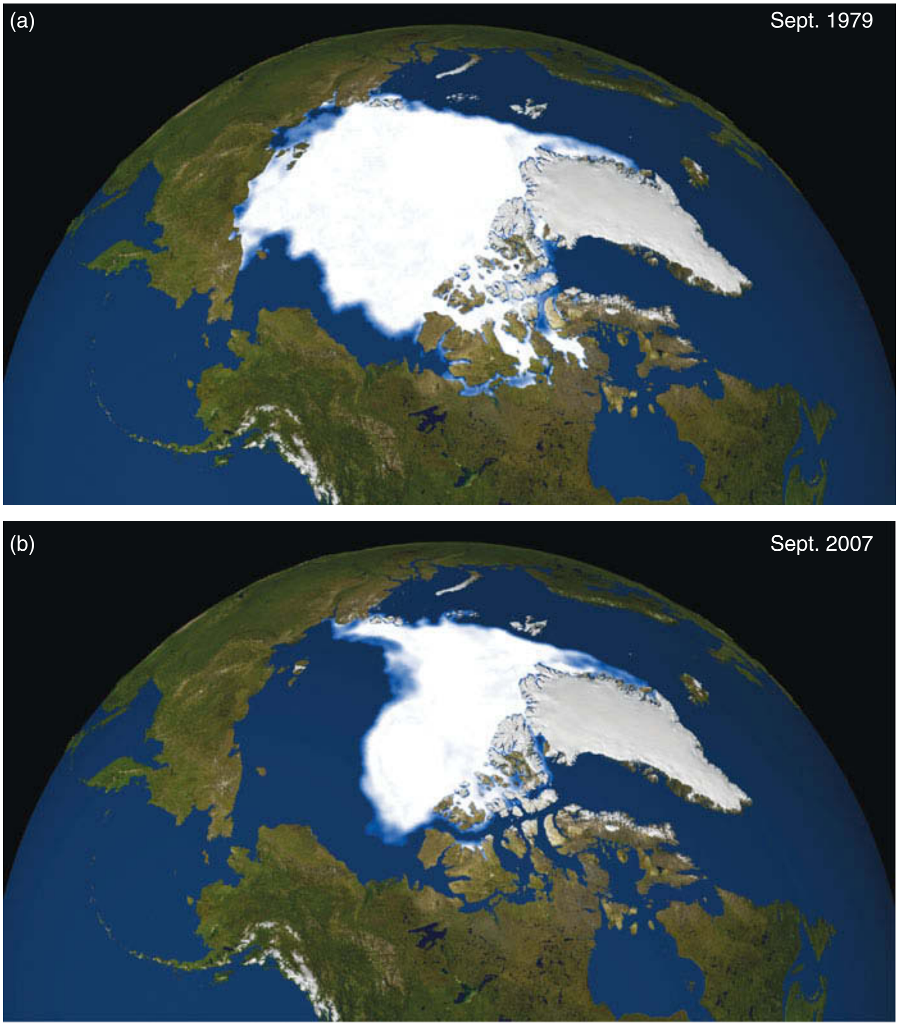


Figure 4.13 A satellite view of Arctic sea ice cover in September 1979 (top) and September 2007 (bottom).

Arctic, which is almost three times larger than the drawdown in annual mean ice extent (Figure 4.14).

Permafrost

Permafrost soils are another harbinger and driver of climate change (Figure 4.15). A soil is designated as permafrost if its temperature has been below freezing for two years or more. The frozen layer may be hundreds of

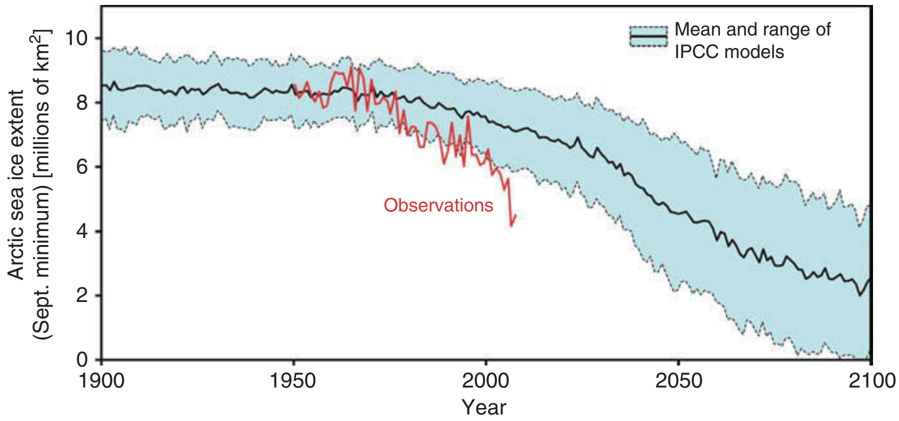


Figure 4.14 Extent of Arctic sea ice at the summer minimum (September) from observations and according to IPCC models. Sea ice extent has shrunk by almost half since the 1960s, faster than expected.

Figure 4.15 Vast quantities of organic carbon are preserved in frozen Arctic soils. When the permafrost melts, the soil carbon breaks down into CO_2 and methane.

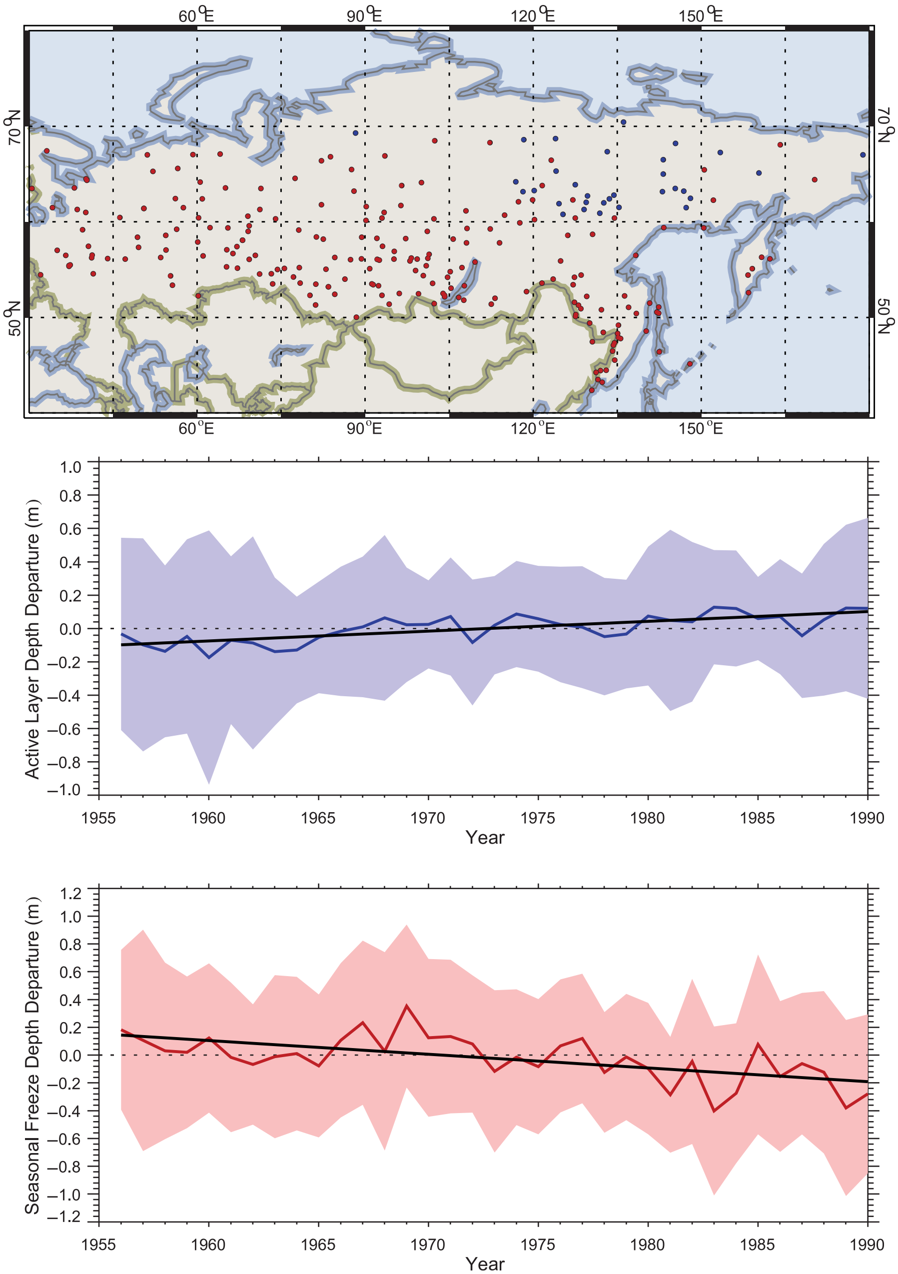


Figure 4.16 In regions where the deep soil is frozen year round (blue symbols on map), the thickness of the summer thaw zone has been increasing (the melting penetrates deeper) (middle plot). In regions where soils are not frozen in summer (red on map), the depth of freezing in the winter has been getting shallower (bottom plot).

meters deep in some places. The frozen condition protects a large amount of fossil carbon in the form of peat deposits. When frozen peat thaws, it begins to decompose, producing CO_2 and methane (another greenhouse gas), a potentially important climate feedback that was not included in the IPCC scenarios for the future (Chapter 6).

The *Fourth Assessment Report* cites 15 studies reporting temperature trends in permafrosts, and all of them show warming. The surface layers of permafrost may melt in summer, forming what is called the active zone. The active zone has been getting thicker over the years, in dozens of locations where it is being monitored (Figure 4.16, middle plot). In winter, a frozen layer may form at the soil surface in non-permafrost soils. In hundreds of stations where this is being monitored, the thickness of this seasonally frozen zone has decreased (Figure 4.16, bottom plot).

When ice layers within the soil melt, the soil column collapses, leaving behind an irregular soil surface, toppling trees and undermining buildings and roads. Thawing changes the hydrology of the soil, freeing water to flow and collect, but also opening subsurface flow channels, draining lakes away overnight. Satellites show that the area of lakes in Siberia has increased by 10% in areas of continuous permafrost, while in areas of discontinuous permafrost to the south the area of lakes has decreased by 10%, over the past three decades.

Summary

Ice plays many roles in the climate system, in the diagnosis and the prognosis for human-induced climate change. Mountain glaciers, snow, sea ice, and permafrost are melting around the world. There are regional variations in climate, and exceptions to the general melting trend, in particular sea ice near Antarctica. However, taken together, observations of snow and ice provide powerful support for the warming trend as measured by thermometers at weather stations.

Sea ice reflects sunlight, until its melting amplifies the warming from greenhouse gases. The ice in the Arctic in particular has been melting faster than had been predicted, and when it goes the climate impacts could be profound. The Greenland ice sheet could be affected by a change in high-latitude Northern Hemisphere climate. The ice sheets in Greenland and Antarctica hold enough water to flood the continents by 70 meters, a change that would be visible on a grade-school globe of the Earth. The ice sheets appear to be responding to warming so far much more quickly than had been predicted, and in ways which hadn't been thought of. The unpredictability of ice sheet flow makes it impossible, so far, to make a reliable forecast for future sea level rise.

5 How the oceans are changing

The oceans are a major player in the climate system. They cover two-thirds of our planet – hence most of the energy from the sun, which drives the whole climate system, goes into the oceans first. Ocean water can store a large amount of heat. This heat storage capacity of the oceans is a thousand times larger than that of the atmosphere, and it causes what is sometimes called "thermal inertia": the climate response lags behind the forcing (i.e., the drivers – the concept of forcing was explained in Chapter 2), as it takes time for the oceans to warm up. That has reduced the global warming seen thus far – and it makes us committed to more warming in future, even if greenhouse gas concentrations were stabilized today.

The oceans also move large amounts of heat around the world through ocean currents – this can have a big impact on regional climate, hence the interest in how ocean currents might be changing. The oceans are also the main source of water vapor for the atmosphere and thus for the precipitation falling on our planet. And the fish we take from the oceans have for millennia played an important role in human diet, with the quest for fish shaping many facets of our history. The oceans also turn out to be a major sink of the carbon dioxide that we are releasing into the atmosphere – we will discuss below how this is a blessing and a curse at the same time. Last but not least, we are interested in the oceans because changes in sea level have the potential to threaten our coastal cities and ecosystems with flooding.

These are just some of the ways in which the oceans affect and shape the lives of all of us. At the same time, the oceans still retain much of their mystery. Taking measurements at sea involves great effort and expense, and the oceans remain a rather poorly sampled part of the climate system. But with quite a few new data since the last IPCC report, things have become a lot less murky. So let us discuss what we know about the changes that are going on in the oceans.

The oceans are heating up

In previous chapters we have discussed how the radiation budget of the Earth has changed, mostly through the effect of heat-trapping greenhouse gases. We have also discussed how the surface temperature of the planet is rising – and in fact we have already shown the measured changes in sea surface temperatures when we discussed the changes in global mean temperature (see Figure 3.2).

But there is more to ocean temperatures than just noting the warming of the surface waters. How far and how quickly the warming penetrates the depths of the ocean has major implications: for example, it tells us how much heat the ocean is storing, and it determines how much the sea level rises because of water expanding as it warms. Another important issue is how quickly the warming reaches the sea bed in different regions, as this affects bottom-dwelling organisms, and a warming of the sediments at the sea bottom controls whether and how much methane will bubble up from the sea floor.

Data about ocean temperatures at depth come from research ships and from "ships of opportunity," commercial ships equipped with expendable bathythermographs (so-called XBTs). These are electronic devices that are thrown overboard and record temperature on the way down, sending data back over a thin wire that breaks when the device has reached its maximum depth. Research ships, in contrast, use more sophisticated equipment that is winched back on board after each measurement, but this requires the ship to be stopped for an hour or more for each measurement. More recently, autonomous vehicles called Argo floats have come into use (Figure 5.1). They cruise up and down the oceans taking measurements over a specified depth range, sending data off to a satellite at regular intervals when they surface. However, after publication of the IPCC report it was discovered that some of these Argo floats had faulty pressure sensors, which caused a spurious cooling in the data for 2003–2005. Despite being just a short-term "wiggle," which changed none of the conclusions about the longer-term warming trend, this was puzzling to many oceanographers. After removing the faulty data from the analysis, this cooling has gone.

Figure 5.2 shows how the amount of heat stored in the oceans has changed since 1955. We said the ocean is poorly sampled – but this still means that 8 million measured temperature profiles have gone into constructing this figure! It shows that the heat content has some interesting short-term wiggles, but overall it has been going up: the oceans are warming. Over the past 50 years, the heat content has increased by about 10^{23} joules. This is a huge amount of heat by human standards: you'd have to burn 40 trillion tons of coal to generate this much heat, which is 8,000 years worth at the current global coal usage (and, thus, far more coal than exists on the entire planet). One thing this shows is that trapping just a little extra heat from the sun can give us vastly more energy than all fossil fuels. But what does this number really mean for climate?

One way of looking at it is to divide the ocean heating rate by the total surface area of the Earth: that gives you a heat uptake rate per square meter, and the number turns out to be half a watt per square meter. That can be compared to the climate forcings discussed in Chapter 2 of this book. There we found that humans have so far altered the radiation balance of the planet by 1.6 W/m^2. From the ocean data, we now know that 0.5 W/m^2 of this amount disappears into the ocean – they are used up to heat the ocean water. That leaves us only 1.1 W/m^2 that we still need to get rid of in other ways, namely by radiating it into space. Thus, at this point in time, the atmosphere only needs to be warm enough to radiate an extra 1.1 W/m^2, not 1.6 W/m^2. That's why, thanks to the ocean heat uptake, the atmosphere is not as warm now as it would otherwise be.

We can make a simple calculation as to how much warming this has saved us. We have stated earlier that the radiative effect of CO_2 doubling is 3.7 W/m^2, and that this in equilibrium (when ocean heat uptake has stopped) leads to a 3 °C warming (that's the best estimate of the "climate sensitivity", discussed

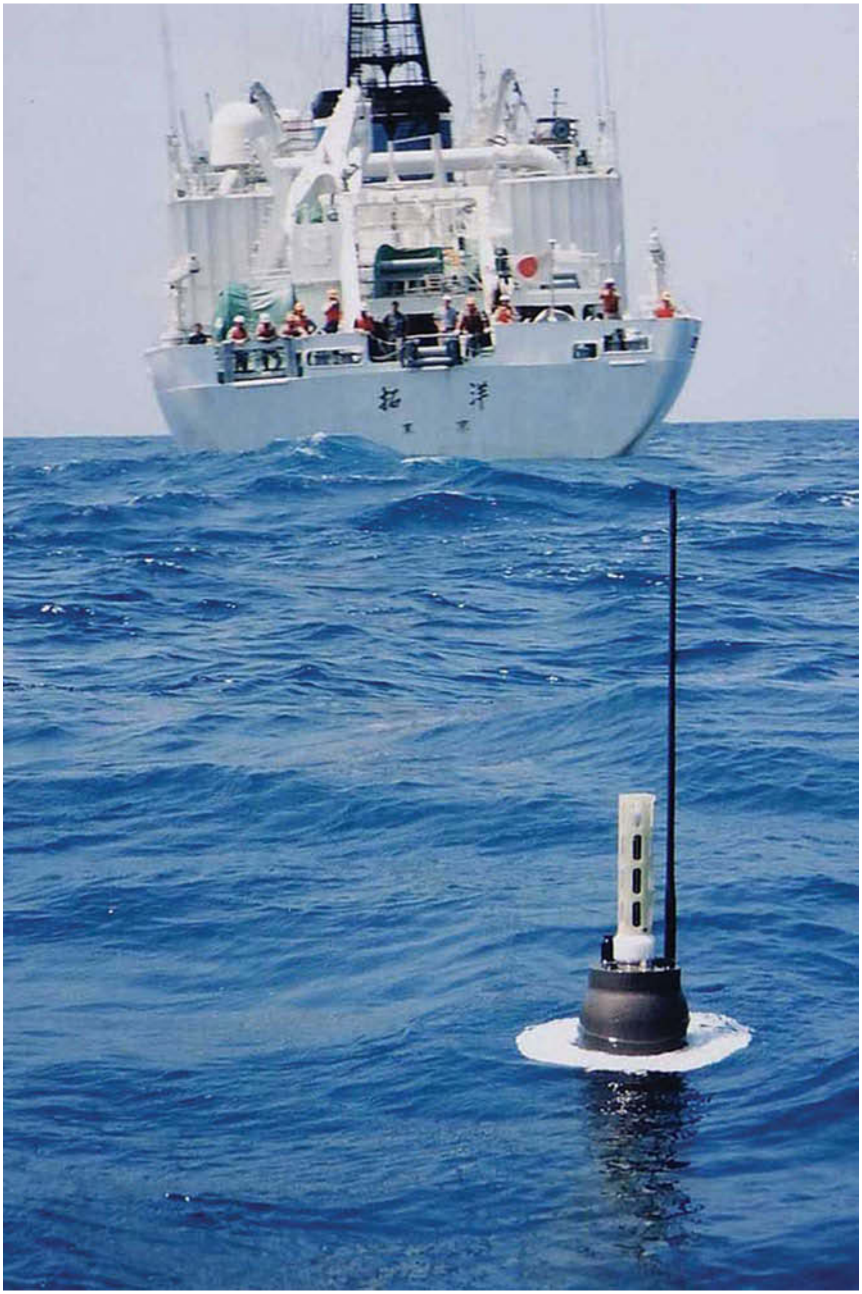


Figure 5.1 An ARGO float shortly before recovery by the Japan Coast Guard vessel *Takuyo*.

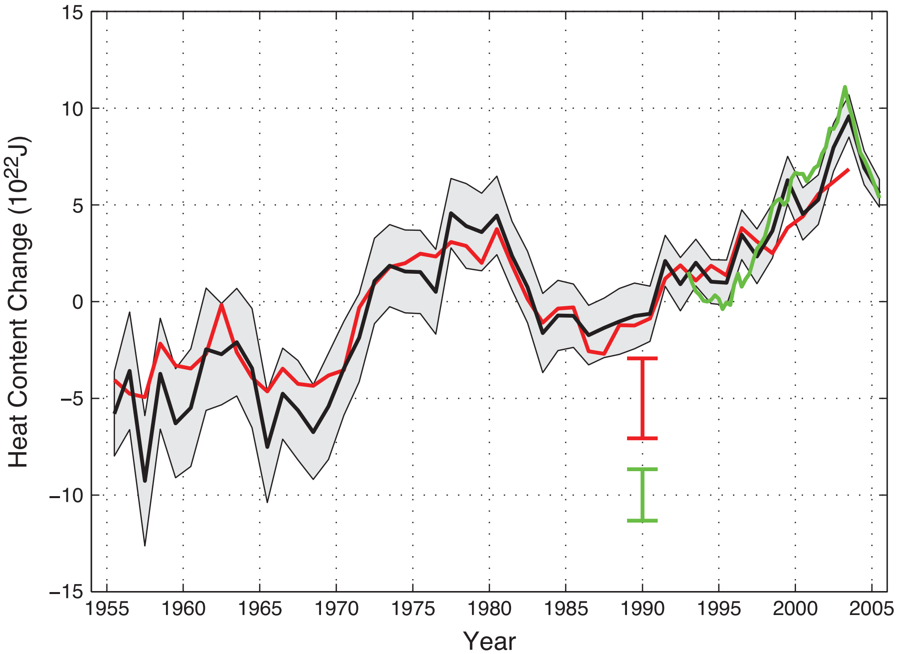


Figure 5.2 Heat content changes in the upper 700 meters of the global ocean. The black, red, and green lines represent different data analyses by different groups of researchers. The gray band is the 90% confidence interval for the black line. In addition to "wiggles" caused by natural climate variability, a clear upward trend of ocean heat content can be seen as the oceans are warming up.

in Chapter 6). Then 1.6 W/m^2 will lead to proportionally less warming, namely to 1.3 °C (that is 1.6/3.7 times 3 °C). But if we factor in the heat that disappears into the ocean depths, we've now only got 1.1 W/m^2 left to heat the surface – global warming at this point in time, due to the human-caused change in the Earth's heat budget, should therefore be 0.9 °C (that's 1.1/3.7 times 3 °C). The ocean heat uptake has thus spared us 0.4 °C until now. That is a temporary effect, though. If our disturbance of the climate system remained constant at those 1.6 W/m^2 discussed above, the oceans would gradually warm up until they reach a new steady state and stop taking in any more heat – that is, temperatures would rise that extra 0.4 °C in the coming centuries, even if we stopped increasing the greenhouse gas concentration any further from now on.

The 0.9 °C warming predicted by theory happens to be almost exactly the warming that is observed. Given the uncertainties in climate sensitivity, in radiative forcing and in ocean heat uptake, the almost exact agreement of predicted and observed warming is of course somewhat lucky. It does show, however, that the observed warming is entirely consistent with our best estimates of the forcing and of the sensitivity of the climate system, and that the human influence is able to explain the entire observed warming. We needed those measured ocean heat uptake numbers to be sure of this!

But stop: what if not only the ocean, but also other components of the climate system were hiding some heat away? That would call the above calculation into question. The IPCC report includes an estimate of the other possible heat sinks. That includes the heat stored in the land masses and in the atmosphere, as well as the heat used for melting ice. (If I turn ice at 0 °C into water at 0 °C, this uses up quite a bit of heat without changing the temperature.) It turns out that all these are very small compared to the ocean heat storage; taken all together, they add about 10% to it.

What is remarkable is that melting ice is using up such a tiny fraction of the extra heat coming in. While melting continental ice contributes about 40% to the ongoing global sea level rise (discussed below), it uses up only 1% of the heat budget. What this shows is that the transfer of heat to the ice is very inefficient. If this heat transfer were to be made more effective, say, by making the ice sheets "wet," e.g. by parts being soaked in meltwater or even sliding into the ocean, then the melting could accelerate a lot. We need to remember that the amount of heat available from the greenhouse effect clearly is not a limiting factor on ice melt: there is more than enough heat. The limiting factor is how effectively you can get this heat into the ice.

Sweet or salty?

Apart from temperature, the second most important property of sea water is its salt content, which oceanographers for historical reasons measure in per mille. Typical ocean water contains 35 grams of salt (mostly sodium chloride, familiar to us as table salt) per kilogram of sea water, i.e. 35 per mille or in other words 3.5%. It's the small variations around this average value that make the salt content, or "salinity," so interesting to scientists. First, changes in salinity affect the density of sea water (the more salt it contains, the heavier it gets), and differences in water density drive ocean currents. And second, any observed changes in salinity are a sensitive indicator for how precipitation, evaporation, river runoff, and ice melt have changed.

Overall, 2.3 million measured salinity profiles were used in the IPCC analysis, and they show that some remarkable changes have occurred over the past decades. For the Atlantic Ocean these changes are shown in Figure 5.3. We see a basic pattern of mid- to high-latitude waters getting less salty near the surface, while tropical and subtropical waters are getting saltier. We can

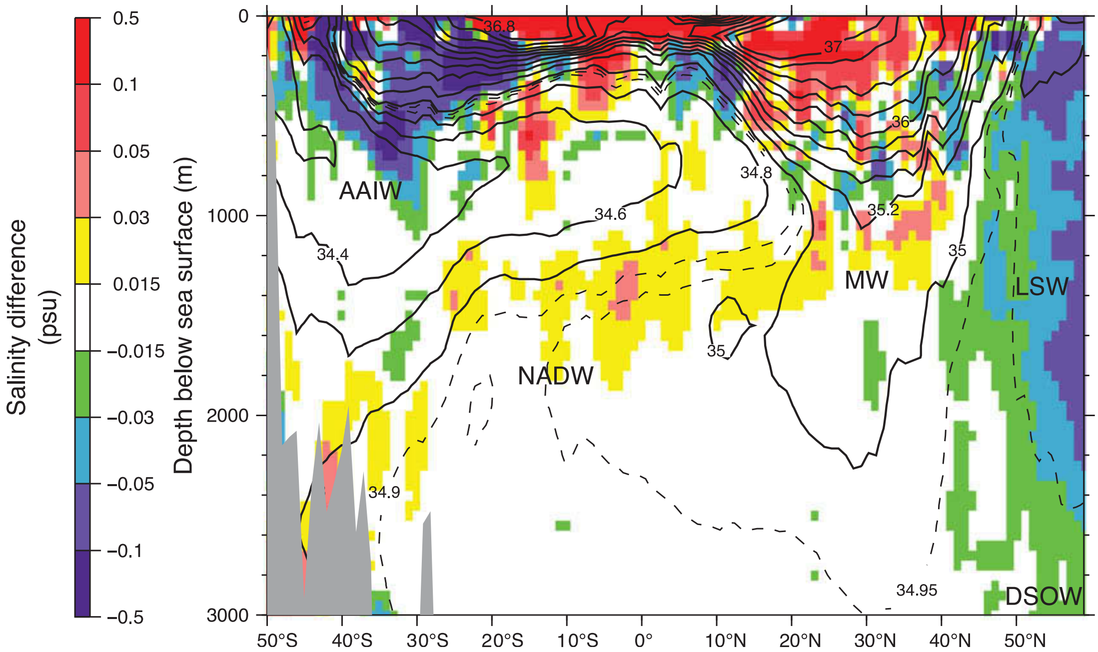


Figure 5.3 Salinity change in the Atlantic Ocean from the period 1955–69 to the period 1985–99, shown as a latitude versus water depth plot. Between those time intervals, the ocean waters got saltier in the tropics and subtropics near the surface, while they got fresher in mid-latitudes. The labels refer to distinct water masses: e.g., AAIW stands for Antarctic Intermediate Water, LSW for Labrador Sea Water and NADW for North Atlantic Deep Water.

also see how these changes are spreading down into deeper waters according to the known ocean circulation pathways. For example, the freshening reaches down to 3,000 meters north of 50 °N, where the ocean is known to mix down to large depths. And we can see fresh (blue-green) anomalies spreading towards the equator from the mid-latitudes below the surface, roughly following the contours of constant salinity that are shown as black lines. A similar pattern is found in the Pacific.

There is a simple explanation for this pattern: the water cycle of the atmosphere is getting stronger. The water cycle normally transports water vapor, coming from excess evaporation from the dry and sunny subtropics, up to higher latitudes where it rains (or snows) down. That's why the oceans generally are most salty in the subtropics and least salty in higher latitudes. If this pattern is enhanced, by more evaporation in the subtropics and more rain in higher latitudes, we get the kind of changes that are actually observed in the oceans. In addition to the direct measurements of rainfall changes discussed earlier, these salinity changes are strong evidence that the water cycle is indeed accelerating. And while it is hard to reliably measure trends in noisy rainfall data, the ocean shows us the net effect of the long-term trend directly. As the ocean acts like a huge bucket accumulating all the rain over time, the noise (i.e., the short-term fluctuations) plaguing the rainfall measurements just averages out. The salinity changes, which can be measured to very high precision, are therefore a reliable indicator.

Oceanographers love the distinct water masses of the world ocean like a connoisseur loves particular vintages of a good wine, and the IPCC oceans chapter spends many pages describing in great detail the changes in water masses in different parts of the world. There is no doubt that a systematic pattern of significant changes is indeed occurring in the oceans over the past 30–50 years, for which we have reliable data. This pattern is consistent with global warming and with what we know about the global ocean circulation.

Are ocean currents changing?

We've discussed temperature and salinity so far, so what about currents? Many people have heard about the possibility of the North Atlantic Current (the extension of the Gulf Stream across the Atlantic towards Europe) shutting down – a scenario that even made it into a Hollywood disaster movie, *The Day After Tomorrow*. So is there any indication that the North Atlantic Current or any other ocean current is changing? The short answer is: we neither have any convincing evidence for changes in ocean currents, nor can we rule them out.

The reason for this uncertainty is that ocean currents are difficult and expensive to monitor over any extended period, which would be required to detect long-term trends. To measure the flow in the North Atlantic Current, say, it obviously is not enough to just measure the speed at one point – you have to properly sample it in many places. And it's not good enough to measure it one month and then come back ten years later to see how it has changed, since there are big variations on all time scales – from day to day, from month to month, from year to year, and longer. The ocean is turbulent.

Another reason is that we don't expect to see any big changes yet as a result of global warming. Model simulations suggest the North Atlantic Current is likely to weaken significantly over the twenty-first century (we will discuss model scenarios for the future in Chapter 7). But even if you take a rather pessimistic climate model scenario, one where the North Atlantic Current shuts down completely as a result of global warming, it weakens only by less than 10% until today in such a model. That is still within the internal variations that the current shows in models even without any global warming, so a 10% change wouldn't be of too much significance, even if it could be measured. And a 10% past change would be at the limit of what one might be able to measure. Hence, based on what models say, we simply don't expect to see any exciting ocean current changes yet in the data.

The North Atlantic Current is just a part of a gigantic slow overturning motion of the Atlantic Ocean, where huge amounts of water (about 15 million cubic meters per second) sink down in northern latitudes, in the Greenland-Norwegian Sea and the Labrador Sea. At 2 to 3 km depth, this water flows southward across the equator. Near the surface, the sinking water is replaced by water coming north across the equator, moving through the Caribbean and along the Gulf Stream until it heads towards Scandinavia in the North Atlantic Current. There have been some intriguing hints of changes in this overturning circulation. The most prominent was when British oceanographers reported a 30% reduction in this overturning, based on measurements across the Atlantic repeated five times between 1957 and 2004. However, the IPCC report rightly concludes that measuring only at five points in time is not enough to reliably determine a trend, given the now-recognized intrinsic variability in the ocean on all time scales.

Another part of the big overturning motion is the deep overflow of water from the Nordic Seas into the open Atlantic near Iceland. Scientists from the region in 2001 reported a weakening of a key part of this overflow, but later the current started to recover. This shows that this record is still too short to determine a meaningful trend. As mentioned in Chapter 3, another intriguing hint is the cooling south-east of Greenland found in the surface temperature trends of the past century (Figure 3.3), but a detailed analysis of this is lacking. Overall the evidence is inconclusive, and we simply do not know whether the giant Atlantic overturning has weakened or not. We need to make sure to have the appropriate observation systems in place so that we will be able to notice any signs of the current changing in future.

Sea level rise

One important consequence to be expected from a warming of the climate is a global rise in sea level. There are two main reasons for this.

First, the water in the oceans expands as it gets warmer; this is called "thermal expansion." As almost every other substance, sea water takes up more space when heated. The effect is very small, but since the oceans are on average 3,800 m deep, an average expansion of the ocean water by one hundredth of a percent would cause a sea level rise of 38 cm.

Second, additional water enters the ocean from the melting of ice on land (see Chapter 4). Cold climates, like the ice ages discussed in Chapter 6, come with a lot more ice on land. At the height of the last ice age (only 20,000 years ago), such huge ice sheets had formed that sea level was 120 m lower than today. In warm climates, ice sheets are smaller or gone altogether – if one completely melted the ice sheets we have left today in Greenland and Antarctica, sea level would rise globally by about 65 m. In fact, during most of the past 500 million years the planet was so warm that it was essentially free of ice. The ice sheets we have now started to form only about 40 million years ago.

So is sea level actually rising? Since 1993, satellites are continually measuring global sea level changes. They reveal that sea level indeed is steadily rising, and at a rate of 3.4 mm per year (that would be 34 cm over a century, if this rate were unchanged).

How long has this sea level rise been going on for? Before 1993, we do not have satellite data, so information on sea level changes comes from measurement stations along the coasts (tide gauges). Two issues need to be dealt with when using these data. First, they do not provide a good global coverage. Although there are hundreds of such stations, they are all located along coastlines. In a sense that may not be so bad, since we are more interested in sea level changes along our coasts than in the open ocean, where they don't affect anyone. But we do need a proper global number to do the sums of whether the observed rise matches what we know about how much meltwater enters the ocean and how much thermal expansion there is (see below). The second problem is that tide gauges measure sea level not relative to some fixed level in space (like satellites do), but relative to the land. If the land sinks, for a land-based instrument it looks as if the sea level goes up. Since we know that some parts of coastline are sinking and others are rising, tide gauge data need to be corrected for this effect before they tell us something reliable about sea level. These corrections can be done, but they add a source of uncertainty.

With that said, a number of different global tide gauge data studies are telling us that, over the twentieth century, sea level has risen by about 17 cm (plus or minus 5 cm). That's a significantly lower rate (1.7 mm/year) than the one found for the most recent period from the satellites (but both data sets agree where they overlap), indicating that sea level rise has accelerated in recent decades. The rise since the year 1870 is shown in Figure 5.4.

Further back in time, before the twentieth century, we have sea level information from so-called proxy data – indirect evidence for where sea level was at a given point in time. These show that nothing like the rate of

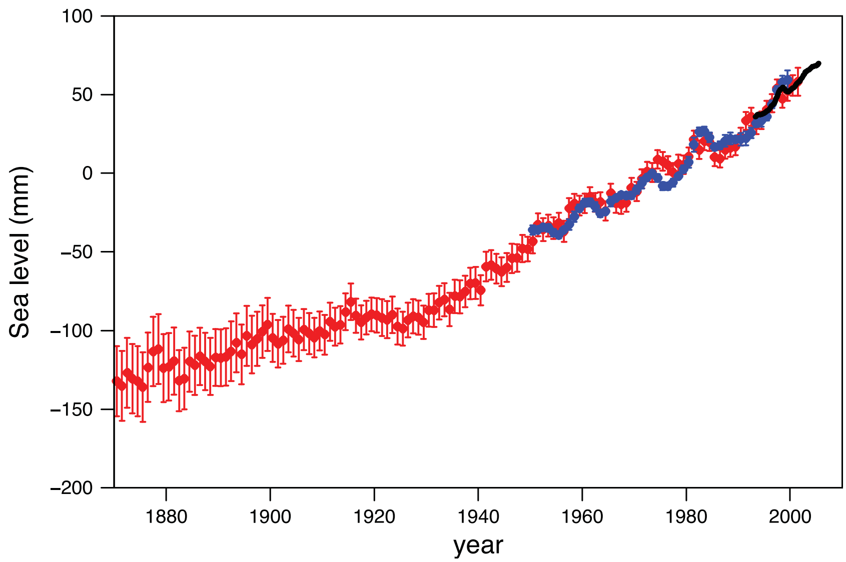


Figure 5.4 Change in global sea level since the year 1870. The red curve shows reconstructed global sea level, the blue curve shows tide gauge measurements at coastal stations, and the black curve the satellite measurements which started in 1993. The data reveal a global rise in sea level by about 20 cm since 1870.

sea level rise observed in the twentieth century occurred in the previous two millennia. Just imagine if a similar sea level rise had been going on already for a long time (say, at a rate of 1.7 mm/year). Then two thousand years ago, during the time of the Roman Empire, sea level would have been 3.4 m lower than now! And Roman structures such as harbor walls and salt-water ponds, the remains of which still exist today, would have been located high and dry, well above sea level at the time, which obviously makes no sense. The IPCC report finds that any remnant after-effect of the huge (120 m) sea level rise at the end of the last ice age is most likely zero over the past 2,000 years and at most 0.2 mm/year, a tiny fraction of the sea level rise observed in the twentieth century. The recent sea level rise is thus a modern phenomenon – as we indeed would have expected, since nothing like the global warming found in the twentieth century has occurred in any other century for the past millennia.

Can we explain which processes caused the sea level rise? The report analyses the past decade (the period 1993–2003 to be precise) as well as the past four decades (1961–2003). In Chapter 4, we saw that melting land ice would have contributed 0.7 mm/year in the past four decades, and 1.2 mm/year in the last decade. We can also compute the contribution from thermal expansion by using data on the rise of ocean temperatures. For the past four decades, the best estimate is 0.4 mm/year, only a quarter of the observed rise.

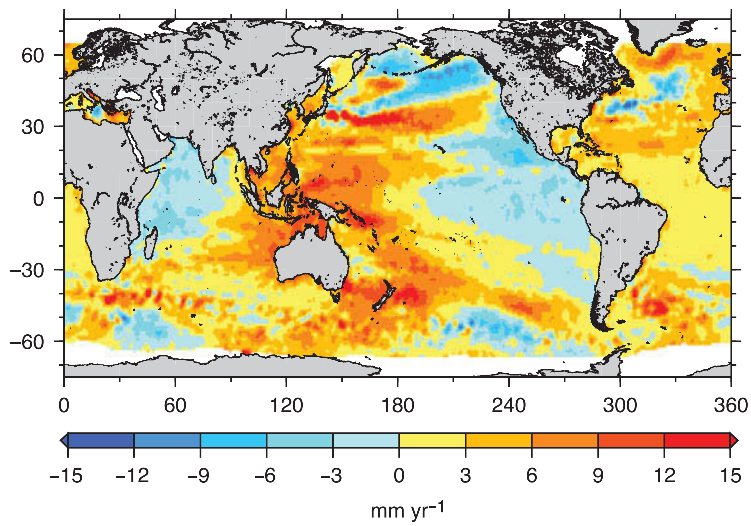


Figure 5.5 Short-term trends in sea level measured from satellite over the period 1993–2003.

Together with ice melt this yields 1.1 mm/year, while the observed rise is 1.8 mm/year for this period. There is thus a shortfall of 0.7 mm/year – we cannot fully explain the observed sea level rise over this period. The reason for this shortfall is not yet understood – either it is explained by errors in the estimates cited above (their estimated uncertainties are just enough to allow such a shortfall), or there is some additional reason for the rise which is not taken into account – for example ground-water mining for irrigation purposes, which could also add some water to the oceans, but which is thought to be small and roughly compensated by water storage in reservoirs. The effect of water storage has been analysed in more detail by Ben Chao and colleagues from the National Central University of Taiwan since the IPCC report appeared. It seems to be surprisingly large: so much water has been stored in reservoirs over the past 50 years that this would have lowered sea level by 3 cm. This makes the observed rise by 7 cm over the past four decades all the more puzzling.

For the past decade things look better. The thermal expansion part is estimated as 1.6 mm/year, half of the observed rise. Together with ice melt this yields 2.8 mm/year, close enough to the observed 3.2 mm/year to agree well within the uncertainty.

In addition to the global mean sea level rise, the satellite data with their global coverage also reveal regional differences. These are shown in Figure 5.5. This map shows that sea level rise over the last decade has been far from uniform. In large parts of the ocean sea level has in fact fallen, for example in most of the Indian Ocean and in eastern parts of the Pacific. The pattern looks similar to that derived from ocean temperature measurements, which is to be expected and which confirms that the data are sound. The cause of the observed pattern is likely to be natural variability: we expect the ocean waters to move around in response to changes in winds and to heat or cool according to the climate oscillations mentioned in Chapter 3, namely El Niño/Southern Oscillation, the Pacific Decadal Oscillation or the North Atlantic Oscillation. For example, El Niño can cause sea level variations between different years of 20 cm in the tropical Pacific – that is of the same magnitude as the global trend over the past hundred years. We therefore do not expect the trends shown in Figure 5.5 to continue into the future; rather we expect this to be a snapshot of oscillations that are superimposed on the long-term global trend. And indeed, when looking at the longer-term sea level changes (1961–2003), the pattern already looks rather different. But as the global sea level keeps rising steadily, we expect this rise to eventually become larger than any regional natural oscillations. In other words, we expect sea level to go up everywhere in the long run, even in those places where it has dropped over recent decades.

The oceans are turning sour

We have so far discussed changes in temperature and salinity, in ocean currents, and in sea level. But there is one more aspect of the ocean that we need to talk about and that is equally important, although less familiar to most people. It is the delicate system of ocean chemistry, the cycles of carbon, oxygen, and nutrients, which are intricately interwoven with the fabric of life in the sea.

Let us start with carbon in the ocean. As the carbon dioxide concentration of the atmosphere is rising, some of this CO_2 is taken up by the ocean surface waters. This is because gases are exchanged through the sea surface, and this gas exchange strives towards an equilibrium between the gas in the water and in the air in contact with it. Therefore, in the surface ocean we expect the concentration of dissolved CO_2 to increase in proportion to the rise in concentration in the air. And in those places where we have the long-term measurements to show it, that is exactly what has happened.

So, how much of the CO_2 we put into the atmosphere has ended up in the ocean? This question cannot be answered just by looking at dissolved CO_2 in the ocean, because unlike in the atmosphere, CO_2 in sea water gets involved

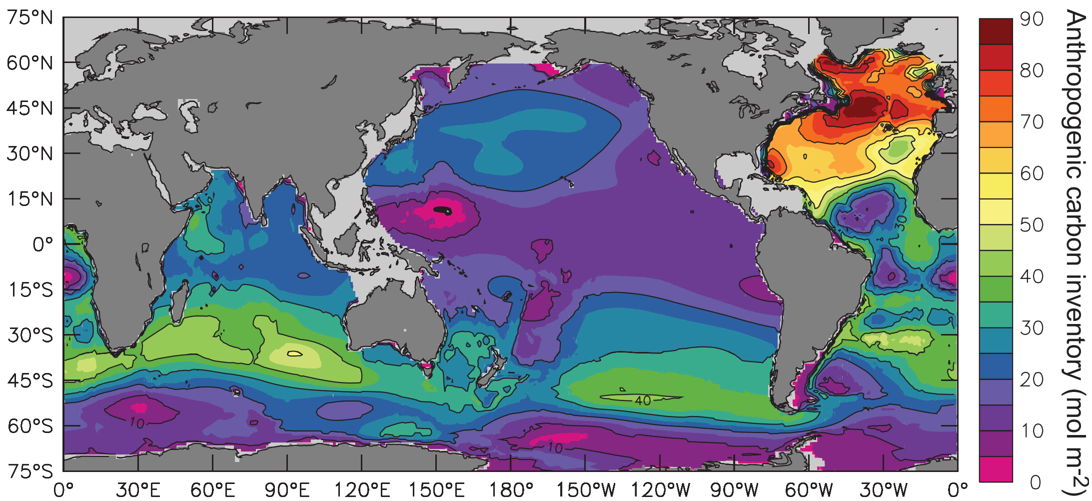


Figure 5.6 The amount of anthropogenic carbon stored in the ocean as of 1994, based on thousands of measurements from research ships.

in chemical reactions, so it does not remain there in the form of CO_2. Some of it turns into carbonate and bicarbonate, and some is used by living things in the sea and turns into what is called organic carbon; for example, plankton. To make a grand inventory of where all the carbon atoms went that we dug up as coal or oil and then burnt, we have to sum up all those different kinds of carbon found in the ocean. And we have to go and measure all over the oceans, since it takes thousands of years to mix a substance through the whole ocean. The atmosphere is mixed in a year or so, that's why we just need to measure CO_2 in one place there (as long as that place is remote from any sources like cities or industry).

So oceanographers have gone out to sea and measured nearly ten thousand vertical profiles of oceanic carbon. From these measurements one can calculate how much carbon has been taken up by the ocean since pre-industrial times. The result is the map shown in Figure 5.6. The first thing it shows is that, everywhere in the ocean, the carbon content has increased – the numbers are all positive. Sometimes one reads claims in the media that perhaps the atmospheric increase in CO_2 is not caused by humans but is a result of CO_2 coming out of the ocean, like it did when climate warmed up at the end of ice ages. These measurements prove that this is not the case: rather than releasing CO_2 to the atmosphere, the ocean actually has taken up CO_2 from the atmosphere. CO_2 has increased in the ocean as well as in the atmosphere, since a lot of additional carbon has been added to the climate system from fossil fuels.

These measurements also reveal the total amount that has been taken up so far by the ocean: 118 billion tons of carbon, with an error bar of plus or minus 15%. That's a huge number, but how does this compare with the total carbon emitted? Those 118 billion tons are 30% of the total human-caused CO_2 emissions (those from fossil fuel use plus those from deforestation). Put another way, it is 42% of the net flux from land to atmosphere (which is anthropogenic emissions minus the carbon uptake by the biosphere), or 48% of the fossil fuel emissions only. All these percentages are sometimes cited, which may cause confusion, but they all mean the same absolute numbers. Overall, from what we have emitted in total so far, 45% remains in the atmosphere, 30% has been taken up by the ocean, and the remaining 25% has been taken up by the land biosphere (mostly by trees).

There is some indication that the fraction taken up by the ocean has been decreasing, since for the period 1980–2005 it was smaller than before, but the evidence was still considered rather uncertain in the IPCC report. Several more recent studies have since confirmed this concern. Measurements by Corinne Le Quéré and coworkers (2007) have shown a decline in recent decades for the Southern Ocean and the North Atlantic, the two main regions of CO_2 uptake by the ocean. Scientists certainly are concerned that the ocean uptake may decrease in future as the ocean warms up (CO_2 does not dissolve as well in warmer water, as you can find out by heating your soda). Other factors may also reduce the ocean carbon uptake in future.

The fact that the ocean has taken up so much carbon from the atmosphere sounds like a blessing. If this were not the case, atmospheric CO_2 concentration would already be much higher and climate would have warmed more. But scientists are now realizing that this ocean CO_2 uptake is in itself a huge problem: it makes the ocean waters more acidic. This is very simple chemistry – CO_2 dissolved in water makes carbonic acid. The effect can easily be calculated, and long-term measurement stations are showing it directly (Figure 5.7). Acidity is measured in units called "pH" – the lower the pH value, the more acidic the water is. Since pre-industrial times, the pH value of the surface ocean has already dropped by 0.1 units. This corresponds to a 30% increase in the number of the chemically aggressive hydrogen ions in the water.

The reason why this is very important is because of its effect on marine life. Many marine organisms build hard shells that are made of calcium carbonate ($CaCO_3$) (which comes in two forms called calcite and aragonite). Familiar sea shells are made from this, but more importantly so are the shells of the main microscopic plankton species that form the basis of the marine food web. And coral reefs, which host the most beautiful and diverse of marine

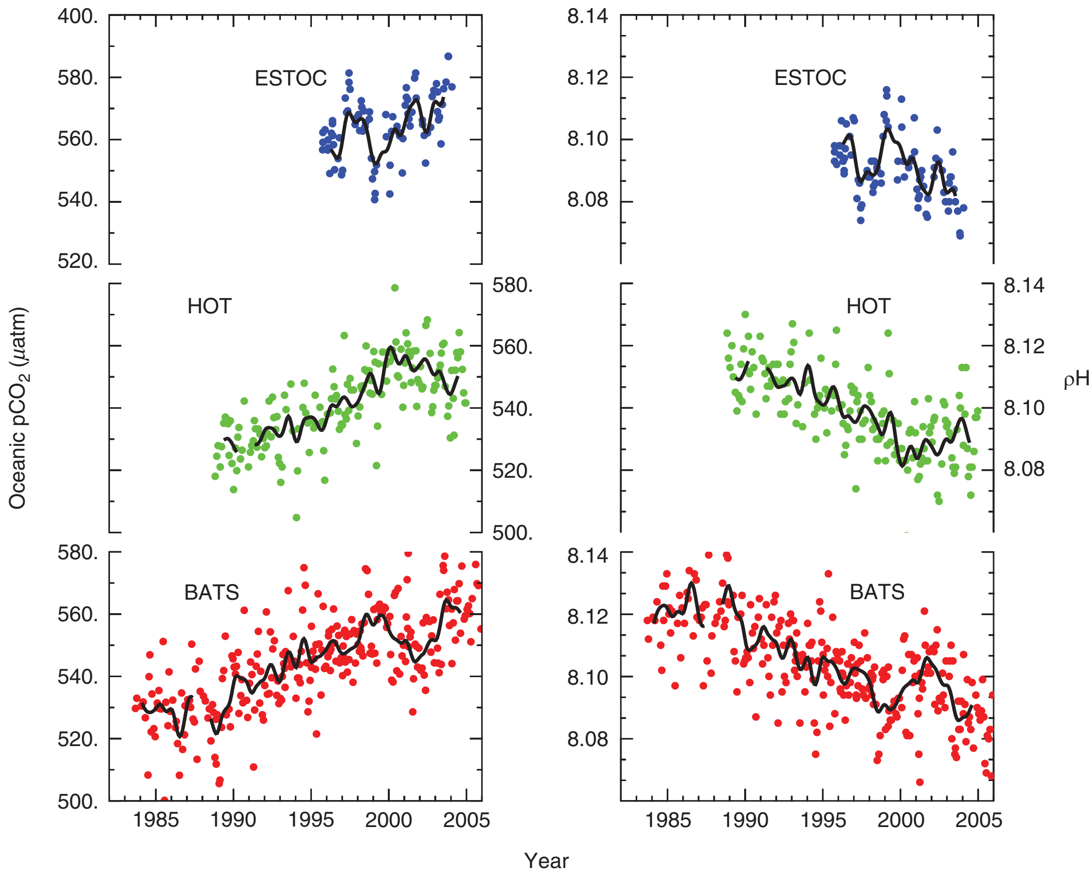


Figure 5.7 Changes in the CO_2 content of surface ocean waters (left) and of their pH (right). Blue dots show measurements in European waters, green dots in the Pacific near Hawaii, and red dots in the Atlantic near Bermuda.

ecosystems, are also built from calcium carbonate. This marine life can only thrive when there is an over-abundance of calcium carbonate in sea water. Put more technically, calcium carbonate needs to be super-saturated, so that these organisms can extract it from the water to incorporate it into their shells. There is a well-defined chemical threshold where calcium carbonate switches from being super-saturated to under-saturated – and by adding CO_2 and making sea water more acidic, we are pushing the ocean towards that threshold.

In fact, this threshold can be seen for real in the ocean: while the surface waters are super-saturated, the deep waters are under-saturated in calcium carbonate for natural reasons. The dividing line (called the "saturation

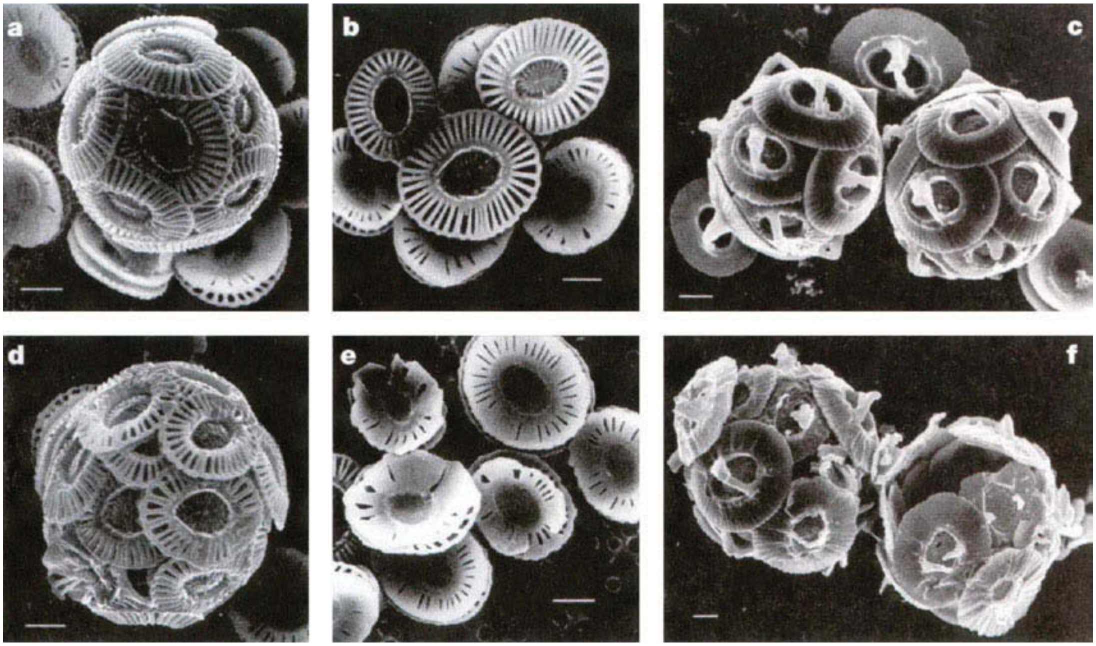


Figure 5.8 Calcium carbonate shells of microscopic algae. Top row shows the shells of healthy organisms, bottom row shows shells grown in sea water enriched with CO_2.

horizon") is at different depths depending on location, varying between 200 m depth in high latitudes and 3,500 m depth in parts of the Atlantic. What happens to the shells of dead plankton that sink down below the saturation horizon? They dissolve, as under-saturated water is corrosive to these shells. That's why the saturation horizon is often compared to the snow line in the mountains, with the snow flakes being the microscopic shells constantly drifting down from the biologically productive surface waters. Where the ocean bottom is above this line, the shells remain intact and form white sediments that are analyzed by scientists to give information about past climates. The white chalk cliffs of Dover are made from this type of calcareous sediment that was uplifted above the sea surface.

Measurements show that this saturation horizon is moving upwards in the water column, consistent with the uptake of anthropogenic CO_2 by the ocean. This raises concerns for marine life – particularly in the Southern ocean, where the saturation horizon is already very shallow at only 200 m depth. Laboratory experiments where plankton were grown in water enriched with CO_2 show that their growth is impaired. According to model simulations, by the year 2050 the changes in ocean chemistry will start to harm marine life if the atmospheric CO_2 concentration continues to rise. For coral reefs, the IPCC report concludes that the impacts of acidification may be "severe" – corals produce aragonite, the form of calcium carbonate that is more susceptible to acidification. As this is a relatively new topic for science, we are only beginning to understand the likely impacts of acidification of the oceans.

Although Earth's history has seen higher CO_2 concentrations than those expected this century (see Chapter 6), these probably did not turn the ocean too acidic because the CO_2 changes happened over millions of years, not within a century. There is no evidence for an ocean pH value more than 0.6 lower than the pre-industrial value during the past 300 million years. On very long time scales, the ocean has mechanisms to buffer the CO_2 changes. The current acidification problem is therefore due to the extremely rapid rise in CO_2 concentration that we are now causing.

Summary

Oceanic measurements show that the oceans are heating up. At the ocean surface, temperatures have changed in a similar way as in the atmosphere, although in recent decades the warming has been slower than over land. This is to be expected, given the large heat storage capacity of the oceans. Warming is greatest near the surface of the ocean, but a warming trend is now evident down to ocean depths beyond 1,000 m.

Salinity in the ocean is also changing, in a global pattern that is consistent with an enhanced atmospheric water cycle. This means enhanced evaporation in subtropical regions, where a salinity increase is found, and enhanced rainfall in higher latitudes, where salinity is declining.

Changes in ocean currents have not yet been conclusively documented. Model simulations suggest that any such changes should still be too small to detect amongst the natural variability that exists in the ocean on all time scales. Ocean currents are only poorly sampled with measurements, making changes hard to detect.

Sea level has risen by about 17 cm over the twentieth century, and by 3.4 mm/yr since satellite measurements started in 1993. This rise is a modern phenomenon, very likely a result of the concurrent climatic warming. Both the thermal expansion of sea water and the melting of ice contribute similar shares to sea level rise, but their exact contributions are not yet fully understood.

Apart from these climatic changes, there are also important chemical changes measured in the ocean. The oceans are taking up a large amount of CO_2 from the atmosphere through gas exchange at the sea surface. About 30% of the total human-caused CO_2 emissions have ended up in the ocean in this way. This makes the ocean water more acidic, a worrying trend that is likely to cause a severe threat to marine life within this century if it continues unchecked.

6 The past is the key to the future

Paleoclimatology, the study of past climates, is an expanding pursuit for the IPCC. There was some treatment of past climates even in the very first IPCC report published in 1990, but the coverage in the *Fourth Assessment Report* is in much greater depth and detail. Past climate changes can tell us something about the sensitivity of climate to atmospheric CO_2 concentration and other changes in radiative forcing, independent of climate models. One important question that the study of past climate change might answer is, can past (natural) processes be affecting present-day climate evolution? Could the recent warming have natural causes?

As we gaze back into deepest time, we must rely on "proxy measurements" of past temperatures, ice sheet distributions, and atmospheric composition. For the most recent times, say the past thousand years or so, temperature records can be constructed using the widths of tree rings, and the temperatures inside ice sheets or the Earth (called borehole temperatures). Further back in time, measurements of the chemistry of calcium carbonate ($CaCO_3$) sea shells, such as the proportions of the heavy and light isotopes of oxygen or the concentration of trace elements such as magnesium, can be used to infer changes in past climate.

Gas concentrations can be measured in bubbles trapped in polar ice cores dating back to 800,000 years ago so far. Beyond this, other clever methods have been derived to estimate CO_2 concentrations in the deepest past, such as by analysis of $CaCO_3$ deposits in ancient soils, or counting the vent cells, called stomata, on the under sides of leaves. As we extend our scope into the deepest past, the uncertainties in climate reconstruction increase, and we also see generally larger climate changes.

Climate changes over millions of years

On time scales of millions of years, the climate of the Earth undergoes major changes, from the ice-free "hothouse" climates of millions of years ago to the icy worlds such as that we live in today. In a hothouse climate, the climate feels nearly tropical all the way to the poles. Reconstructions of CO_2 levels from the last 400 million years are shown in Figure 6.1. There is a pretty wide uncertainty range in the CO_2 concentrations, but in general the CO_2 concentrations were much higher than today during most of this period. The last tens of millions of years had low CO_2 concentrations, just like a similar period around 300 million years ago. During both these low-CO_2 epochs, big ice sheets formed on the continents (also shown in the figure) as we find them today on Greenland and Antarctica. The warmest times correspond with the highest CO_2 concentrations, according to the reconstruction.

The Paleocene Eocene thermal maximum (PETM)

Figure 6.2 shows temperatures over the past 65 million years. The long-term trend shows a gradual cooling. But the data also show other interesting

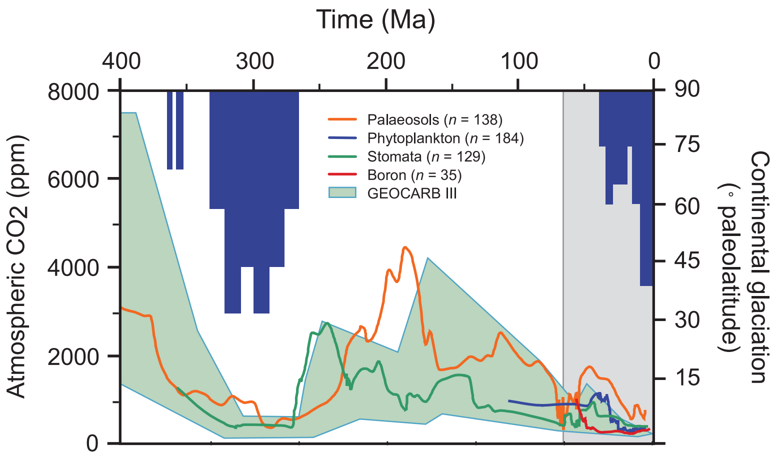


Figure 6.1 Reconstructions of atmospheric CO_2 concentrations in the deep past. The graph shows both proxy data (colored lines) and model estimates (green range) over the last 400 million years. The blue solid regions indicate the latitude reached by ice sheets on continents.

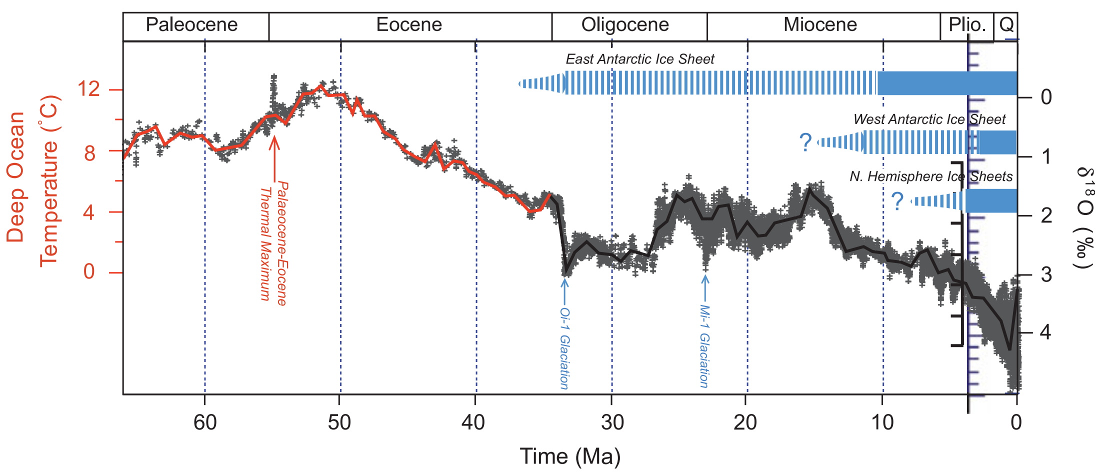


Figure 6.2 Temperature reconstruction over the past 65 million years. It is based on oxygen isotopes from $CaCO_3$ in deep sea sediments, which reflect the temperature of the deep ocean and also the amount of water frozen into continental ice sheets. Overall a cooling trend is observed over the past 65 million years, consistent with the slow decline in CO_2 concentrations caused by tectonic changes.

features, like a brief warm spike around 55 million years ago. This is known as the Paleocene Eocene thermal maximum climate event, and it may have been a pretty good analogue to our current global warming climate event. The PETM is recorded primarily in changes in the abundances of carbon and oxygen isotopes in deep sea sediments (Figure 6.3). The event begins with a spike in

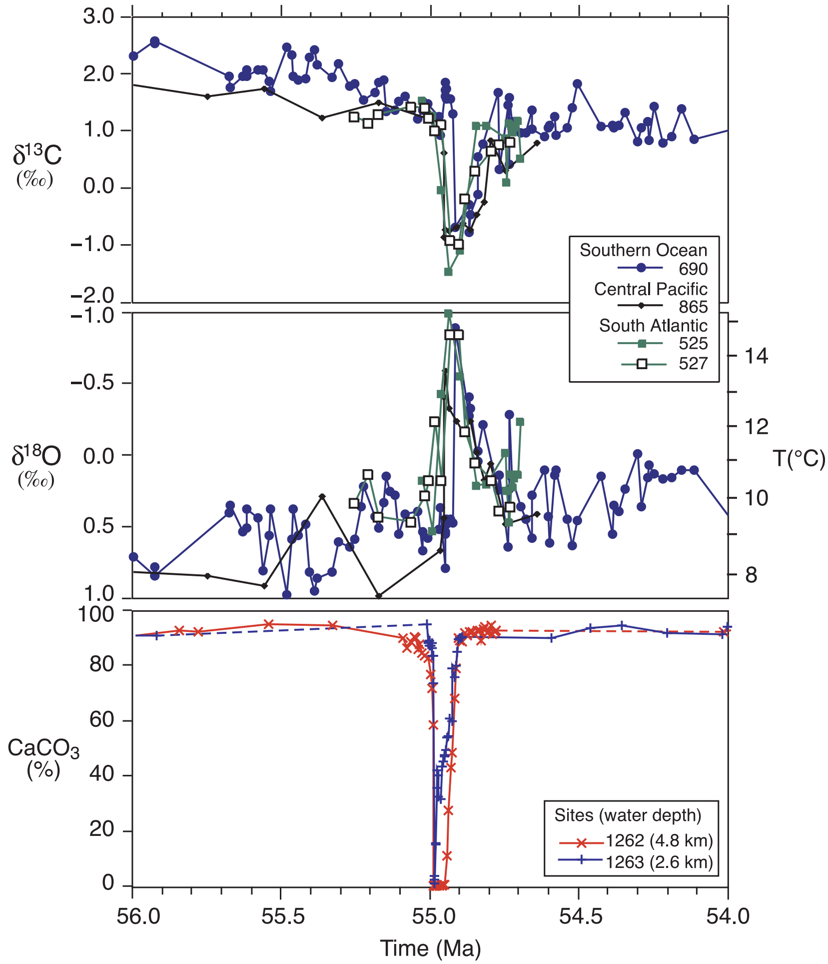


Figure 6.3 Sedimentary traces of the Paleocene Eocene Thermal Maximum event, an analogue for our global warming. The top panel shows the carbon isotope record of a massive release of CO_2. The oxygen isotope data in the middle panel reflect warming of the deep ocean. Acidification of the ocean from the CO_2 dissolved away the $CaCO_3$ on the sea floor (bottom panel).

the abundance of carbon-12 relative to carbon-13 preserved in $CaCO_3$, caused presumably by the release of a slug of CO_2 to the atmosphere from some biological source such as organic carbon or methane. The length of the CO_2 release time period is uncertain, but it was probably in the range of one to ten thousand years. The change in carbon composition was mirrored by a warming in the deep ocean, reflected by the oxygen-18 composition of the $CaCO_3$ preserved at that time. The carbon anomaly, and the warming, both subsided over the next approximately 150,000 years.

The PETM event is not really useful for calibrating or checking our models for how much the Earth will warm from higher CO_2 concentrations (a quantity called the climate sensitivity) because we don't know very well how high the CO_2 concentration was then. One could calculate how much carbon was released from the change in the carbon isotopic composition in the sediment cores, but there is uncertainty because it's not clear exactly how isotopically light the released carbon was. Methane, for example, has a very exotic ratio of carbon-12 to carbon-13, so that it would take a relatively small amount of methane carbon to generate the observed isotope signal in the sediment cores. If the carbon came from a volcano instead it would take much more carbon to generate the observed isotopic shift. One useful observation is that it took over a hundred thousand years for the CO_2 concentration and the warming to recover, just as we expect for the warming from fossil-fuel CO_2. Another is that sediments from this time are devoid of calcium carbonate (from sea shells), which apparently dissolved because of ocean acidification by CO_2. This we also expect in our future if we do not stop the CO_2 increase. The acidification of the ocean during the PETM led to the extinction of a number of species that make calcium carbonate shells, such as foraminifera.

Pliocene

About three million years ago, there were no ice sheets in the Northern Hemisphere. The temperature may have been 10–20 °C warmer in the high northern latitudes, and perhaps 5–10 °C warmer in the North Atlantic. Carbon dioxide concentrations are estimated to have been in the range of 360–400 ppm, comparable to the present concentration (385 ppm in 2008), although there are no ice core bubble samples of air from this long ago, so the CO_2 estimate is not very reliable.

The startling aspect of the Pliocene climate is that sea level was 15–25 meters higher than today, even though the global average temperature was only about 1.5–2 °C warmer. Let's keep track of changes in sea level in the past, as they relate to changes in global temperature, in Figure 6.4.

Glacial cycles

The glacial/interglacial cycles set the stage for evolution of the human species, and shaped the landscape of the present-day Earth (Figure 6.5). The largest physical change in Earth's climate through the glacial cycles is the growth and

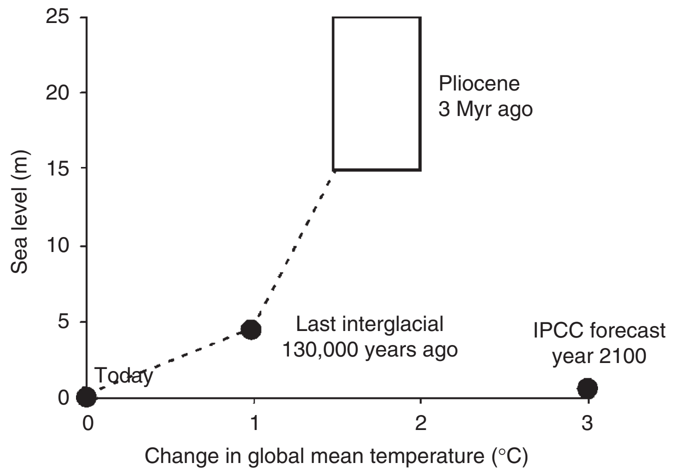


Figure 6.4 Sea level values correlated with changes in the mean temperature of the Earth. Past changes showed a correlation of 5 to 10 meters per °C temperature change. The forecast for the year 2100, excluding the possibility of accelerated flow of the major ice sheets, is for only about half a meter, and about 3 °C of warming, much less sea level rise per °C temperature change.

Figure 6.5 The huge glaciers of the last ice age have left their mark on the landscape of our planet. This valley in New Zealand's South Island was once filled with ice, as the overgrown lateral moraine running up along the side of the valley shows. The helicopters in the foreground are parked on this moraine.

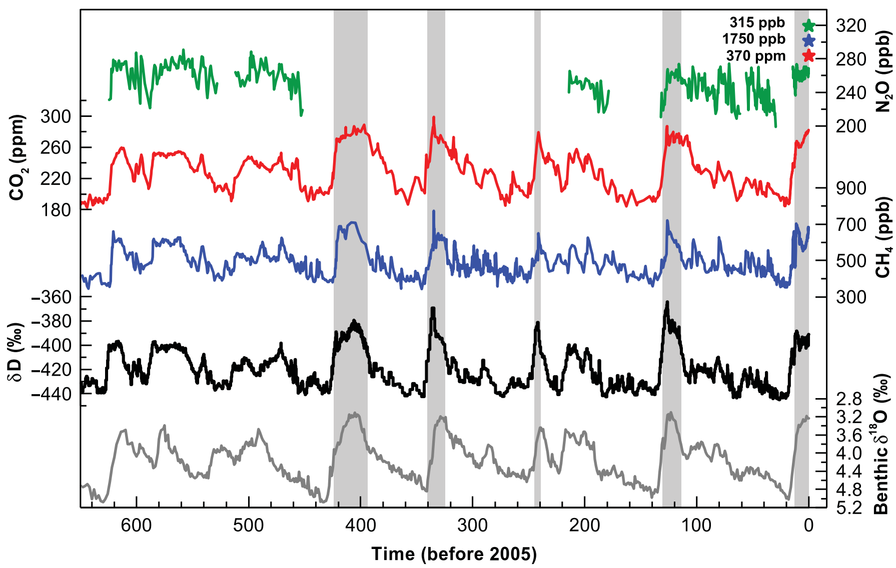


Figure 6.6 Atmospheric chemistry and climate from the Antarctic Vostok ice core. The deuterium isotopic composition δD in the fourth curve reflects the local temperature in Antarctica. The bottom curve is oxygen isotope data from the deep ocean, reflecting the amount of water frozen into continental ice sheets, and the temperature of the deep ocean.

meltback of major ice sheets in North America (the Laurentide) and Northern Europe (the Fennoscandian ice sheet). The most recent ice age reached its peak intensity only about 20,000 years ago. Because the glacial cycles happened so recently in Earth's history (in fact, the glacial cycles would probably continue into the future in a natural world), scientists are able to reconstruct many aspects of the glacial climate more confidently than they can some of the more ancient climate changes (Figure 6.6 and Figure 6.7).

The advances and retreats of the ice sheet correlate in time with wobbles in the Earth's orbit, the so-called Milankovich cycles described in Chapter 1. The Earth's orbit oscillates between circular and somewhat elliptical, the tilt of the poles grows more and less extreme, and the direction of the tilt spins like a wobbling top, all on time scales of tens of thousands of years and more. The total amount of energy that the Earth receives from the sun, averaged over the year and over the surface of the Earth, doesn't vary by much as the orbit changes, but the distribution of sunlight, with latitude and with season, changes quite a bit. As the orbital wobbles rearrange the distribution of heating around the globe and around the year, the climate of the Earth overall seems to follow the changes in sunlight intensity in the Northern Hemisphere summer in particular. The changes in summer sunlight intensity are large,

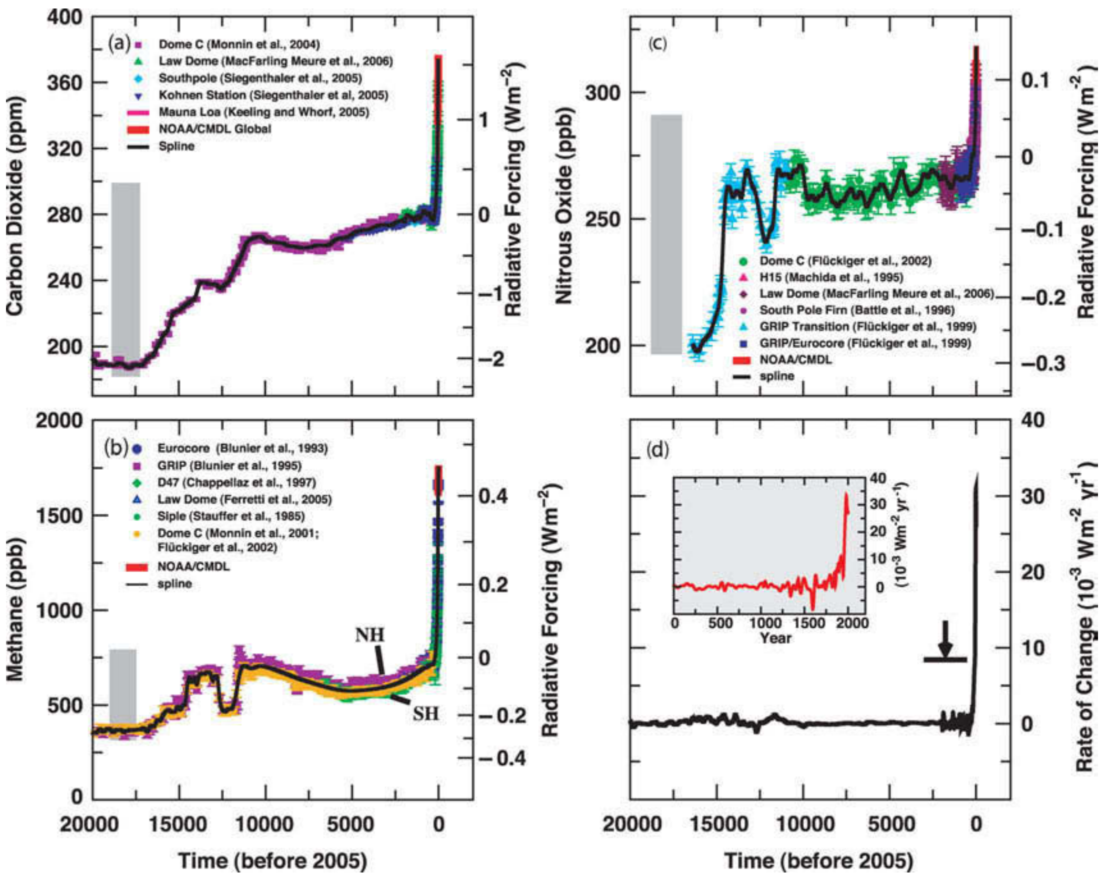


Figure 6.7 Changes since the last ice age in the concentrations and the radiative forcings (Chapter 2) of greenhouse gases. The fourth panel (d) plots the rate of change in the radiative forcing, showing that the climate forcing is changing much faster now than it has ever been since the ice age. (See IPCC (2007), The Physical Science Basis, Figure 6.4 for references.)

around 30 W/m^2, compared with the globally averaged change from doubling CO_2, which is about 4 W/m^2. When northern summer sunlight is weak, the ice sheets grow.

In addition to the orbital forcing of climate, the CO_2 concentration of the atmosphere drops naturally during glacial times and goes up during warm intervals (Figure 6.6). No one knows for sure what the factors are that drive these CO_2 changes, but it is generally believed that the ocean must be largely responsible, because it is the only source of CO_2 that is large enough, and can provide CO_2 to the atmosphere quickly enough, to do the job.

There are several factors that are responsible for the colder temperatures of the glacial climate (Figure 6.8). One is the lower CO_2 concentration,

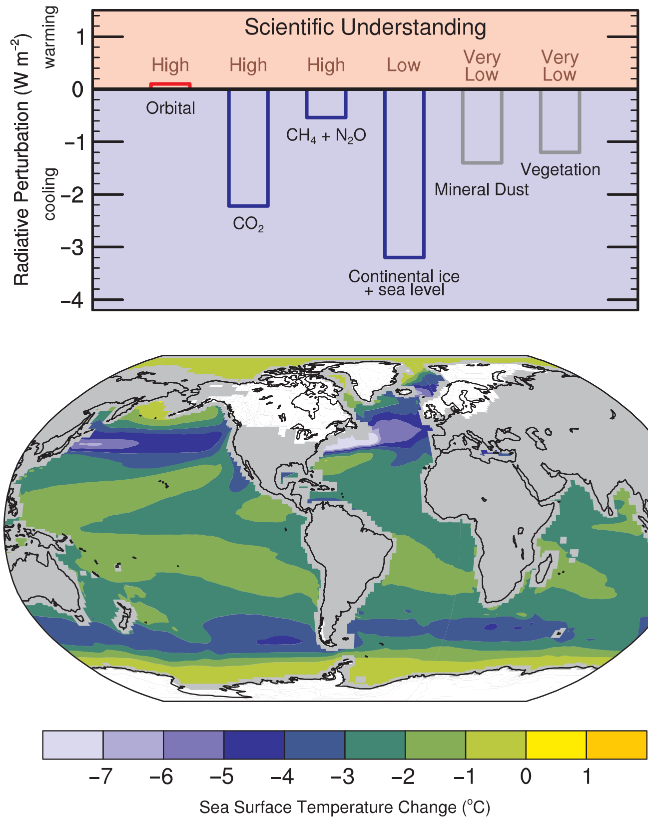


Figure 6.8 Climate of the last glacial maximum, 20,000 years ago. Top shows the radiative forcings that drove the cooler climate, and bottom shows the change in temperature relative to the preindustrial climate.

weakening the greenhouse effect. The radiative forcing from CO_2 was about 2 W/m^2, comparable to the human impact on the greenhouse effect today from fossil fuel CO_2. Methane, another greenhouse gas, was also less abundant in the glacial atmosphere. Another cooling factor is reflection of sunlight back to space by the ice sheets and sea ice. The glacial world was dustier than today, because it was more arid, and the dustier air also reflected sunlight.

The correlation between CO_2 and temperature over the past 650,000 years is a striking visual suggestion of the role that CO_2 plays in climate. This however is an easy figure to oversimplify. For one thing, as shown in Figure 6.8 (top panel), the glacial/interglacial temperature changes are driven by multiple factors, not just CO_2, so in principle the CO_2 and temperature need not be this well correlated, if the other cooling factors were not also correlated together fairly tightly. Also, it is likely that the changes in CO_2 concentration are ultimately driven by changes in temperature. The first few centuries of the transition from the glacial world to the interglacial world, according to ice cores in Antarctica, show the temperature going up before the CO_2 started to rise. This does not mean that rising CO_2 doesn't also drive the Earth to warm. Most of the total temperature change took place after CO_2 began rising. The direction of cause and effect need not be just one way; when causation goes both ways in a loop such as this, we call it a feedback loop. In this case it is an amplifying (positive) feedback.

It is chilling to note that the feedbacks going into the glacial world generally act in the direction of making a cold climate colder; that is to say, they are generally positive, amplifying feedbacks. The gases and the ice and the dust seem to act as amplifiers of the relatively small initial trigger, the wobbles in the orbit of the Earth. If the Earth system similarly amplifies our global warming from CO_2 emission, it will be very bad news.

Last glacial maximum

The last glacial maximum climate provides a quantitative test bed for the climate models used to predict the future of global warming, because the climate changes were large enough to sample a different climate state than today, and because the data are good enough to provide a stringent test of the model performance. This model/data comparison is coordinated within the Paleoclimate Model Intercomparison Project, an ongoing effort. The participants account for ice sheets, and greenhouse gases, but the forcings due to vegetation changes and dust are not yet accounted for in the scenarios that the project is currently using. The coolings predicted by the models are comparable to estimates from the field, if anything perhaps a bit less cooling (in Greenland, for example, or in the tropics), which is what you might expect given that the dust and the land surface changes, both of which would lead to some cooling, are not included. Patterns of vegetation change predicted by the models are comparable with the reconstructions based on pollen data. The overall change in the amount of carbon stored on land in biomass and soils is also in reasonable agreement between models and data. If anything, the models predict too much change in the amount of carbon stored in the land biosphere, suggesting that the land biota models may respond more strongly to CO_2 fertilization than the real world does.

The climate of the glacial world enabled several studies to estimate the climate sensitivity of the Earth, as shown in Figure 6.9. This estimate is consistent with the climate sensitivity derived from the more recent instrumental record or from models, as described at the end of this chapter.

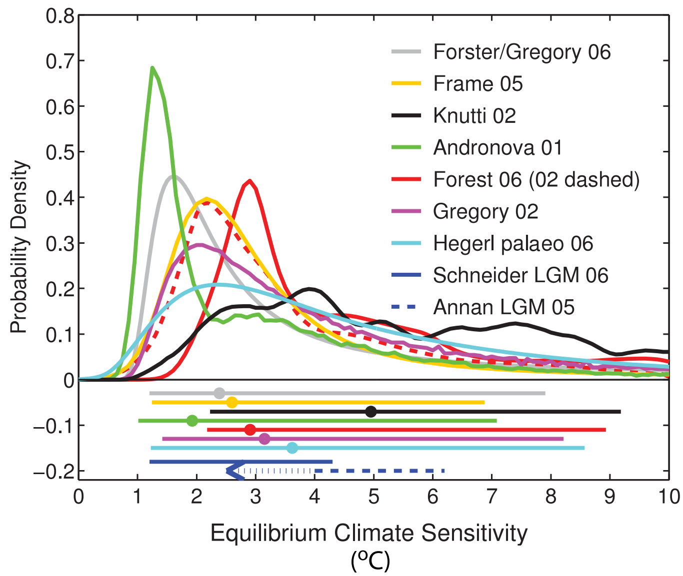


Figure 6.9 Estimates of the probability distribution for the climate sensitivity, how much the Earth would warm in equilibrium under a doubling of atmospheric CO_2 concentration. The estimates from the glacial climate, labeled "LGM", are consistent with the rest, which are based on more recent climate changes. (See IPCC (2007), The Physical Science Basis, Figure 9.20 for references.)

Previous interglacials

The ice core record contains a number of interglacial intervals comparable to ours. The duration of the warm intervals seems to be governed by the precession cycle of the Earth's orbit around the sun, which is the cycle of where in the Earth's elliptical orbit the Northern Hemisphere summer comes. Typically, past interglacial periods lasted for say 10, or 30, or 50 thousand years. Our current interglacial has lasted about 10 thousand years, raising the idea that a new glacial interval might start soon. However, the *Fourth Assessment Report* concludes that it is unlikely that the natural evolution of Earth's climate is going to descend into a glacial climate in the immediate future, say the coming centuries. The Earth's orbit around the sun is nearly circular now, which means it doesn't matter as much where the Northern Hemisphere summer occurs in the orbit, and so the precession cycle is relatively weak. The last time the orbit was in this configuration was about 400 thousand years ago, which was the time of an exceptionally long interglacial interval. The implication for the future is that it is unlikely that any natural cooling such as the onset of an ice age will ameliorate or slow the warming from anthropogenic CO_2.

The last interglacial climate lasted from 130 to 120 kyr ago. The global mean temperature was a bit warmer than today, by about 1 °C. Warming in the high latitudes was much more pronounced, presumably because of a pronounced high-latitude ice albedo feedback. The CO_2 concentration was comparable to the preindustrial value, about 280 ppm. The warmer temperatures may have been the result of the different orbital configuration. The really startling thing about this time was the state of the Greenland ice sheet, which melted in the southern half of the island, raising sea level by about 4–5 meters. This observation provides another data point on our Figure 6.4.

Abrupt climate changes

The ice core records tell of a number of instances where the climate changed very suddenly (Figure 6.10). One definition of "abrupt" might be a climate transition that is much faster than the change in the forcing that drives it, a sudden flip between two relatively stable regimes. Another definition might be a climate transition that is faster than the time scales of adaptation, for example how long it takes to move a forest. An abrupt climate change may take just a few years, and the new climate may persist for a thousand years.

Between 70 and 30 kyr ago there was a series of abrupt climate changes of a class called Dansgaard–Oeschger events. These are clearest in the Greenland ice core data but are also evident from other parts of the world. For example, atmospheric methane concentration decreased, indicating that the climate changes reached into the swamps in the tropics. The D-O events have a well-defined cyclicity about 1,500 years long, in a sawtooth pattern of slow cooling punctuated by sudden warming. The mechanism that caused the D-O events is still unclear, but tracers of ocean salinity and deep circulation point to changes in the deep ocean circulation and sea ice in the North Atlantic.

The Laurentide ice sheet collapsed several times during glacial time generating abrupt climate episodes called Heinrich events, in which the ice sheet collapsed into an "armada of icebergs" (Chapter 4). The icebergs carried pebbles and rocks that originated from the region of Hudson's Strait, spreading them over the entire North Atlantic sea floor as far south as Spain. Enough ice calved into the ocean to raise sea level by as much as 15 meters in one to ten centuries. The fresh water discharge from the ice was enough to

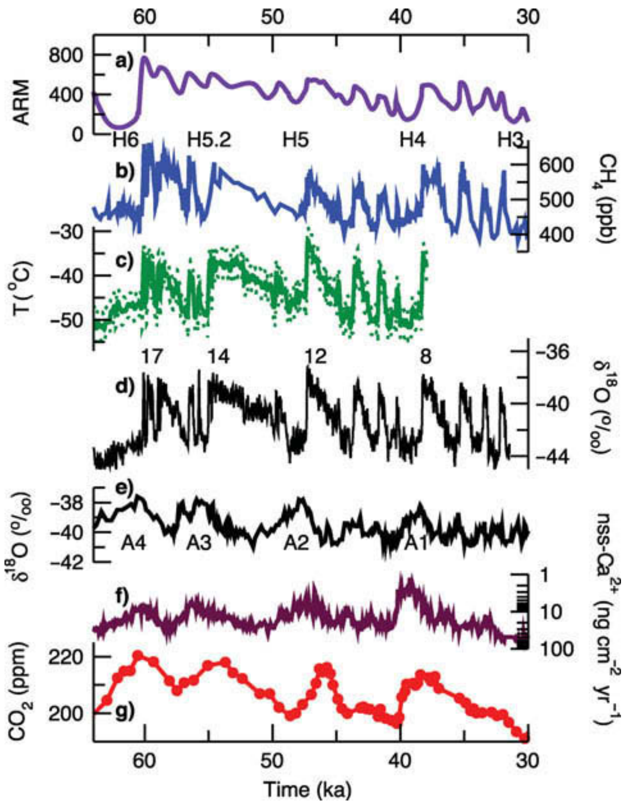


Figure 6.10 Ice core data from the time period from 30 to 70,000 years ago show abrupt climate changes. The abrupt changes are apparent in the atmospheric CH_4 concentration (curve b, driven by rainfall and area of freshwater swamps), and in the local temperature in Antarctica (curves c and d).

completely stop the overturning circulation in the North Atlantic, leading to climate impacts worldwide. Our understanding of how the Laurentide ice sheet produced so many icebergs so quickly is too rudimentary to predict whether the Greenland ice sheet could similarly collapse in the future.

Other abrupt climate events were triggered by direct fresh water dumps into the North Atlantic Ocean. These include the Younger Dryas and the 8.2 kyr climate events; both may have been caused by the sudden spilling of large ice-dammed lakes in North America. The IPCC considers it likely that business-as-usual climate change could slow down the overturning in the coming century, but estimates less than a 10% risk of a major abrupt climate transition, caused by human emissions, in this century.

Our current interglacial period

The climate of the last ten thousand years has been much more stable than the turbulent climate of the glacial world. Atmospheric CO_2 concentrations reached 260 ppm after the deglaciation, and rose slowly to 280 ppm in 1750. This period of stability is called the Holocene.

Variations in climate were apparently regional rather than global in scope (Figure 6.11). Models are able to simulate many of these patterns as resulting from slow changes in the orbit of the Earth. There do not appear to be any global cycles of climate through the Holocene. An apparent 1,500-year cycle from some North Atlantic climate records does not seem to correlate with climate changes elsewhere in the globe, which all seem to march to their own drummers. Warmth in one part of the globe is typically balanced against cooling someplace else, driven by changes in how the winds or the ocean currents carry heat around the world. In contrast with this, the warming of the past few decades has affected nearly every place on the surface of the Earth.

Monsoon rainfall patterns, such as those in Asia, Africa, and the American southwest, seem to have a strong susceptibility to change, both in coupled

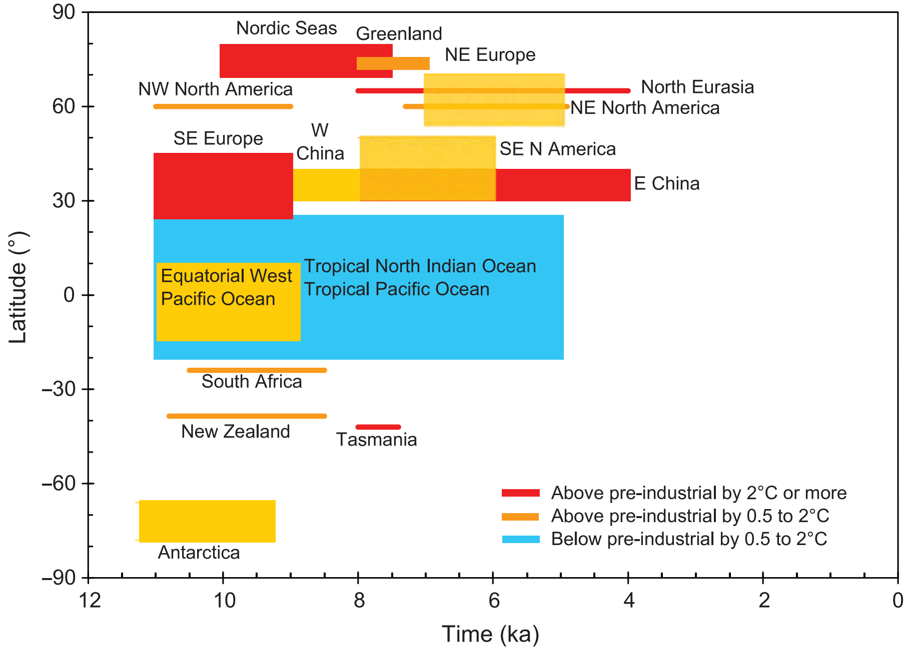


Figure 6.11 Times and latitudes when the Earth was warmer or cooler than present through the last 12,000 years.

climate models and in the real world. Changes in the land surface, such as the loss of vegetation, act to amplify the effects of a monsoon change, so that changes in monsoon intensity tend to be abrupt, even in response to a slow change in forcing such as a shift in Earth's orbit around the sun. An example is the drying of the Sahara, which was a relatively green savanna landscape until it turned into a desert around five thousand years ago (Figure 6.12).

The last 2000 years

Global and regional climates varied significantly through the time period of the last 2,000 years, as documented by tree rings and other "proxy" forms of temperature reconstruction. The *Third Assessment Report* in 2000 highlighted the first such reconstruction, of the Northern Hemisphere, by Michael Mann and his colleagues in 1999. This curve later became known as the "hockey stick" due to its shape. The 2000 IPCC report concluded that the twentieth century was likely to have been the warmest of any century during the past 1,000 years, that the 1990s were likely the warmest decade, and that 1998 was likely the warmest year. "Likely," in IPCC parlance, means at least a 66% chance of being true.

The "hockey stick" became a symbol for the IPCC report, and those skeptical of global warming challenged it on many fronts. The hockey stick has been reproduced by independent researches since then, and a special panel of the US National Academy of Sciences investigated the various challenges to the Mann *et al.* reconstruction and vindicated it in 2006. More importantly, science progressed, and the *Fourth Assessment Report* now includes a dozen different reconstructions of the past millennium (Figure 6.13). All of these support the original IPCC conclusions from the original hockey stick curve. Based on the newer reconstructions, the IPCC now goes further and concludes that the average Northern Hemisphere temperature during the second half of the twentieth century was very likely higher than during any other 50-year period in the last 500 years, and likely the highest in at least the past 1,300 years.

Models are able to simulate the evolution of climate through the last two millennia, with some caveats. One is that the changes in solar heating through time are uncertain by about a factor of three. During the Little Ice Age, there were periods of several decades at a time when the sun had no spots. Such a condition has not occurred since satellite solar intensity measurements have been available, just about the last twenty years. So it is impossible to know directly how weak the sun was during the Little Ice Age. However, there is indirect information about solar intensity from radioactive elements

Figure 6.12 Rock art from the mid Holocene period bears witness to the fact that the Sahara was much wetter then. The photo was taken at Wadi Draa in Morocco, where hunters would have once waited for game that is not found in the bone-dry valley today, seen in the background.

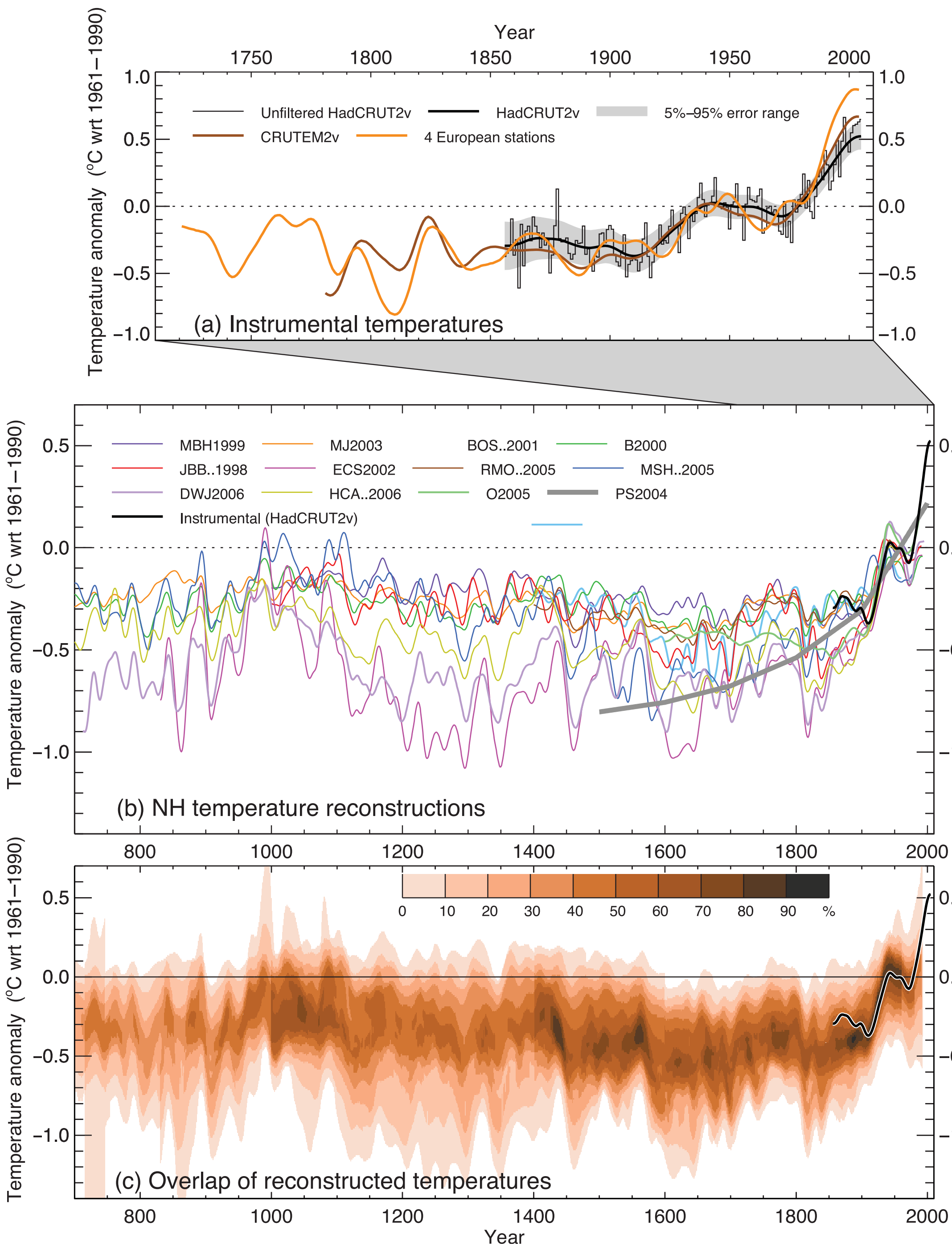


Figure 6.13 Reconstructions of the average temperature of the Northern Hemisphere over the past 1,300 years.

produced by cosmic rays. When the sun is bright, its magnetic field shields the Earth from cosmic rays, and the production of carbon-14 and beryllium-10 slows down. The concentration of these isotopes in ice cores provides a record of the past intensity of the sun.

The climate impact of volcanic eruptions in the past is not known very precisely, either. Ice cores preserve evidence of volcanic dust and aerosol deposition with the ice, but they provide no real information about how long the aerosol remained in the atmosphere (typically up to a few years), or exactly how much sunlight it caused to be scattered back to space.

In summary, the climate changes in the past 2,000 years can be explained as resulting from natural changes in the radiative forcing of climate, as best as we can determine the past forcings. In contrast, the warming of the past few decades cannot be explained solely by natural changes in climate forcing; the only way to explain the present warming is with rising CO_2.

The instrumental period

Good climate records from direct measurements, thermometers, and other meteorological devices, have been available since about the year 1860. The global average temperature from these measurements is plotted as the black line in Figure 3.18, on both panels. The record shows an overall warming trend throughout the last century, with a period of mild cooling from 1940 to 1970, and strong warming since about 1970. The figure also shows the results of an extraordinary array of thirteen independent climate models from scientific groups around the world. The models differ from each other in their details, but the climate forcings that the models are subjected to are all the same, specified by IPCC as part of their model intercomparison process. There are two different types of model runs here, one set in the top panel of the figure that includes the human perturbation on the Earth's radiation balance (greenhouse gases and aerosols), and another in the bottom set that does not. Without exception, the model runs that include the human influence on climate do a pretty good job of simulating the warming in the last few decades, while the "natural" models fail to get the warming right. The comparison between models and observations is broken down into regions in Figure 3.19. In general, warming has been more intense on land than over the ocean, and more intense in high latitudes than in low latitudes. This is true for models as well as observations. The models are doing a nice job of reproducing what is observed.

Several telltale "fingerprints" of greenhouse gas forcing are found in the instrumental climate record. One is that the stratosphere is cooling while the ground surface warms. A greenhouse gas has that effect, because it acts like a radiator fin for the stratosphere, allowing heat to escape. If the warming were due to an increase in solar irradiance, we would expect the stratosphere to warm along with the troposphere. The simultaneous warming of nearly the entire surface of the Earth is unprecedented in thousands of years, consistent with atmospheric CO_2 concentration that is higher than it has been in over half a million years.

Summary

The evidence, from the deepest past all the way to the most recent historical times, hangs together in support of a key role for atmospheric CO_2 in regulating climate. Millions of years ago, the Earth was tropical to the poles, and there is evidence that CO_2 concentrations were substantially higher then. The Paleocene Eocene thermal maximum event, 55 million years ago, was a strong warming in response to a rise in atmospheric CO_2 concentration analogous to fossil fuel CO_2 release. The Earth stayed warmer than it had previously been for a hundred thousand years.

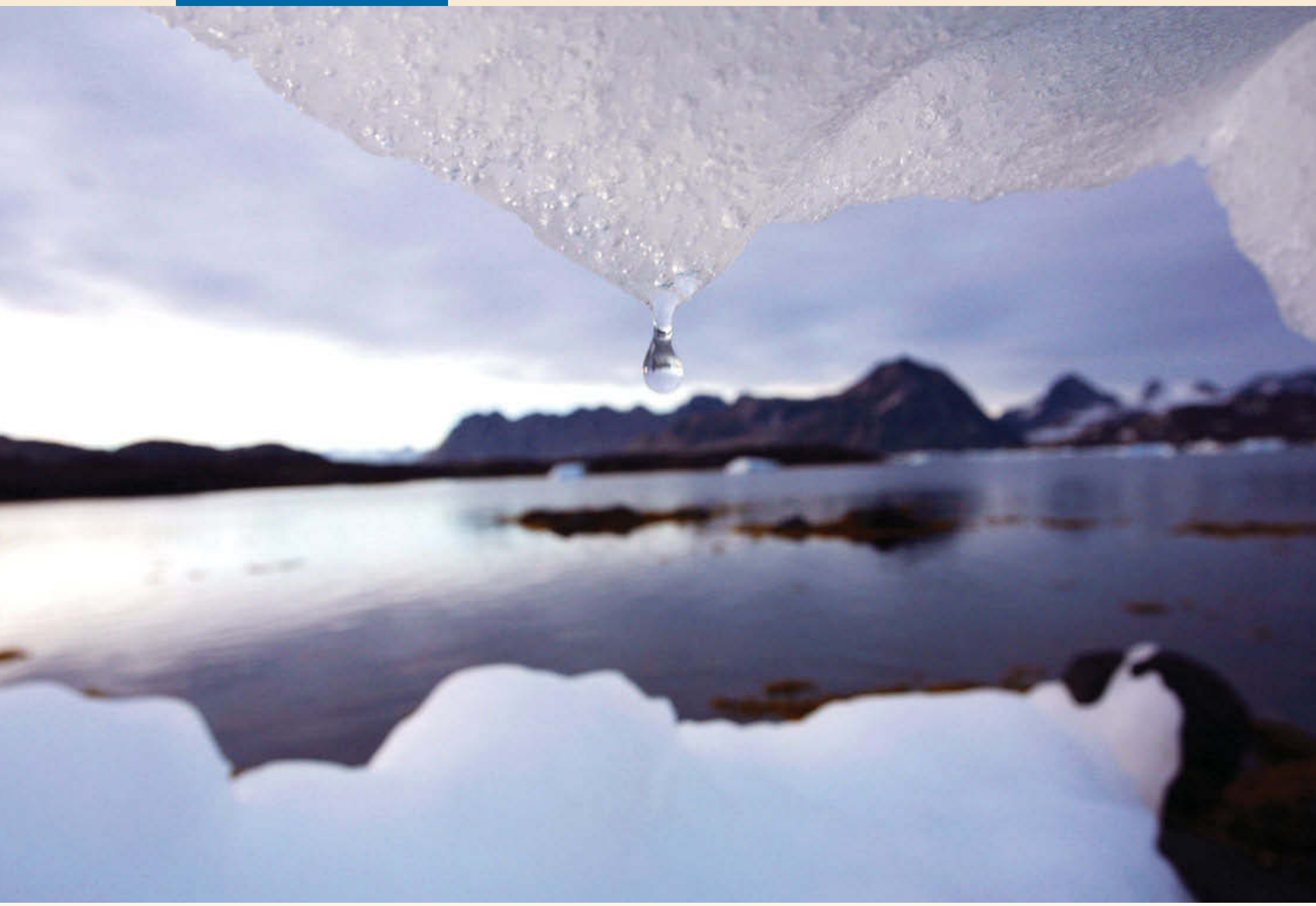
As the atmospheric CO_2 concentration gradually fell over the past tens of millions of years, the Earth cooled and ice sheets started to form. The climate of the last two million years has been dominated by the growth and melting of ice sheets, in particular in North America and Europe. These glacial cycles were triggered by variations in the Earth's orbit around the sun, but they are exacerbated by systematic changes in the CO_2 concentration of the atmosphere. Analysis of Earth's climate through the glacial cycles tells us that climate can affect atmospheric CO_2, and also that atmospheric CO_2 affects the climate.

The glacial world also tells us that Earth's climate has the potential to flip abruptly from one mode of operation to another. Abrupt regional climate transitions in the past are only dimly understood, which means that it would also be difficult to predict any future abrupt changes in advance. An abrupt climate change can take just a few years, and the new climate might be stable for a thousand years. Natural climate changes in the past were mostly driven by changes in forcing that are very slow, such as orbital variations (10,000 years and longer) or changes in the intensity of the sun (centuries). There are faster climate forcings such as volcanic eruptions and the 11-year sunspot cycle, but they are small. Yet the natural changes in climate during the glacial time tended to be much faster than these slow forcings, because the Earth's climate is a nonlinear system that can flip between multiple stable states. In contrast to the past, the climate forcing in the future, the rise in atmospheric greenhouse gases, is taking place on a much faster time scale of decades.

We are now in an interglacial climate interval, an oasis of stability compared to the bluster of the fierce glacial climate. There have been climate changes in the past thousand years, the most well known of which are the Little Ice Age (1350–1700) and the Medieval warm period (800–1300). These times correlate with apparent changes in solar luminosity. The past century has been one of warming mostly, in particular since about 1970. In contrast with the Little Ice Age and Medieval warm times, this last burst of warming since about 1970 cannot be blamed on the sun, but can be explained quite well as the result of rising greenhouse gas concentrations in the air.

The study of past climates serves as a reality check for the climate models used to forecast the Earth's response to our CO_2 release. The past gives us no reason to doubt the fidelity of the forecast for the future; in fact the past strengthens the forecast.

7 What the future holds



Only the final two chapters – Chapters 10 and 11 – of the IPCC Working Group 1 report deal with the future development of our climate. Although only a small part, this is the part of IPCC reports that tends to attract the most media and public attention. The numbers for future warming and future sea level rise are the most widely quoted statements from the IPCC reports, and leaked (and often wrong) numbers circulated in the media months before the report was finalized and published. A great deal of futile (since often erroneous) media speculation and analysis was devoted to the question of whether the IPCC had revised the numbers up or down since the last report (we will come to this issue below). Of course, the media deal with news, and anything that says ". . . greater than previously expected" or ". . . less than previously expected" is "news." On the other hand, "climate is warming just as previously expected" just does not sound like a newspaper headline.

The somewhat one-sided public interest in the future is perhaps one reason why the public tends to think that climate science consists mostly of computer modeling. In reality, painstaking collection and analysis of data is a much bigger part of climate science, and this is reflected in the chapters of the IPCC report dealing with observed past (and ongoing) changes in the climate system. For the future, however, models are indeed all we have. This is why to us scientists the future is not as interesting as the past. Only about the past do we have real data that show what has happened to the climate system, on which we can base a scientific analysis and understanding. Only with data from the past can we test our models and check where they perform well and where they still have their weaknesses. Only because climate models have been tested on the past do we have confidence that they can also give us useful information about the future. For example, many models have now been tested on how well they can simulate the climate of the last ice age (see Chapter 6).

Scenarios or predictions?

Climate models are our crystal balls to get a glimpse of the future, an age-old dream of humanity. But what they offer is not a *prediction* – rather, it comes as a bundle of *scenarios*. It is important to understand the difference. Natural scientists can in principle not predict the future of climate, because it depends on human actions. How much warming we will see in the next hundred years or so strongly depends on how much more carbon dioxide we put into the atmosphere. That is a matter of choice, not a pre-determined future that can be calculated today. What we can do, however, is calculate scenarios in "what if" style: what effect would it have if we dig, say, another 500 billion tons of carbon up from the Earth's crust and put it into the air? And what if we emit a thousand billion tons? This type of scenario can inform the decisions that we take about the future.

Such scenarios only calculate the effect of specified human emissions – they usually do not include natural factors of climate change, such as future changes in solar activity. One reason is that we simply cannot predict changes in solar activity, future volcanic eruptions, or meteorite strikes. But more importantly, human influences on climate will very likely outstrip any natural changes by far within this century. Solar activity may go up or down as it has done in past centuries – but this has only caused changes of a few tenths of a degree in global temperature in the past, while we are now talking of human-caused warming of several degrees. And volcanic eruptions will occur, but will likely only have a small and passing effect, like the Pinatubo eruption of 1991 did. We humans are relegating such natural climate changes to a side show in the twenty-first century – unless something really unexpected happens. And regardless of their size – we cannot do anything to stop natural climate changes. But this should not stop us from taking full responsibility for the changes we are causing ourselves.

How future climate is computed

Before we reveal the results of the future projections, we should briefly explain how they are obtained. First, the scenarios for the *emissions* of various greenhouse gases (how much we put into the air each year) are converted into future *concentrations* of these gases (how much is in the air at any given time). For CO_2, this is done using carbon cycle models. These take into account that not all CO_2 that we blow through our smoke stacks and car exhausts remains in the atmosphere – some is taken up by the oceans and biosphere over time. In the last decade (the 1990s), only about 40% of the CO_2 we emitted remained in the air. We have caused emissions of 29 billion tons of CO_2 per year (23 billion tons due to fossil fuel burning and cement production, 6 billion tons due to deforestation), but the amount of CO_2 in the atmosphere has increased by only 12 billion tons. This "airborne fraction" will not necessarily remain constant in the future, though. How the carbon cycle will respond involves some uncertainty, so that the future CO_2 concentration is somewhat uncertain, even if emissions were known.

Not only CO_2 is included in these emissions scenarios; they also include other gases like methane, nitrous oxide and various synthetic gases such as chlorofluorocarbons (CFCs – the very gases also causing the ozone hole, apart from adding to global warming). All gases are sometimes combined as a "CO_2 equivalent concentration" – that's just the CO_2 concentration that would have the same climatic effect as the given mixture of all these gases. We have currently reached a CO_2 concentration of about 380 ppm, but if we include the effect of the other greenhouse gases we have added, overall it is as if the CO_2 concentration had already increased to 450 ppm. These scenarios further include emissions of aerosol particles ("smog") which have a cooling effect on climate. The emissions scenarios are described in detail in a special IPCC report published in 2000, called the *Special Report on Emission Scenarios* or SRES. Economists and other experts have put quite a bit of thought into constructing these scenarios as they have to be consistent. For example, a scenario that involves burning a lot of coal in power plants in developing countries will involve not only high CO_2 emissions, but also the corresponding high sulfur aerosol emissions which will offset part of the warming.

The future concentrations of various greenhouse gases and aerosols are then fed into climate models. These models start typically in preindustrial times in the eighteenth or nineteenth centuries, and they simulate climate driven by observed greenhouse gas and aerosol data and natural climate drivers such as solar activity up until the present. There they switch to being driven by the concentrations from the various scenarios running into the future, up to the year 2100 or longer. The models use equations of thermodynamics, hydrodynamics and others to calculate how climate will change. They solve these equations on a grid covering the Earth. In such a model, the sun rises each morning and sets at night, ocean currents flow, winds blow, clouds form, rain and snow fall, and so on, controlled by the laws of physics, just like on the real planet Earth. They are thus physics-based models, not statistical models. This point is often misunderstood by lay persons and journalists, who tend to think that climate models predict the future somehow by feeding in temperatures from the past and extrapolating those into the future.

There are different types of climate models. Some are very simple models based on equations that describe just the most basic aspects of the planetary heat balance. And many are highly sophisticated "general circulation models" or GCMs, which simulate weather and climate around the world in great detail. In between is a growing group of so-called "intermediate complexity models", aiming for a compromise between realism and computational speed, to allow many long-term simulations. All these models nowadays include at least atmosphere, ocean, and sea ice. Then there are specialized models to calculate particular aspects of climate change, such as the behavior of mountain glaciers. The full range of available climate models has been used for the future projections shown in the IPCC report. The same future scenarios have been simulated with a lot of different climate models (up to 21 different GCMs), developed and run by competing groups of scientists in different laboratories and countries. This kind of "ensemble" of model simulations is prepared by the different groups especially for the IPCC reports. This is an exceptional case in that the IPCC instigates and coordinates a research activity; otherwise its job is merely to summarize and assess scientific work performed independently by researchers around the world and published in scientific journals.

The "ensemble" approach of using many models to compute the same things has two advantages. First, the differences between the model results provide a way to estimate the uncertainty in the calculations. This is behind many of the quantitative uncertainty statements found in the report, e.g., when it is stated that the warming will be "very likely" in a certain range – very likely meaning with 90% probability. And second, in many graphs the average of all model results is presented. There are good theoretical reasons why the average over many models should provide more accurate and reliable results than one individual model. You may wonder: wouldn't it be better to just show results of the best model? The problem is that we do not know what the best model for future climate is. We cannot even name a clear winner for reproducing present-day climate, where we have data to check the performance, since all models have different strengths and weaknesses. One model may perform poorly in the stratosphere but do well on clouds and rainfall patterns; another model may perform particularly well in the tropics but show weaknesses for high-latitude processes, and so on. Nevertheless, model comparison and evaluation exercises do reveal quality differences between models, and it is tacit knowledge amongst modelers which models are quite good and which ones not so. The IPCC has thus far shied away from excluding models that do not pass certain quality checks. It is plausible that an ensemble of models where poorly performing models have been eliminated would provide even better results than an ensemble of all models, and we believe that this should be seriously considered for the next IPCC report.

How warm will it get?

After such a lot of prelude, here are the long-awaited numbers! Table 7.1 gives the globally averaged warming over this century. For the lowest emission scenario, the B1 scenario, the expected warming ranges from 1.1 to 2.9 °C – this is for the period 1990 to 2095, so it comes on top of the 0.6 °C warming already seen up to 1990. For the highest emission, warming ranges from 2.4 to 6.4 °C. Given the uncertainty, forget about the decimals: the bottom line is that we will end up somewhere between 2 and 7 °C warmer (in global mean!) than preindustrial climate by the end of this century. Some of these scenarios are pictured in Figure 7.1.

The IPCC does not say which of these scenarios is more likely – that is because the scenarios involve different economic and policy choices. Which one we will follow depends on us, and it is not the role of the IPCC to judge how likely certain human economic or policy choices are; it is to provide scientific background information that helps to make these choices. On the other hand, the IPCC did not consider implausible scenarios, with economic developments way outside past experience. Unfortunately, neither did the IPCC consider

Table 7.1. **Projected global average surface warming and sea level rise at the end of the twenty-first century**

Case	Temperature Change (°C at 2090–2099 relative to 1980–1999)[a] Best estimate	*Likely* range	Sea Level Rise (m at 2090–2099 relative to 1980–1999) Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	0.6	0.3–0.9	NA
B1 scenario	1.8	1.1–2.9	0.18–0.38
A1T scenario	2.4	1.4–3.8	0.20–0.45
B2 scenario	2.4	1.4–3.8	0.20–0.43
A1B scenario	2.8	1.7–4.4	0.21–0.48
A2 scenario	3.4	2.0–5.4	0.23–0.51
A1FI scenario	4.0	2.4–6.4	0.26–0.59

Notes:

[a] These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth System Models of Intermediate Complexity and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs).

[b] Year 2000 constant composition is derived from AOGCMs only.

scenarios that include deliberate and successful emission reductions made to reduce climate warming. All of the SRES scenarios are so-called “non-mitigation” scenarios: they are meant to tell us what might happen if we do not take political action to combat global warming. Of course, to make informed choices, society and policy makers also want to know what happens if we *do* take action to reduce emissions. Preparations are already underway to include such scenarios in the next IPCC report; until then, it has to be considered a serious shortcoming of the IPCC that results for mitigation scenarios have not been systematically assessed, despite the fact that several such scenarios are discussed in the scientific literature (see Chapter 9).

The yellow line in Figure 7.1 is not a scenario – it is an illustration of what would happen if we immediately stopped the further increase of greenhouse gases in the atmosphere. To stop the rise in CO_2 concentration, the *emissions* would need to be cut immediately by about half (remember the airborne fraction discussed above); that’s why this is not a realistic scenario but merely a thought experiment. In this case, global warming would immediately slow

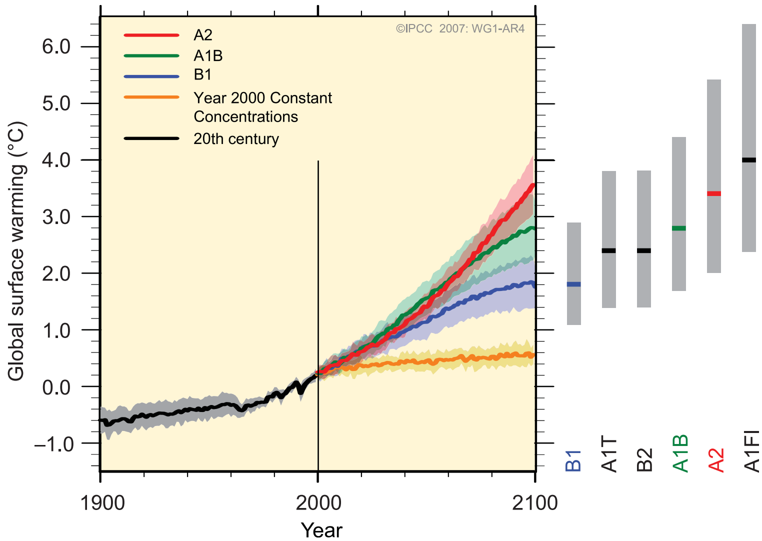


Figure 7.1 The red, green, and blue lines (with shaded uncertainty ranges of one standard deviation) show future warming for the emission scenarios A2, A1B, and B1, respectively, based on many simulations with a range of climate models. The yellow line shows the small future warming that would still arise if greenhouse gas concentrations were kept constant at their year 2000 levels. For 1900–2000, observed global temperature is shown for comparison. To the right of the graph, the bars show warming by the end of the century for additional emission scenarios, as well as a more comprehensive analysis of the uncertainty ranges (gray) – these depict the numbers given in Table 7.1.

down, and we would only expect a modest warming of about 0.6°C this century. Sometimes this is called the "commitment", since in a way it's the climate change we've committed to by the rise of greenhouse gases we have already caused. That's not strictly true – by cutting our emissions to zero, greenhouse gas concentrations could be made to fall over the next decades (due for example to the ocean uptake of CO_2), so in that stricter sense we are not committed to further warming.

Let's discuss the scenarios a bit more. Why is the temperature rise still so uncertain, even for a given emission scenario? There are three main reasons. The first is the uncertainty in *climate sensitivity*. That's a number that tells us how sensitive the climate system is to a change in radiation budget, or specifically to a doubling of CO_2 concentration. This number is uncertain because of feedbacks that can amplify or weaken the climate response. These feedbacks work through changes in snow and ice cover, in cloud cover and in water vapor content of the air. All these factors change in a changing climate and then in turn affect the climate: they “feed back” on it. The largest uncertainty comes from cloud cover changes.

The best estimate for *climate sensitivity* is a central point of each IPCC report, intensely debated by the experts. In the first, second and third reports, the uncertainty range for climate sensitivity was always given as 1.5–4.5°C, and there has never been enough convincing evidence to narrow down this range. Now, the IPCC has changed the range for the first time: in the current report it is given as 2–4.5°C, with a best estimate of 3°C.

There are many different approaches to determine climate sensitivity, using climate models, data from twentieth century warming or distant climatic changes in Earth’s history, or a combination of these. Using models has the advantage that it is based on physical understanding of the individual feedbacks, which is continually being refined. Using past climatic data has the advantage that we learn from how strongly the climate system has actually responded in the past, so we see the overall effect of all feedbacks, whether we understand them or not. The IPCC report lists thirteen studies that have attempted to constrain climate sensitivity, and practically all arrive consistently at a best estimate near 3°C. That is remarkable, given the very different methods, models, and data sets used. However, how tightly this number can be constrained depends on the method. For example, it is possible to construct physically plausible models with very high climate sensitivities (well beyond 5°C), but data from Earth’s history strongly speak against such a sensitive climate – it would have made the last ice age, with its low CO_2 concentration, even colder, much colder than is supported by paleoclimatic data (see Chapter 6).

The climate sensitivity applies to a climatic equilibrium, reached after a very long period (thousands of years) of unchanging, doubled CO_2 concentration. In reality, greenhouse gas concentrations and climate evolve over time, and this adds a second type of uncertainty: how fast does the climate catch up with the change in greenhouse gas concentrations? This depends almost entirely on the behavior of the oceans, because they can store such a huge amount of heat that it takes many decades for them to warm up (see Chapter 5).

The third and final uncertainty in these future projections comes from the carbon cycle feedback. As mentioned above, we don’t know for sure how much of the CO_2 we emit will be taken out of the air by oceans and forests. Forests and soils may even start to release CO_2, rather than taking up some: they may turn from sink to source as they come under increasing climate stress and suffer from droughts, pests and fires. For the A2 scenario, for example, this could add up to 1°C warming by the end of the century, and

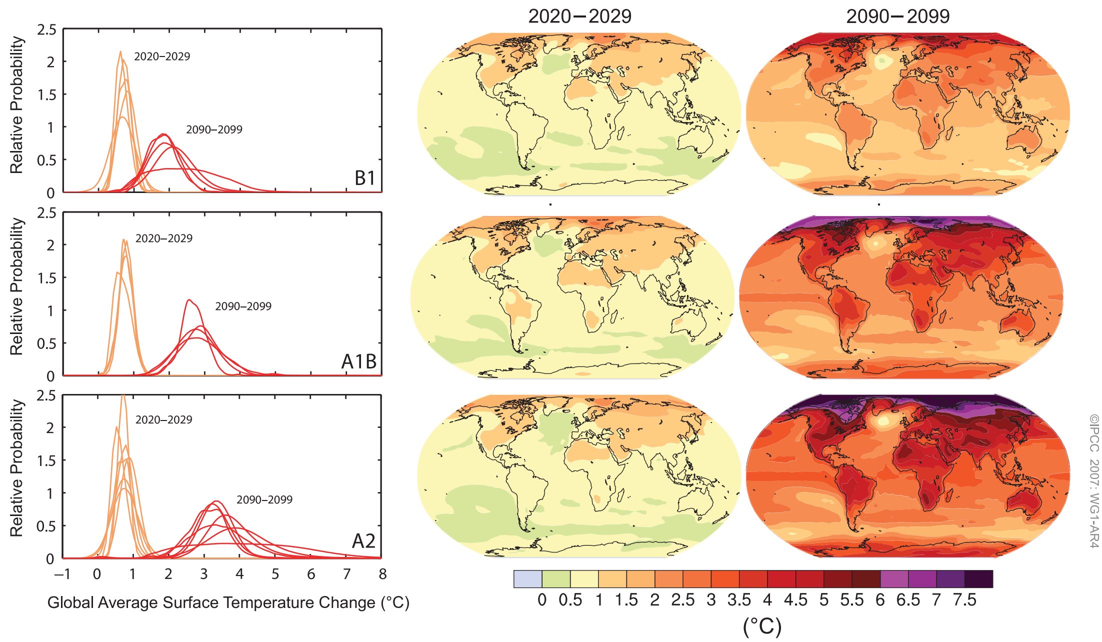


Figure 7.2 Projected surface temperature changes for the late twenty-first century relative to the period 1980–99, for the B1 (top), A1B (middle) and A2 (bottom) emission scenarios. Note the greater warming over land areas and the minimum of warming over the northern Atlantic.

this uncertainty is included in the range given in the table. Scientists have in recent years become more pessimistic about this carbon cycle feedback; that is why the upper end of the projected warming is higher than in the previous report (where the maximum warming until 2100 was given as 5.8 °C).

Looking only at globally averaged temperatures can give quite a misleading picture of future warming. Figure 7.2 shows maps of the expected warming, and it is immediately clear that it is not uniform. The greatest warming is expected in the Arctic, with about twice the global average. Also clear is the greater warming over land than over the ocean, which increases further from the coasts. Humans live and grow food on land, so the warming of the land areas is much more relevant than the global mean number for us. The smallest warming is expected over a region of the northern Atlantic; this is due to a slow-down of the Atlantic ocean circulation in the models and is a feature also seen in observed temperature trends (compare discussion in Chapter 3 and Figure 3.3).

Few people will be surprised that extremely cold weather and frost days will become less frequent, while hot spells become more frequent in a

Figure 7.3 The European heat wave in summer 2003 not only caused over 35,000 human casualties but was also associated with a major drought and large agricultural losses. This photo was taken in Lorraine in northern France, normally a fertile farming region.

warming climate. This is indeed what the models predict. More intense, more frequent, and longer-lasting heat waves are expected in the future. Events like the big European heat wave of summer 2003 (which caused a major disaster with at least 35,000 fatalities) will become more common; hopefully adaptation measures will make us better prepared so that loss of life will be not as bad as in this example. Although it still cannot be very well quantified just how much the incidence of extreme events will increase, studies suggest that the changes could be surprisingly large. This is partly because there are some factors that amplify extremes. For example, in a heat wave the soil tends to dry out. This leads to even worse heat, because the cooling effect of evaporation fizzles out once the soil moisture is gone. As an indication of the size of the changes, one study found that, towards the end of this century, extremely hot summers would occur at least 20 times more often than now in almost all land areas, in some regions even 100 times more often. On the other hand, cold air outbreaks in winter in one study declined by 50–100% in most areas.

Rainfall changes

Precipitation changes will probably have a bigger impact on human society and ecosystems than temperature changes. Plants need water to grow. Our society is heavily dependent on secure water supplies, not only for agriculture. On the other hand, many human settlements are vulnerable to flooding. In Chapter 3 we have seen that significant changes in rainfall have already been observed. So what will the future bring?

Figure 7.4 shows how future patterns of rainfall are expected to change. The maps show that the already dry subtropical areas are expected to get drier, while the deep tropics and the high latitudes are expected to get wetter. In many mid-latitude regions (for example in the northern half of Europe) the change depends on the season: drier in summer (when farmers need the rain), wetter in winter (when the risk of flooding increases). Regions that may especially suffer from reduced rainfall are the Mediterranean and southern Africa. In equatorial east Africa, rainfall will increase according to most models, and the same holds for the summer monsoon regions of southern and south-eastern Asia.

With precipitation, regional differences are particularly important, as precipitation will increase in some regions but decrease in adjacent areas. Projections are limited by the coarse resolution of current global climate models, which typically have a grid box size of 200 km or so and provide useful results only on scales larger than about a thousand kilometers (see Figure 1.4). Basic physical mechanisms are often well understood and robust across all models – for example, the subtropics get dryer and subpolar regions wetter. But large uncertainties, even in sign, then occur near the boundaries of these regions, as these borders are placed somewhat differently in different models. Various techniques are used to “downscale” climate model results, either with high-resolution regional models or with statistical techniques linking the large-scale climate changes to local climate observations. Such downscaling is crucial for example in mountain areas, where the local topography has a big impact on local rainfall and snowfall patterns.

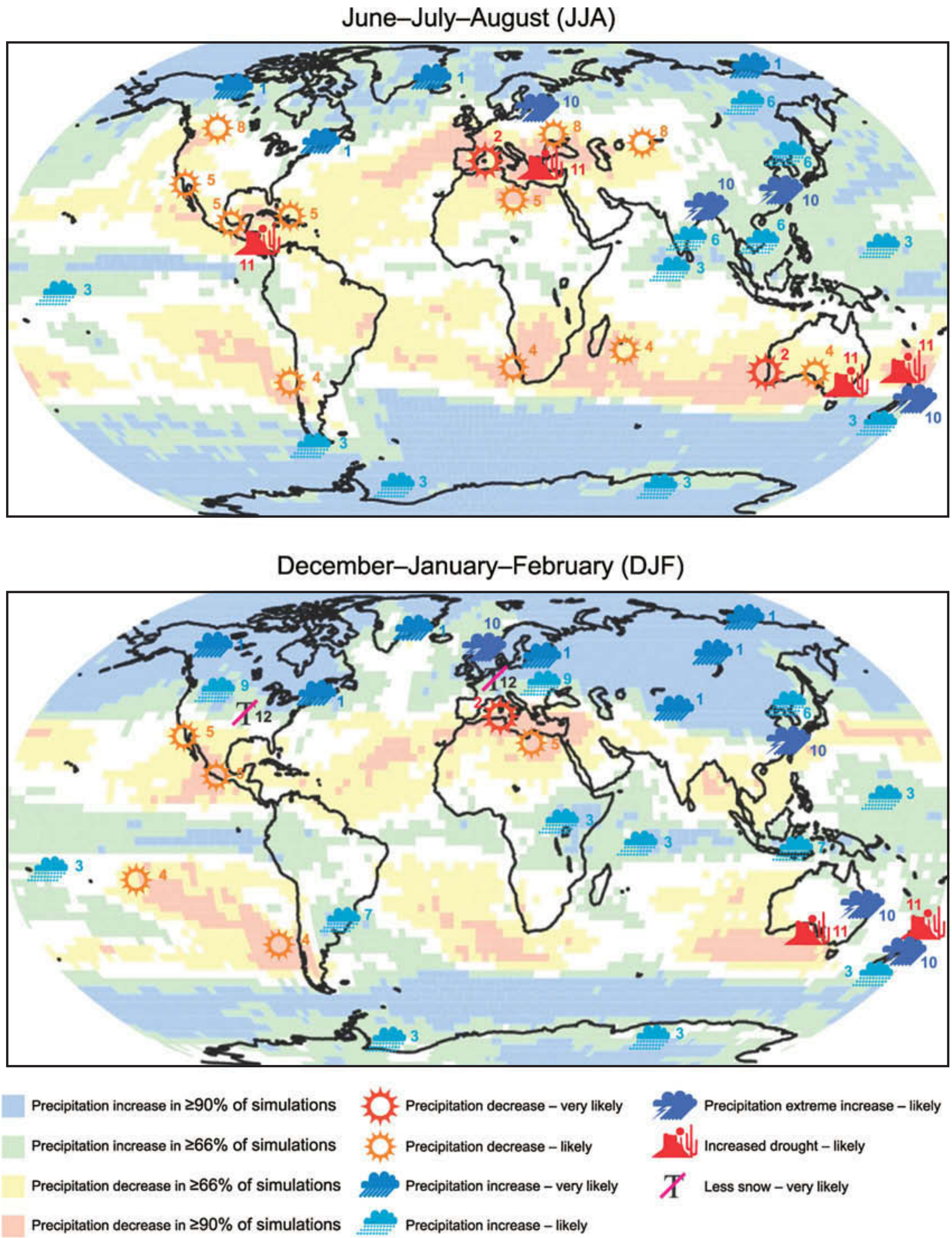


Figure 7.4 Summary graph of robust findings on regional climate change for mean and extreme precipitation, drought, and snow.

Regional results are discussed in detail in the final chapter of the IPCC report for Africa, the Mediterranean and Europe, Asia, North America, Central and South America, Australia and New Zealand, the Polar Regions, and Small Islands. Space does not permit us to go through all these regions here, but as an example of the type of information that can be provided we show the projected summer rainfall changes for North America in Figure 7.5. In high latitudes, rainfall is expected to increase substantially, while in low and middle latitudes a large decrease is expected.

But once again these are merely the average changes, and at least equally important are changes in extremes. Unfortunately, changes in future rainfall extremes are not nearly as well understood as some other aspects of climate, so the uncertainties are quite large. The models indicate that our future world could be plagued by greatly increased drought problems, leading to a die-off of vegetation in some regions. The land area affected by extreme drought conditions could increase from presently about 1% of the land surface to about 30% of the land surface at the end of this century. Experience with earlier, natural climate changes sounds a warning bell, too: in the mid-Holocene, some four to five thousand years ago, North America suffered severe drought conditions for centuries, while climate was locally warmer due to a different configuration of the Earth's orbit (see Chapter 6).

The flip side of droughts is floods resulting from large amounts of rain falling over a short time. A recent example is the severe flooding in Great Britain in June and July 2007. In England and Wales the period May to July in 2007 was the wettest (406 mm rainfall) since records began in 1766, breaking the previous record of 349 mm by far. This coincided with unusually warm temperatures. Such flooding events are expected to increase in a warmer world, as we discussed in Chapter 3. The models show that future rain will not be as evenly distributed over time as in the past – it will come, to a larger part, in intense heavy falls, with long dry spells in between. There are thus three reasons why, paradoxically, with global warming, the risk of *both* drought and severe flooding will likely increase. First, the already wet regions tend to get wetter and dry regions tend to get dryer as the normal water cycle of our planet is enhanced. Second, in many land areas, rainfall increases in the wet winter months but decreases in the dry summer months. And third, even in the same region and same season, both extremes can become more frequent as short bursts of heavy rain are interspersed with increasingly long dry spells. As with drought risk, the increase in flood risk is expected to be large (see Figure 7.7), although it is still hard to predict exactly how much the rainfall extremes will change.

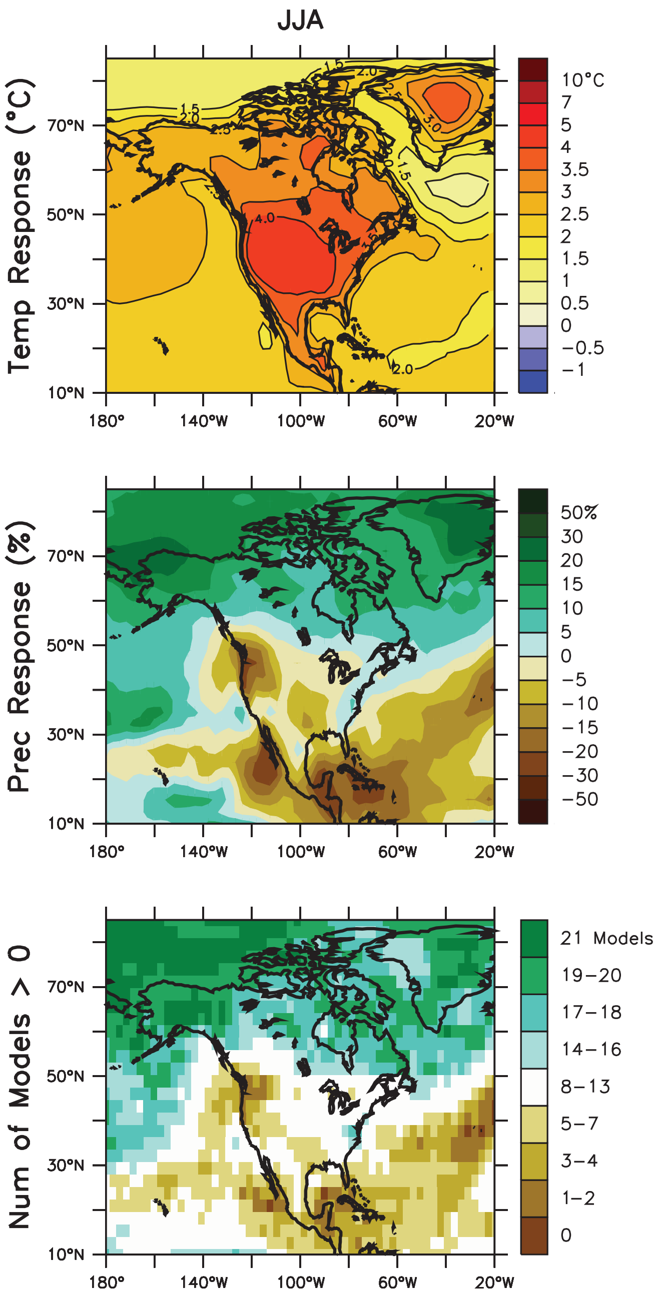


Figure 7.5 Summer precipitation changes over North America by the end of this century, given as percentage change relative to the period 1980–99. Note the decline in summer rainfall over most of the USA and an increase in Canada.

Figure 7.6 Flooding in Oxford, United Kingdom, July 2007.

How high will the seas rise?

One of the most controversial issues in preparing the IPCC report was the future rise of sea levels. Sea levels will rise as a result of global warming, both because the existing ocean water expands as it heats up, and because additional water will flow into the ocean as mountain glaciers and ice sheets melt. That much is entirely uncontroversial. Equally uncontroversial is the fact that this is already happening: global sea level is already rising, as the ocean warms and ice melts (see Chapter 3). What is less clear is just how much and how fast sea level will rise in future.

The main reason for the scientific debate is that we do not yet understand very well how the large ice sheets in Greenland and Antarctica will respond to global warming. In the long run, these ice sheets have by far the biggest potential to raise sea levels. Greenland contains enough ice to raise the seas globally by 7 meters, and Antarctica 57 meters! Thus, melting just a small fraction of this ice could raise the seas worldwide by several meters. In Earth's history of the past 40 million years, sea levels have been as much as 120 meters

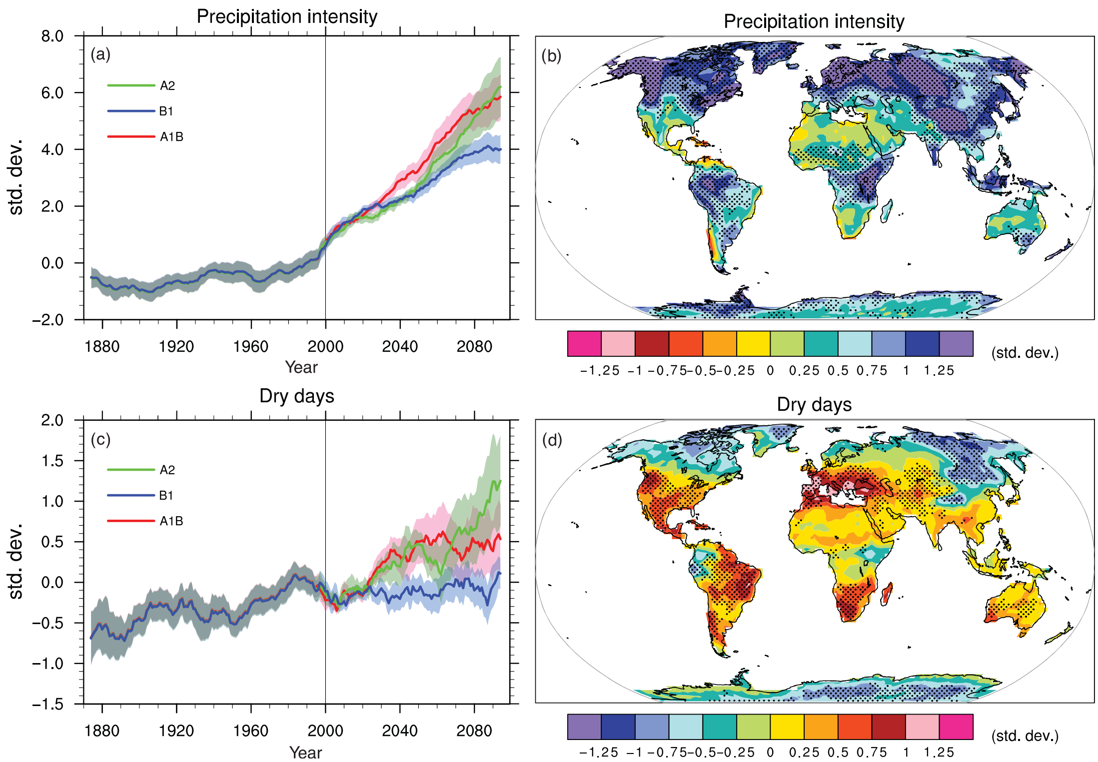


Figure 7.7 Simulated changes in precipitation extremes. At top the precipitation intensity is shown, defined as the amount of water that falls on average on a rainy day. At bottom the number of dry days is shown. In each case, the left panel shows the global changes over time for different emission scenarios, and the right panel shows the spatial patterns. Note that both the number of dry days and the precipitation intensity are expected to increase globally (except for the B1 scenario).

lower or 65 meters higher than today, as the ice sheets grew or vanished in the ups and downs of global climate (see Chapter 6). In comparison, melting all mountain glaciers and small ice caps would only raise sea level by less than one meter, and thermal expansion of the ocean water will also likely add less than a meter – at the very most two meters over the next thousand years (assuming global warming remains below 5°C). The two big ice sheets are thus clearly the "big gorillas" of the sea level question. Unfortunately, what they are going to do is about as hard to predict as what a wild gorilla in the jungle will do if you throw stones at him.

Behind this uncertainty lies the complex physics of ice flow. Ice sheets are not static slabs of ice. Rather, they are constantly moving, in a dynamic and potentially precarious balance of the snow added on the top, the ice lost at the margins and the huge glaciers flowing from the interior towards the edges and into the sea. If you just want to know how fast a piece of ice melts when exposed to certain weather, like a block of ice from your freezer put out on the garden table, that's relatively easy to calculate. This kind of simple mass balance calculation (including also the snow added each year) leads to the conclusion that for typical global warming scenarios, it would take thousands of years to melt the Greenland ice sheet. But as we have learned in recent years, this picture is far too simplistic. Big outlet glaciers and ice streams in Greenland and Antarctica have accelerated several-fold, raising the question: what if the ice sheets literally start to slide into the ocean, rather than just slowly melt?

The IPCC report discusses two disturbing mechanisms. Unexpected by many, it has been found that outlet glaciers have started to flow much faster when the ice shelves floating on the sea in front of these glaciers break up. It seems that this floating ice holds back the continental ice behind it – possibly because the floating ice does not float freely but in many places is grounded or stuck to rock outcrops and small islands. Many of these floating ice shelves are considered very vulnerable to even small warming – around the Antarctic Peninsula, a number of ice shelves have already disintegrated in a spectacular way in recent years. The second mechanism is that meltwater forming on top of the ice sheets percolates down through cracks to the ice sheet base, where the ice used to be frozen to the underlying rock. The water getting down there can act like a lubricant and make the ice start to slide faster. These processes are not fully understood and thus not yet properly included in the ice sheet models that are used to compute future sea level rise – and therefore they are not included in the sea level scenarios presented in the report.

The sea level rise scenarios are also included in Table 7.1 shown above, and, depending on emission scenario, they range from 18 to 59 centimeters global rise over this century (see Figure 7.8). Many media reports focused on the fact that the upper number is lower than in the third IPCC report, which gave a range of 9 to 88 cm. Some reports wrongly claimed that sea level rise is considered less serious now than it used to be. However, the change in range is not due to more recent models giving lower results than older models – rather, it is just due to differences in how the results are summarized and reported. As is pointed out in a footnote of the report, recent models do not give significantly different results from older models, and had the uncertainties been reported in the same way as in the third IPCC report, the numbers would have come out almost the same.

We spare the readers the technical details and just point out that 59 cm is by no means the upper limit for the expected sea level rise. The numbers

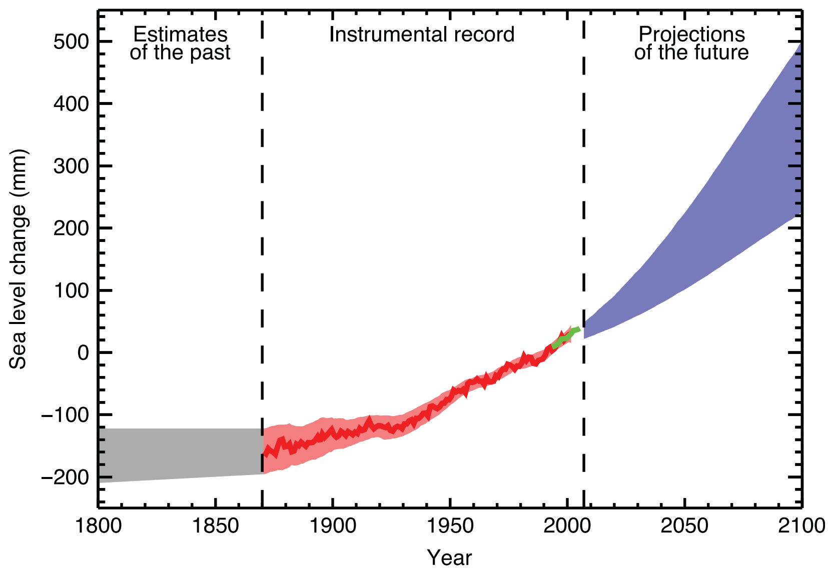


Figure 7.8 Sea level rise projections by the IPCC (blue range, numbers as in Table 7.1) compared to past sea level changes.

given in the IPCC range include almost no – in some cases even a negative – contribution to sea level rise from the two big ice sheets, as it is assumed that the amount of ice on Antarctica will grow due to greater snowfall, largely compensating the mass loss from Greenland. If the ice sheets go into accelerated decay by ice sliding, as many scientists fear, this would come in addition to the range given above and shown in Figure 7.8 – the IPCC estimate explicitly does not include the kind of dynamical changes in ice flow discussed above. In fact, as we discussed in Chapter 4, Antarctica has been losing, not gaining ice in recent years. Also it should be noted that the sea level range given in the table does not correspond to the full "likely temperature range" presented in the same table – a surprisingly misleading presentation by the authors of the summary. For the A1FI scenario, the likely temperature range is 2.4–6.4°C warming, but sea level rise has only been evaluated for scenarios up to 5.2°C warming. Going up to the full 6.4°C would have added roughly 15 cm to the range. A final point is that the models used for the projections underestimate past sea level rise. For the period 1961–2003, the models on average give a rise of 1.2 mm/year, while the data show 1.8 mm/year, i.e. a 50% faster rise. In short, the 18–59 cm range given in the summary of the report does not provide the full story on sea level rise and in our view tends to downplay the real risks. When considering the full information in the report,

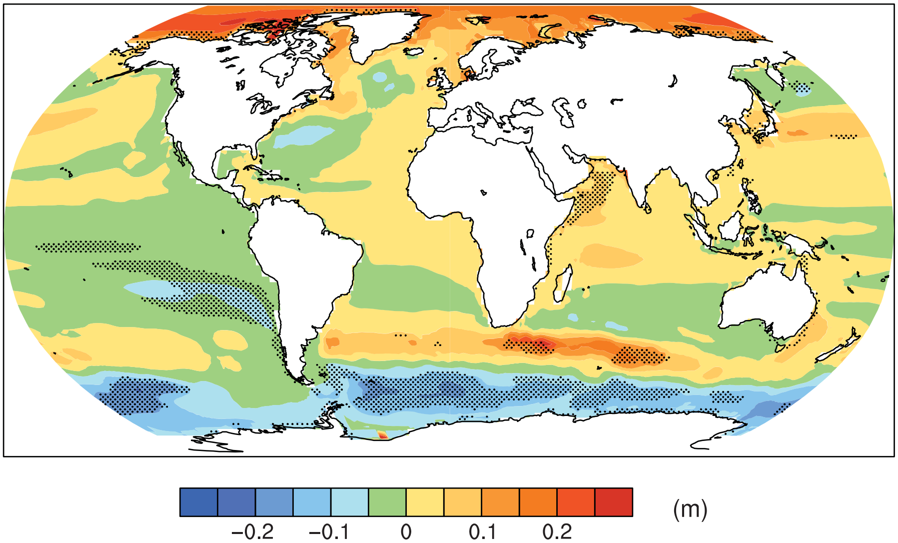


Figure 7.9 Local sea level changes projected by the IPCC. These changes are associated with changing ocean currents and are in addition to the global sea level rise. In the Arctic Ocean, sea level is expected to rise by around 20 cm more than the global average, while in the Southern Ocean it is expected to rise less than the global average.

it becomes evident that a rise by over one meter by the end of this century cannot be ruled out.

A number of studies published since the IPCC report have attempted to estimate the potential future sea level rise with methods other than climate models, given that these are not yet able to simulate all the relevant processes reliably. One of us (S.R.) has correlated the observed rate of sea level rise with temperatures over the last 120 years and found a simple link between the two. If this observed link continues unchanged during this century, sea level could rise by up to 1.4 meters. James Hansen, head of the NASA Climate Institute in New York, has argued that in the long run, even current CO_2 levels would likely cause several meters of sea level rise, based on paleoclimatic data. He fears that global sea level could rise by two meters by the year 2100.

So far we've just discussed the global average sea level. But sea level rise is not expected to be the same everywhere: Figure 7.9 shows a map of how regional sea level changes may differ from the global mean number. Some regions, such as the Arctic and northern Atlantic oceans, the north Indian Ocean and the seas around Japan, can expect between 5 and 20 cm of extra

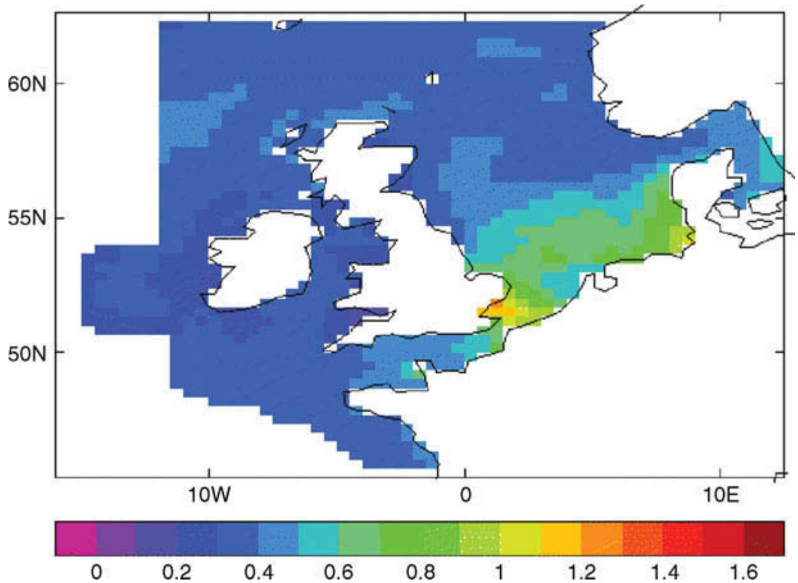


Figure 7.10 Change in the extreme water level in the North Sea due to a storm surge expected once every 50 years. In parts of the North Sea, this 50-year flood may run over a meter higher than now, despite a sea level rise out in the open ocean of less than 40 cm.

sea level rise. These numbers present an average across all models – the uncertainty surrounding them is large. A below-average sea level rise is mainly expected in the Southern Ocean, where few people would benefit.

The negative impacts of sea level rise occur mainly during storm surges – on a calm day, even a meter higher sea level wouldn't be a problem along most coastlines. The risk of storm surges at a given place not only depends on the sea level rise in the open sea, which is what global models can calculate. It depends also on changes in wind conditions, on the shape of the coastline and sea bed, and on vertical land movements, such as the still ongoing uplift of Scandinavia in response to the load of the big ice sheets melting away about ten thousand years ago. Therefore, regional storm surge models need to be developed to find out what storm surge risk results from a given rise in sea level. An example is shown in Figure 7.10 for the North Sea region. This example clearly shows how much regional details can modify the "big picture" given by the global models – note in particular the large amplification of storm surge risk in the southern North Sea and especially the Thames estuary, affecting London.

Changing ocean currents?

One reason why sea level will not rise by the same amount everywhere is changing ocean currents. The surface of the sea is not flat, but rather it is sloping gently in balance with ocean currents – that's ultimately one of the weird effects of the Earth's rotation, the so-called Coriolis force. For example, across the Gulf Stream the sea surface is sloping so much that sea level is about a meter higher on the right-hand side of the Gulf Stream than on the left. That's one of the reasons for the patterns seen in Figure 7.9: the sea level coming up in the northern Atlantic and Arctic is linked to the weakening of the North Atlantic Current (see Chapter 5) in the climate models. That leads us straight to the question: what do the models say about the future of the Gulf Stream? Will the North Atlantic Current stop, as in the Hollywood film *The Day After Tomorrow*?

On average, the models show a significant weakening of the Gulf Stream and the Atlantic overturning circulation during the twenty-first century. However, the amount of weakening depends strongly on the model, ranging from no change at all to a weakening of the overturning by over 50%. The reasons for these model differences are as yet poorly understood, but it is known that the stability of ocean currents in models is influenced by poorly known model parameters such as the amount of mixing by turbulence in the ocean. In none of the model simulations does the overturning circulation stop in the twenty-first century. However, in some cases one part of the system shuts down: the process of convection and sinking of water to great depths in the Labrador Sea. The report concludes that it is very likely that the overturning circulation will decrease, but very unlikely that it will abruptly shut down in this century.

But there is a caveat: the runoff of meltwater from Greenland is not yet included in these models. If the Greenland ice melts slowly, the amount of meltwater would likely be too small to have a major effect. But if Greenland ice starts to slide rapidly, meltwater will be added at a rate that would cause a much greater weakening, and in some models could cause the overturning circulation to shut down altogether. We thus return to the same issue already discussed in connection with sea level rise: the uncertainty surrounding the future of the Greenland ice sheet.

We are also touching on a more fundamental issue: we are reaching the limits of the approach taken by the IPCC, namely the approach of projecting the future with the help of climate models. How do we deal with processes that we cannot yet model with confidence, such as the behavior of ice sheets or the stability of ocean currents? And how do we deal with so-called "low probability–high impact" risks? The IPCC statement that a large abrupt transition of the overturning circulation is "very unlikely" sounds reassuring – but it means that the probability is up to 10%. For good reason, the term "extremely unlikely" (meaning less than 5% probability) was not used.

The model scenarios by construction represent the best effort by each modeling group in simulating the future. But they do not represent a proper risk assessment, that is, an exploration of all eventualities. For comparison, imagine a risk assessment performed for building a nuclear power station. If twenty groups of researchers all performed simulations of the most likely functioning of the power station, and none of these twenty simulations showed any catastrophic failure, would this mean the power station is completely safe? Obviously not, and therefore this is not how such a risk assessment is approached. The information that the risk is considered "very unlikely", namely less than 10%, is not very useful, even if this number stood on a firm basis (which it does not, and several expert elicitations have shown than many experts disagree with it). If you go to a doctor to discuss the possible risks of an operation, and all he tells you is that it is "very unlikely" that something will go seriously wrong, this is not what you need. You want to know, say, whether the failure rate is one in a thousand or one in ten thousand – that the doctor guesses that it is less than 10% doesn't help much with the decision.

A shut-down of the Atlantic overturning circulation would be a massive change in the operation of the planet's climate system, with consequences that we are only beginning to understand. An "ice age", as in the Hollywood movie, is certainly not on the cards. Within this century, even a regional cooling much below present temperatures would be unlikely, since the warming by greenhouse gases would probably more than outweigh the reduced amount of heat transported north by the ocean. However, marine ecosystems and fisheries in the North Atlantic would probably suffer serious decline. Sea level would rise along northern Atlantic shores, and the tropical rainfall belts would likely shift south causing drought problems in some parts of the world.

Ice and snow changes

Another concern about the future is the fate of the sea ice in the Arctic. We noted in Chapter 4 that ice cover of the Arctic Ocean has been shrinking

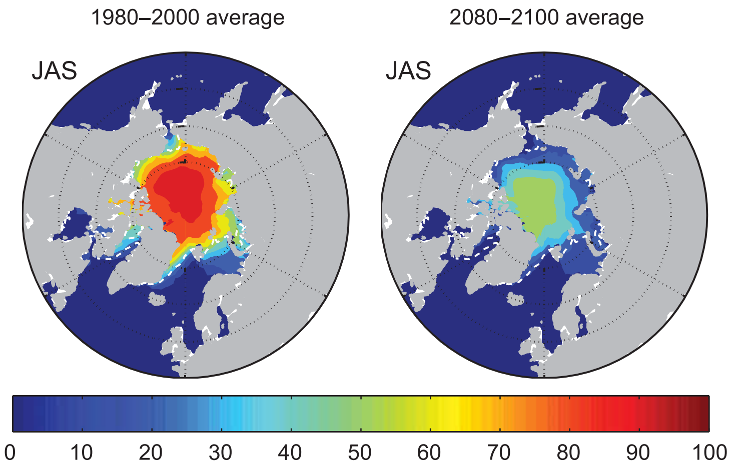


Figure 7.11 Sea ice cover (percentage) in the Arctic Ocean in summer (July–September) in climate models: left for the period 1980–2000, right for the period 2080–2100 for the A1B emission scenario. According to the models, the Arctic Ocean is expected to be largely ice-free by the end of this century. Data suggest that this might happen a lot earlier (see Chapter 4).

significantly in recent decades. Climate models predict that this process will accelerate in the future. By the end of the century, in late summer the Arctic Ocean could be blue open water if warming continues unabated (see Figure 7.11). The sea will freeze over again in the dark and cold polar night, so the Arctic ice cover is expected to become seasonal rather than year-round. The shrinking of Arctic ice cover has a large amplifying effect on the warming in the region, since the ice acts like a mirror reflecting sunlight back into space. The loss of this “mirror” is why the Arctic is expected to warm much more than the global average.

It is interesting that the expected sea ice loss depends highly on which emission scenario is used. For the more moderate B1 emission scenario, less than half of the Arctic summer sea ice cover is lost by the year 2100 in the model simulations.

One of the robust findings of the report is that snow cover in most continental areas will dramatically decrease unless warming is stopped. Figure 7.12 shows this for North America. In large regions, the March snow depth is expected to decline by 50–100% by the end of the century. Most mountain glaciers will likely be gone by then. Overall, the mass of glaciers and ice caps will be cut by more than half (not including Greenland and Antarctica, which we discussed separately above).

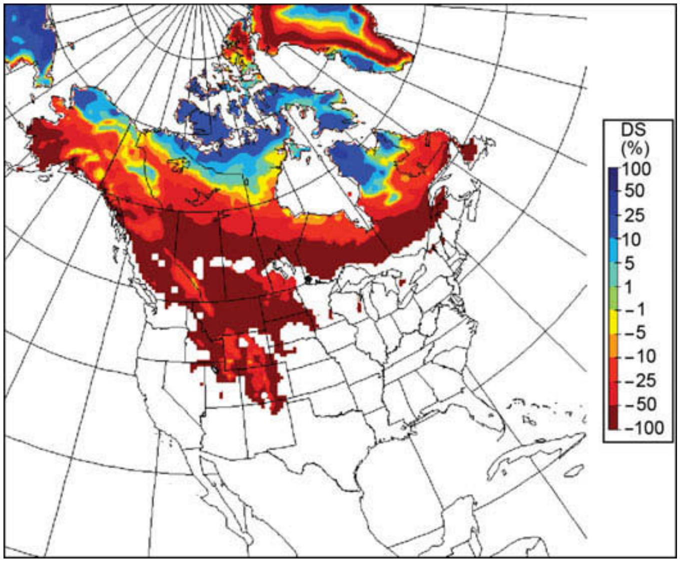


Figure 7.12 Expected change in snow depth in March over North America by the middle of this century, as a percentage. Large areas are expected to become snow-free.

How sour will the oceans get?

In Chapter 5 we explained the problem of ocean acidification, and for the first time the *Fourth Assessment Report* also presents scenario simulations of future changes in ocean chemistry. The outlook is rather bleak, at least if a high-emission scenario is followed – all the more so since the outcome here is rather certain, determined by simple chemistry rather than complex climate feedbacks. The more CO_2 we add to the atmosphere, the more will be dissolved in ocean waters. Within decades, a critical point could be reached where parts of the ocean surface waters become under-saturated with aragonite – this means that the water becomes corrosive to shells of marine organisms, and they will dissolve. The IPCC report calls this development "detrimental to high-latitude ecosystems," as the first affected region will be the Southern Ocean (see Figure 7.13).

By the year 2100, the pH value of the ocean could have dropped by another 0.3 to 0.4 units, in addition to the 0.1 units it has already decreased. This means more than a doubling of the amount of corrosive H^+ ions in the water. The deeper oceans would also be affected. In our view, this direct threat to the health of our oceans would alone be enough reason to halt the further rise of atmospheric CO_2 concentration, even if CO_2 did not also cause climatic changes.

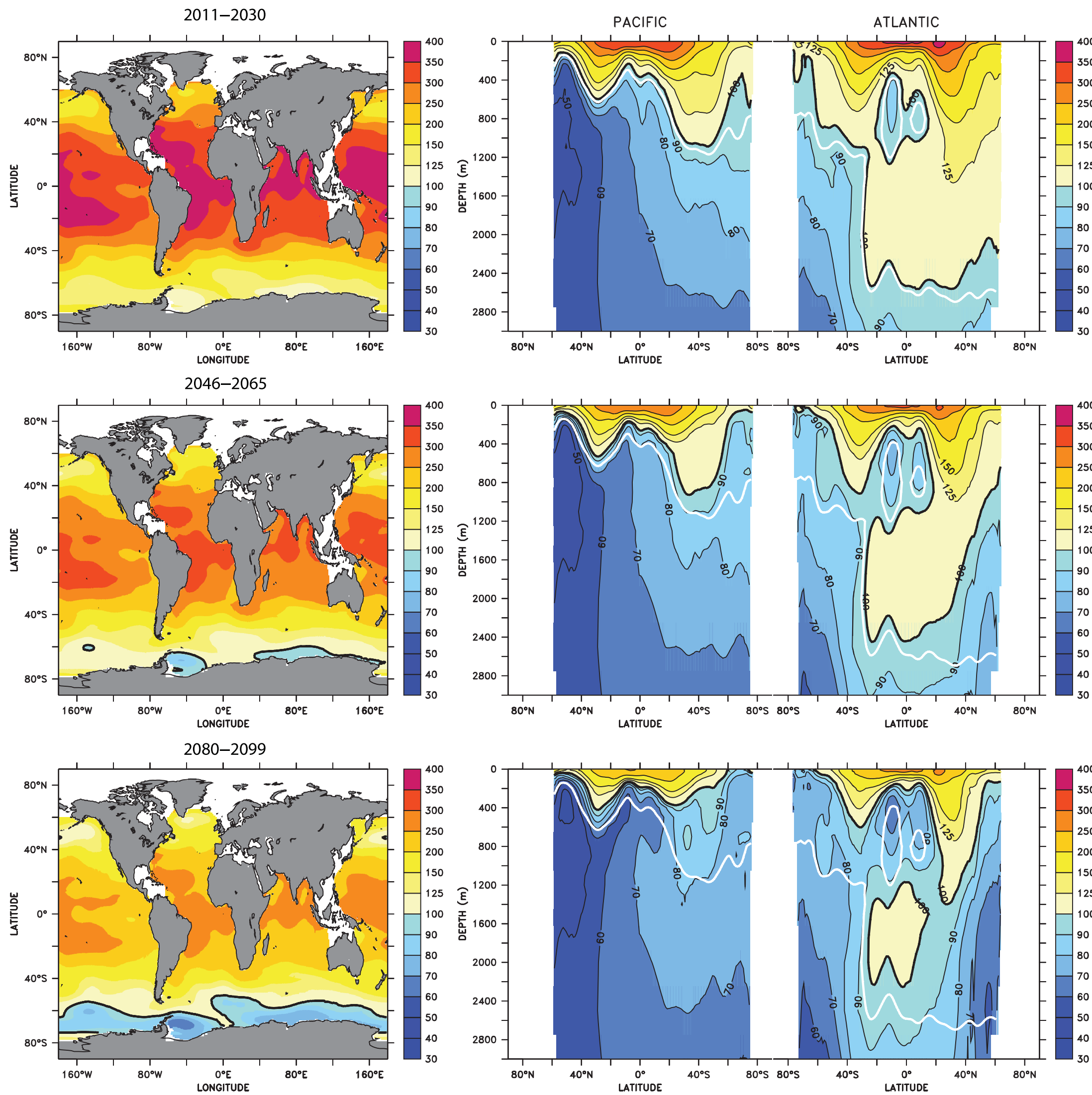


Figure 7.13 Projected level of aragonite saturation of surface ocean waters by the end of the twenty-first century, assuming atmospheric CO_2 concentration reaches 730 ppm by then. Large parts of the Southern Ocean would then be under-saturated (values of less than 100%), threatening the survival of many organisms forming calcium carbonate shells.

Summary

If the emission of greenhouse gases continues to increase, a major global warming will almost certainly occur during the course of this century. Depending on how much we emit, global temperature is expected to rise by at least 1.1°C, up to a whopping 6.4°C. This will make global temperature 2°C to 7°C higher than it was a century or so ago, when the industrial revolution took hold. For comparison: when planet Earth was in the grip of the last great ice age about 20,000 years ago, global temperature was only 4°C to 7°C colder than now.

As a consequence of this warming, many changes to the climate system can be expected. Some of these can be predicted with confidence, while others are still fraught with uncertainty – which does not mean, however, that these changes will be small. Some regions of our planet will get a lot wetter, other regions a lot drier. Heat waves are expected to increase, while outbreaks of cold air and frost days will decline. Drought problems are expected to plague an ever increasing part of the land areas. The risk of flooding will increase in many regions – paradoxically, even in areas also affected by drought. Snow cover will decline drastically. The Arctic sea ice cover will shrink further and probably even largely disappear in late summer – fundamentally changing the image of our planet as seen from space. Most mountain glaciers will disappear, and sea level will rise in global average by 18–59 centimeters – or possibly a lot more, as we discussed above. In addition to the global warming problem, there is the problem of the ocean waters turning increasingly sour, threatening marine life. And these changes will not stop in the year 2100 either: if we do not stop global warming, things will continue to get worse for many centuries.

Such a dire outlook is difficult to accept, and some have accused the IPCC reports of being overly "alarmist." One way to assess this is by checking whether earlier IPCC projections turned out to be correct. With most projections starting in 1990, there is now a period of 18 years for which we can compare the model projections to what actually happened. Carbon dioxide concentrations have increased very closely to what was expected. Global temperatures have risen close to what was projected in the second and third reports, well within the given uncertainty. (The *First Assessment Report* of 1990 calculated a somewhat greater warming, because it only looked at the effect of greenhouse gases and did not include the cooling effect of aerosol particles.) Some aspects of climate have changed noticeably faster than expected; this holds especially for sea level rise and the shrinking Arctic sea ice cover. We do not yet know whether this is a lasting trend or just shorter-term variability. In this sense, the jury is still out – but the evidence so far suggests that the IPCC in the past may have underestimated rather than exaggerated climate change.

8 Impacts of climate change

In the previous chapter we saw how some physical characteristics of the climate system are expected to change – depending of course on how much more greenhouse gases we put into the atmosphere. In this chapter we will discuss how this will affect (and is already affecting) living things on Earth, including us. How will climate change affect plants and animals, ecosystems, and human society? This is a vast and complex topic studied by biologists, ecologists, geographers, social scientists, and many other specialists. The IPCC devotes an entire working group involving hundreds of scientists and the second volume of its assessment report to this issue. We summarize the most important findings in this chapter.

One important question is whether global warming is already having any noticeable effects, despite the thus far small amount of warming of 0.7 °C. Another question is to try and foresee the effects that global warming will have in the future, when it reaches three, four, five, or even more degrees. How serious will the impacts be? Who will be most vulnerable? To what extent can we adapt? How much will this cost?

It is obvious that effects on ecosystems and society are in most cases harder to predict than physical responses such as the melting of glaciers and sea level rise, so we must be aware that large uncertainties exist and surprises are likely. That consequences are hard to predict does not mean that they will be minor or harmless, though. Some impacts of warming may turn out less serious than feared, some even beneficial. Others may be more serious or even entirely unexpected. The difficulty to predict things in a rapidly changing world is a concern in itself. Past experience ceases to be a good guide to the future, and we may end up being ill prepared for what the future holds in store. The further we push our Earth outside of its mode of operation of the past millennia, the further we steer it into uncharted waters.

Are plants and animals already feeling the heat?

In the newspaper we read reports about trees blossoming or birds arriving at unseasonal times, about strange sorts of fish turning up at coasts where they don't belong, or about polar bears drowning. And we ask ourselves: does this have anything to do with global warming? Many biologists have asked the same sort of questions and have documented changes in nature in painstaking detail over the years. But how can we tell whether any observed changes are due to global warming? This is indeed hard to prove for any individual case, as species and ecosystems often suffer from a number of pressures, for example from agriculture. Climate change is just one of several stress factors. The IPCC solved this problem by compiling a mass of data and studies from all over the world and systematically checking how consistent the biological changes are with observed climate change, and especially those aspects of climate change that are likely to be human-caused (see Chapter 3 for more on the attribution of observed climate change to specific causes). This is a great example of the power of big collective assessment exercises like the IPCC – they can put a whole team of scientists to work on sifting through hundreds of studies, bringing them all together in a common framework.

In short, the IPCC's Working Group 2 considered no less than 80,000 data series from 577 published studies. It selected a subset of 29,000 of these, each of which covers at least 20 years in time, ends in 1990 or later and shows a significant trend in either direction. It then checked which of these significant changes are consistent with global warming, and which are not. This exercise covered changes in plants and animals, and also some physical aspects such as changes in snow cover or river runoff. The outcome is shown in Figure 8.1. Most data sets came from Europe and North America, but all continents, including Antarctica, were represented at least with a few studies. The result was overwhelming: in every region of the world, by far most of the biological and physical changes are consistent with warming. This is true for between 90% and 100% of all cases, depending on the region. The IPCC concludes that both terrestrial and marine species are now being strongly affected by observed recent warming.

What are these changes? On land, they involve flora and fauna moving to higher latitudes or to higher altitudes in the mountains. For example, in Britain 36 out of 37 dragonfly and damselfly species have moved north, while in central Spain 16 butterfly species moved the lower limit of their distribution upward by 210 meters. In Europe, the white stork has expanded its range upwards by 240 meters, and several bird species have stopped migrating in winter altogether as it has got warmer. Treelines have widely moved up. Another change is the lengthening of the growing season. The leaves of trees now unfold earlier and migrating birds like the warbler arrive earlier in spring. Overall, spring can be said to arrive earlier by two to five days each decade (see Figure 8.2).

While many of these changes are positive, some species nevertheless are unable to adapt and thus decline in population, vanish from a particular region or even go extinct. An important problem is the fragmentation of habitats due to human land use, which makes it difficult or impossible to move to a different area when the climate changes. Another problem is the fast rate of change, which overstretches the ability of species and ecosystems to adapt.

Usually several causes contribute to extinction. A recent extinction of about 75 species of frogs in the American tropics, for example, was most likely due to fungus outbreaks, which were greatly enhanced by warmer temperatures. The extinction of other amphibians around the world and a butterfly species have been linked at least in part to global warming. The pika, a small, delightful mammal living in the mountains of the western United States, has vanished from many slopes due to warming. The IPCC comes to the worrying conclusion: "new evidence suggests that climate-driven extinctions and range

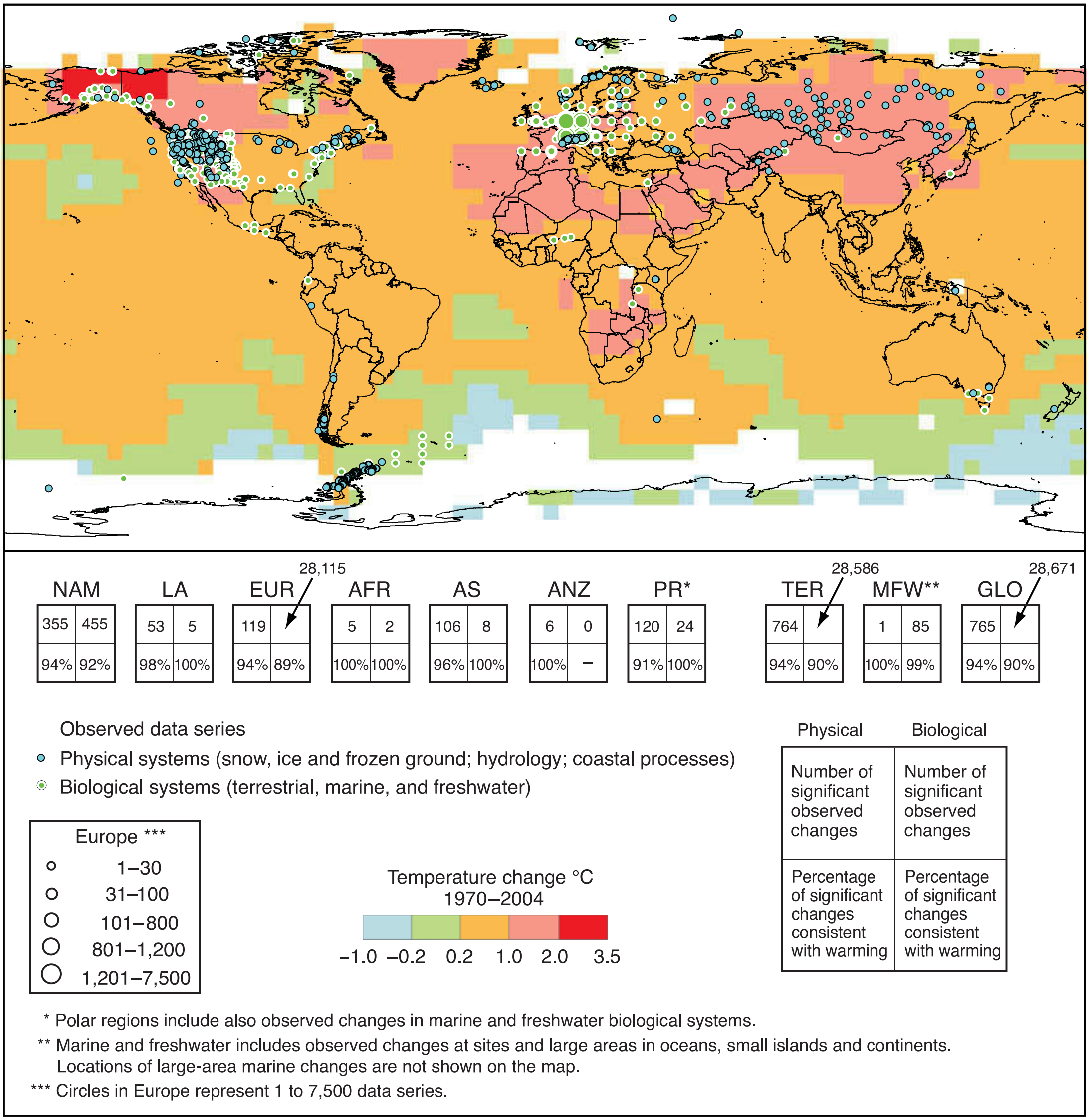


Figure 8.1 Overview map of significant climate change impacts documented thus far, based on 29,000 data sets as discussed in the text. The background colors show observed temperature changes over the period 1970–2004. Colored dots show the locations of data series for physical and biological impacts. The 2 × 2 boxes below the map show the total number of data series with significant changes (top row) as well as the percentage of these consistent with warming (bottom row), on the left for physical and on the right for biological changes. These statistics are shown for different regions as follows: North America (NAM), Latin America (LA), Europe (EUR), Africa (AFR), Asia (AS), Australia and New Zealand (ANZ), and Polar Regions (PR). Also shown are global boxes for terrestrial systems (TER), marine and freshwater systems (MFR), and the entire globe (GLO).

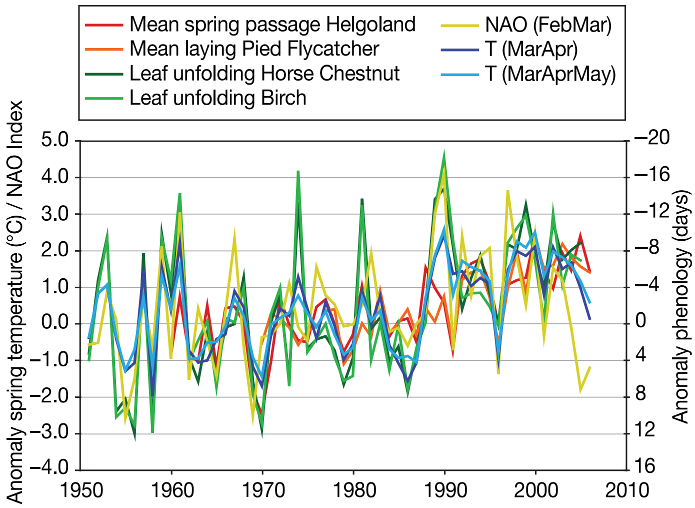


Figure 8.2 Change in the arrival of spring in Germany as seen by a number of biological indicators: the spring passage of birds at the Island of Helgoland (North Sea), the time of egg laying of the pied flycatcher in Northern Germany; and the mean unfolding of the leaves of chestnut and silver birch trees. These times have moved forward by almost two weeks since 1970. This can be compared to changes in observed spring air temperature and the North Atlantic Oscillation (NAO) index.

retractions are already widespread." But most of them are not documented for lack of systematic and accurate observations. One of the prime threats to ecosystems is the invasion of exotic species from warmer regions. For example, weedy heat-loving plants are now spreading into the native flora of Spain, Switzerland, and Ireland. Much discussed is the fate of the polar bears as the Arctic sea ice declines (see Chapter 4), since polar bears can only hunt seals, their favorite prey, on ice. The report finds that the reproductive success and the body condition of polar bears have declined in recent decades, because the earlier breakup of sea ice shortens their hunting season – it forces them to go ashore and start to fast earlier. First-year polar bear cubs have come ashore in poor condition and smaller numbers.

Many impacts on land ecosystems will likely come from extreme events rather than from a change in average conditions. The European heat wave of summer 2003 provides a good example. The productivity of plants ("gross primary production") in Europe dropped by 30% due to drought stress. Oxygen became depleted in deeper layers of lakes during the heat wave. Mollusks declined significantly in the River Saône and recovered only poorly. There were record-breaking wild fires, burning 650,000 hectares of forest across the continent. Over 5% of the total forest area of Portugal burned, more than double the previous record.

Figure 8.3 Deforestation in Brazil. Habitats for wildlife are shrinking and becoming increasingly fragmented due to human land use.

Changes in the oceans include a poleward shift of fish, plankton, and algal species as ocean waters warm. In the northern Atlantic, plankton have moved north by 1,000 kilometers over the past 40 years. Chlorophyll data from satellite and *in situ* observations suggest that, since the early 1980s, the productivity of the global ocean has declined by over 6%. When scientists investigated changes in microscopic plankton over the past 1,400 years using cores drilled into ocean sediments, they found that changes in the past few decades are unique. This suggests that the limits of natural variation in the oceans have already been exceeded. There is also growing evidence that warming is harming coral reefs, although it is hard to tell how much damage is due to other factors such as over-fishing and pollution. When corals get too hot, "coral bleaching" occurs as the reefs expel the microscopic algae (called zooxanthellae) that they need for their metabolism. This makes the corals lose their color, hence the name bleaching. In 1998, the hottest year on record, the hitherto most severe coral bleaching event occurred, killing an estimated 16% of the world's corals.

Figure 8.4 Polar bear mother and cub. The decline of Arctic sea ice is a major threat to the survival of the polar bears, which hunt on the ice.

Lakes and rivers around the world are also warming. Algae have become more abundant in cold lakes at high latitude and altitude, while productivity has declined in some tropical lakes. For several large lakes it has been documented that the spring bloom of phytoplankton (microscopic plants) now occurs four weeks earlier in response to the warming. Interestingly, zooplankton (microscopic animals) often have not been able to keep pace with this shift in timing and their populations have declined, as they no longer emerge at the same time as their food source. Many biologists fear that, in this way, food webs in lakes and oceans that have become established over thousands of years and are often finely tuned will be disrupted. Toxic cyanobacteria are on the rise in some fresh water ecosystems, which is a potential health hazard for humans. In many rivers, warmer water has enhanced the breeding success of fish, while also changing their migration patterns. In North America, fish now start their migration up to six weeks earlier, but more die along the way. Brown trout are moving up to higher altitudes, while more diseased trout are found at the warm end of their range.

Human activities have also to some extent already been affected by warming. For agriculture, the growing season has become longer, and in some northern regions crops are now planted earlier in spring. In particular, the conditions for wine production have improved; for example in Alsace

Figure 8.5 The drying out of the Mediterranean region makes forest fires go increasingly out of control. In summer 2007, record fires destroyed 670,000 acres (270,000 hectares) of forest, olive groves, and farmland in Greece. Eighty-four people lost their lives. The photo shows Mt. Parnes above Athens on June 28, 2007.

in France, the number of days favorable for grape growth – that is, with temperatures above 10 °C – has increased from 170 to 210 days per year over the past 30 years. Productivity of forests has increased in some regions due to the longer growing season and the fertilizing effect of the carbon dioxide gas in the atmosphere (see Figure 8.6). On the other hand, pests are expanding their range, like the bark beetle in North America and the pine processionary moth in Europe. Heat and drought in North America, Australia and the Mediterranean region have contributed to forest fires. Agriculture and forests have suffered in past heat waves, droughts, and floods. As we will discuss below, they are expected to suffer an increasing toll as warming continues.

Impacts of climate change on human health have so far not been well documented; first, for lack of long epidemiological data series, and second, because of the many other factors that affect health. Amongst the few well-established examples is the excess mortality from heat waves in Europe and North America, which bucks the general trend of wealthy populations

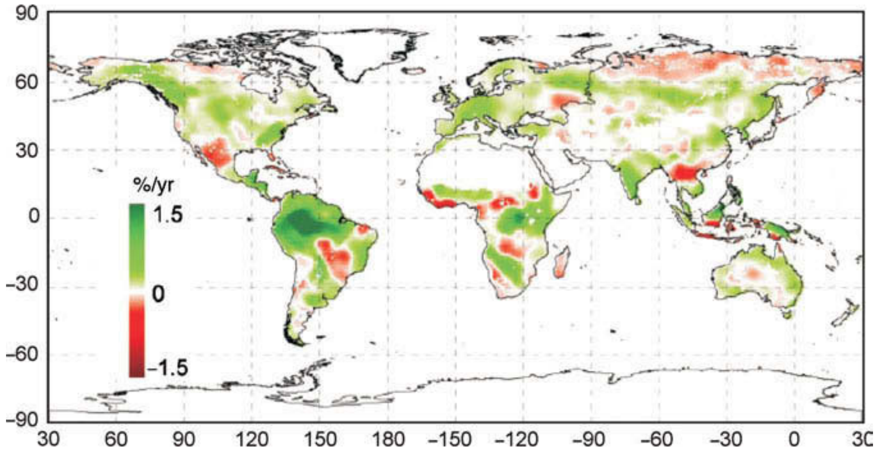


Figure 8.6 Estimated changes in biological productivity of vegetation between 1982 and 1999 based on satellite data. Productivity has increased in most places, consistent with rising atmospheric CO_2 and warming.

becoming less vulnerable to weather extremes. The European heat wave of the year 2003, which likely was the hottest summer at least since the year 1500, caused at least 35,000 deaths – more than all traffic accidents in Europe during the entire year. Data indicate that ticks that carry Lyme disease are spreading northward in Europe, and that the higher incidence of encephalitis correlates with milder temperatures. On the much-discussed issue of a possible spread of malaria due to warming, the IPCC report concludes that the evidence for this already happening is still unclear. Data show that both malaria and the anopheles mosquito that carries the disease have recently spread into highland areas of Kenya that were free of them only 20 years ago. However, it has not been proven whether this is due to the temperature rise or perhaps some other factors. Another health issue is pollen allergies, where the climatic warming has caused the pollen season to start earlier in the year. Health effects can even occur an ocean away from their cause: a dramatic increase in respiratory diseases in the Caribbean has been attributed to increasing drought in Africa, leading to dust storms blowing dust across the Atlantic. Many other examples are discussed in the report.

Given that global warming has so far been quite small, at 0.7 °C over the past 100 years and even less over the time span considered in the studies discussed above, it is astounding that the consequences of warming on nature are already so clearly evident. It is these observed hard facts about actual changes that make the changes projected for the future, for a climatic warming several times greater, all the more plausible.

The future of nature

How well will nature be able to cope with the climate changes that are yet to come in this century? Obviously, ecosystems have shown some resilience during past, natural climate changes in Earth's history. On the other hand, there have also been extinctions of many plant and animal species in the past, many of which have no doubt been caused by climatic changes. And four important things are different now compared to the natural changes over the past two million years or so, the time during which many of the present species and ecosystems have evolved.

The first difference is the *speed* of the change. By far the largest global climate changes of the past two million years have been the oscillations between ice ages (called glacials) and warm periods, called interglacials. The global temperature difference between these amounted to 4 to 7 °C – this is comparable to the changes expected from global warming if we do nothing about it. The most rapid changes occurred at the end of ice ages: the ice went away much more quickly than it came. But still, the global warming at the end of ice ages typically took about 5,000 years. That has to do with the driver of these ice age cycles: the Milankovich cycles of the Earth's orbit, the fastest of which has a period of 23,000 years. That means that the rate of global warming at the end of ice ages was typically just 0.1 °C per century. (Some much more rapid regional temperature changes have occurred, albeit with a much smaller amplitude in the tropics.) We are now looking at a rate of global warming seven times faster during the twentieth century and up to fifty times faster during the twenty-first.

The second difference is the absolute temperature that will be reached. Those past changes by 4 to 7 °C have all played out towards the colder end of the scale – as far as we can tell from the data we have, it has never been much warmer than now in the past two million years. To the contrary: the warm interglacials, which had temperatures similar to those of the Holocene that we have lived in for the past ten thousand years, have been the exception, making up only about 10% of the time. Overall, the past two million years have been dominated by a much colder climate than we have now, so it is not surprising that many plants and animals have evolved for cold conditions. They tide over the warm interglacials near the frigid poles or high up in the mountains. We're now adding 2 to 7 °C *on top* of an already warm interglacial, taking the planet outside the range that most plants and animals have evolved in for millions of years.

The third difference, unprecedented in the history of planet Earth, is that humans have completely transformed a large fraction of the land surface for

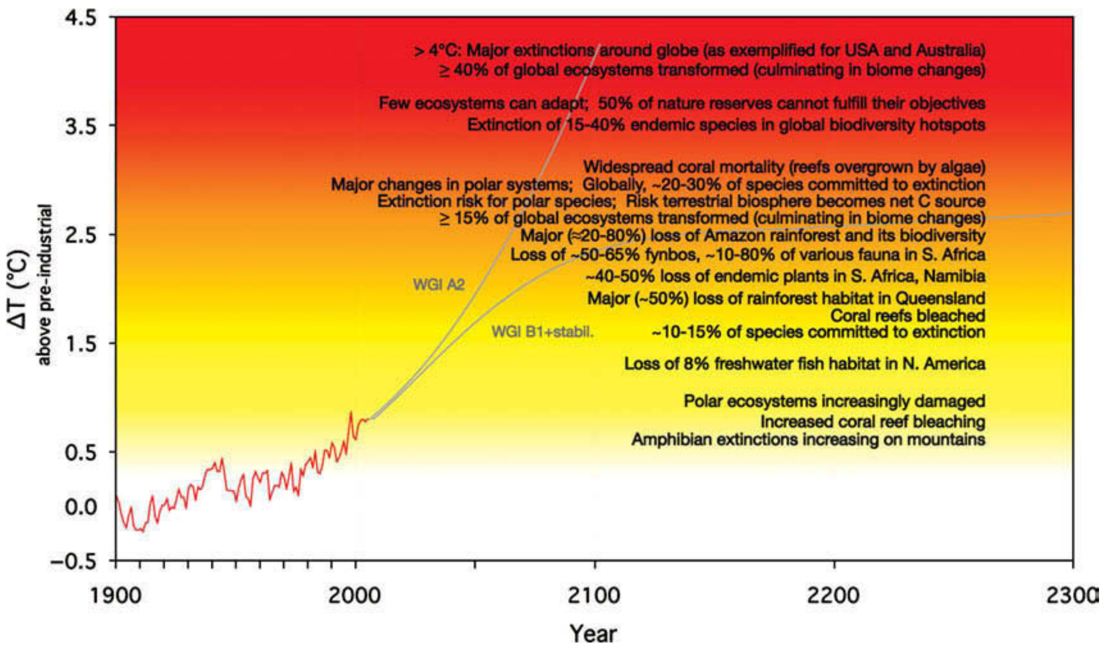


Figure 8.7 Compendium of risks due to critical climate change impacts on ecosystems for different amounts of global warming. Impacts are listed in the graph at their corresponding temperature level.

our own use as farmland, managed forest, roads, or cities. Undisturbed nature is often relegated to remnant fragmented pockets. This means that a gradual migration to different latitudes as the climate shifts is impossible in many cases.

The fourth difference is that we are now causing unprecedented changes to the chemistry of the ocean waters that cover over two-thirds of our planet and host over half of the biological productivity on Earth. According to the report, by the year 2100 the acidity of ocean waters will very likely be greater than at any time during at least the past 20 million years.

These four reasons make climatologists expect a large impact of future global warming on the biosphere. This general reasoning is only the starting point: hundreds of specific scientific studies have examined the likely response of species and ecosystems to warming, based on knowledge about their individual climatic resilience, vulnerability to extremes and geographic conditions. These studies are summarized in the second volume of the IPCC report, and their findings are alarming. An overview is given in Figure 8.7 and Table 8.1.

For a warming exceeding 4 °C, “major extinctions around the globe” must be expected. And even at only 1.5 °C of warming – the lowest level we could still possibly hope to reach – 10 to 15% of all species are “committed to

Table 8.1. ***Projected impacts of climate change on ecosystems and population systems as reported in the literature for different levels of global mean annual temperature rise, ΔT_g, relative to pre–industrial climate – mean and range.***

No.	ΔT_g above pre-ind	ΔT_g above pre-ind (range)	ΔT_{reg} above 1990 (range)	Impacts to unique or widespread ecosystems or population systems	Region
1	0.6			Increased coral bleaching	Caribbean, Indian Ocean, Great Barrier Reef
2	0.6			Amphibian extinctions/extinction risks on mountains due to climate-change-induced disease outbreaks	Costa Rica, Spain, Australia
3	<1.0			Marine ecosystems affected by continued reductions in krill possibly impacting Adelie penguin populations; Arctic ecosystems increasingly damaged	Antarctica, Arctic
4	1.3	1.1–1.6	1	8% loss freshwater fish habitat, 15% loss in Rocky Mountains, 9% loss of salmon	N. America
5	1.6	1.2–2.0	0.7–1.5	9–31% (mean 18%) of species committed to extinction	Globe
6	1.6			Bioclimatic envelopes eventually exceeded, leading to 10% transformation of global ecosystems; loss of 47% wooded tundra, 23% cool conifer forest, 21% scrubland, 15% grassland/steppe, 14% savanna, 13% tundra and 12% temperate deciduous forest. Ecosystems variously lose 2–47% areal extent.	Globe
7	1.6	1.1–2.1	1	Suitable climates for 25% of eucalypts exceeded	Australia
8	1.7	1–2.3	1 °C SST	All coral reefs bleached	Great Barrier Reef, S.E. Asia, Caribbean
9	1.7	1.2–2.6		38–45% of the plants in the Cerrado committed to extinction	Brazil
10	1.7	1.3–3		2–18% of the mammals, 2–8% of the birds and 1–11% of the butterflies committed to extinction	Mexico
11	1.7	1.3–2.4	2	16% freshwater fish habitat loss, 28% loss in Rocky Mountains, 18% loss of salmon	N. America
12	<1.9	<1.6–2.4	<1	Range loss begins for golden bowerbird	Australia

extinction". This is considering climate effects only – not counting the many other pressures on the biosphere from human activities such as fishing, agriculture, pollution, and deforestation. Here is the verdict in the sober scientific language of the IPCC report: "During the course of this century the resilience of many ecosystems (their ability to adapt naturally) is likely to be exceeded by an unprecedented combination of change in climate, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), and other global change drivers (e.g., land-use change, pollution, over-exploitation of resources)."

What does it mean if the "resilience of ecosystems is exceeded"? This "is very likely characterised by threshold-type responses, many irreversible on time-scales relevant to human society, such as biodiversity loss through extinction, disruption of species' ecological interactions, and major changes in ecosystem structure and disturbance regimes (especially wildfire and insects)." In other words: ecosystems may suddenly collapse, forests may go up in flames or succumb to insect infestations, and species that have lived on our planet for hundreds of thousands or even millions of years will rapidly vanish from the face of the Earth. This also means that important functions of ecosystems that we benefit from as humans and often take for granted will be impaired, such as the uptake of carbon dioxide or the provision of food, wood, and other products.

Desert ecosystems are vulnerable to climate change – perhaps surprising at first sight, as one might think that deserts are already so dry and hot that any further heating makes little difference. But deserts are rich in specialised life forms that have adapted to cope with heat and drought – up to a point. Desert plants stabilise sand dunes, and for the Kalahari Desert, it is predicted that a regional warming around 3 °C would reduce vegetation cover so much that most dune fields would be reactivated. That means the sands would be on the move once again. Some desert ecosystems are hotspots of biodiversity. A spectacularly beautiful one is the Succulent Karoo of South Africa, where 2,800 endemic plant species face possible extinction since a global warming of only 2 °C would cut down their suitable habitat by around 80%. Desert birds would be amongst the losers, while desert reptiles, which can cope with harsher conditions, would possibly be amongst the winners of global warming.

Grassland and *savanna ecosystems* are doubly linked to climate: on one hand they are particularly sensitive to even moderate rainfall changes, and on the other hand they have a strong effect on rainfall. If these ecosystems are removed from climate models for the sake of experiment, global rainfall drops significantly. And rainfall amounts make a huge difference to them. Only 30%

Figure 8.8 *Gibbaeum pubescens* flowering near Anysberg, Little Karoo, South Africa. Many endemic plant species of the Karoo face extinction if global warming continues.

more rain can mean five times higher productivity, while a drop by only 15% leads to a net loss of carbon (to cite just one study focusing on Canadian grassland). Predicting the fate of grasslands in future is complicated not only because it depends on regional rainfall changes, which are still hard to compute. There are also complex and competing effects such as the fertilizing effect of more CO_2 in the air, which helps many plants to use water more efficiently. And there is a disproportionate role of disturbances like fires – another aspect that is hard to predict. The few studies that exist see major changes ahead: between 10 and 40% of mammal species could be threatened by the year 2080 or earlier as their ecosystem degrades or vanishes due to droughts and fires.

The so-called *Mediterranean ecosystems* are valued for their high biodiversity and are dominated by shrubs, but include some woodland. They are found, for example, in parts of California, Australia, the Cape region of South Africa and, of course, in the Mediterranean basin. This type of ecosystem is expected to be strongly impacted by global warming. For example, for only about 2 °C warming the Cape Fynbos could shrink by 65% resulting in extinction of a quarter of its species, and 60–80% of species currently found in the southern European Mediterranean region are projected not to persist there. Fire frequency and extent are expected to rise, and in fact are already increasing.

Forests (with a dense canopy) and *woodlands* (with a largely open canopy) today cover about 30% of all land; in the tropics as much as 42%. They are particularly productive ecosystems, but also require particularly favorable conditions (enough rain, not too cold). Forests hold the largest amount of carbon of all ecosystems, amounting to more than twice the amount of carbon currently in the atmosphere. And we are drawing down this carbon store: about one-quarter of the human-caused CO_2 emissions come from cutting down forests. Forests are very vulnerable to disturbances by drought, fire, and insect outbreaks, which can cross a critical threshold through global warming. Most ecosystem models suggest a significant dieback of forests towards the end of this century, even though initially warming and CO_2 fertilization are

Figure 8.9 Lowland rainforest in Danum Valley, Borneo.

Figure 8.10 Morning mist in the Alaskan tundra.

expected to be beneficial for forest growth in many places. As the climate zones shift, forests can adapt by migrating into new areas, for example those formerly too cold and occupied by tundra. Data from past climate changes, however, suggest that trees can disperse into new areas only at a rate of about 200–300 meters per year, which is at least five times too slow to follow the anticipated climate changes. Extinction risks of forest species are expected to increase in most cases. The Amazon forest is expected to suffer from increasing drought conditions, with "major loss of rainforest" predicted for a global warming of only 2.5 °C, causing large losses of biodiversity. In some models, the Amazon rainforest collapses outright.

Tundra and *Arctic/Antarctic ecosystems* are characteristic of the polar regions, which are too cold to support forest. The Arctic is particularly strongly affected by global warming, as the loss of ice and snow cover amplifies the warming there. The area of tundra is expected to shrink as the climate warms, and populations of many Arctic birds such as the red knot are facing a major decline. For the polar bear, the outlook is bleak: at a global warming of 2.5 to 3 °C "polar bears will face a high risk of extinction," if projections of sea ice decline come true. Unfortunately, in recent years, sea ice has declined far more rapidly than any of the model projections suggested. And the polar bear

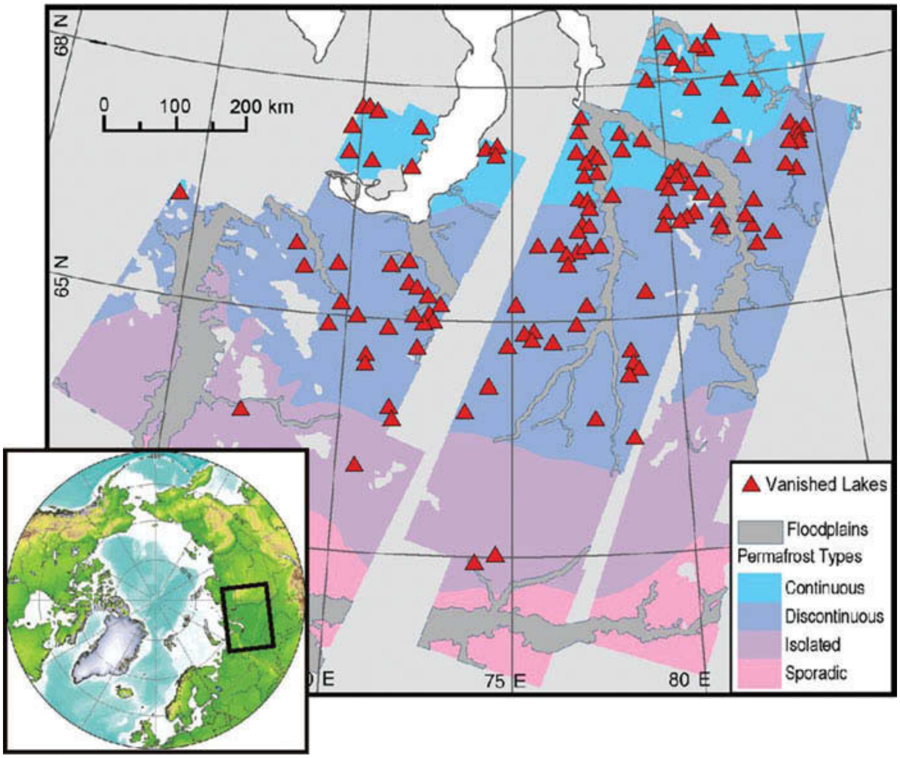


Figure 8.11 Locations of Siberian lakes that have disappeared due to warming since 1970.

is not alone: "Similar consequences are facing other ice-dependent species, not only in the Arctic but also in the Antarctic." Such ice-dependent species include the walrus, narwhal, and bowhead whale. The food security and livelihoods of indigenous people like the Inuit are under threat. Species from neighboring warmer regions, such as the North American mink and southern shrubs, are expected to invade and colonise Arctic ecosystems and adversely affect their unique endemic biodiversity. Many Arctic lakes are vanishing as a result of warming (Figure 8.11). Overall, warming may turn the Arctic region from being a net carbon sink into a carbon source and release more of the greenhouse gas methane, amplifying global warming. New data from Siberia, Canada, and Scandinavia show that the methane release from tundra is much larger than previously recognized. Hence, the fate of the Arctic will eventually affect all of us.

Mountain ecosystems are warming more than average and probably will continue to do so. Snow and ice cover is declining in most mountain areas, often leading to increasing water shortages during the growing season.

Figure 8.12 Baby leatherback turtle on its way into the ocean. Many turtle beaches will be lost to rising sea levels.

Alpine plants and animals are facing a disproportionately high risk of extinction from global warming. In particular, the mountain areas in the interior of continents will face increasing drought problems. But even in the humid tropics, as in Borneo or Costa Rica, mountain plants and animals are sensitive to water stress. Warming has already been shown to cause mass extinctions of amphibians in highland areas. For Europe, a study found that about 60% of all mountain species may be lost.

Lakes, rivers, and *wetlands* will also be strongly affected by further warming. Water quality and oxygen content in lakes is expected to decline, since a warming climate causes a more stable layering of the water. A thin layer of warm water tends to float on top, preventing mixing. Major changes are likely in the composition of species and the growth cycles of plankton. For example, more toxic blooms of blue-green algae can be expected. In tropical lakes, the productivity and fish yield is expected to decline – already the limited warming during the twentieth century has caused the fish yield of Lake Tanganyika to drop by 30%. For 2–3 °C warming, many Arctic lakes will dry out, and migrating species will lose their watering stops. Some will be threatened by extinction.

The *oceans* and *coastal seas* provide many services critical to the functioning of the Earth system, and over one billion people depend on fish as their main animal protein source. Coastal zones are particularly vulnerable to climate change. The main impacts are warming of the water, a reduced nutrient supply of the sunlit surface waters due to more stable layering (as explained above for lakes), sea level rise, loss of ice cover, increased disease risk, and acidification. Some coastal ecosystems are threatened by suffocation, as the increased stratification and reduced mixing can cause a critical loss of oxygen in the water (a "hypoxic event" in the sober language of science). Of particular concern is the accelerating loss of sea ice cover, since the ecosystem associated with the sea ice is the most productive of the Arctic Ocean and supports a substantial food web. Fish, krill, seals, and polar bears will all be affected – and some of the richest fishing grounds on the planet, e.g., in the Bering Sea. At the tropical end of the scale, a sea level rise of only half a meter would wipe out a third of all the turtle nesting beaches in the Caribbean.

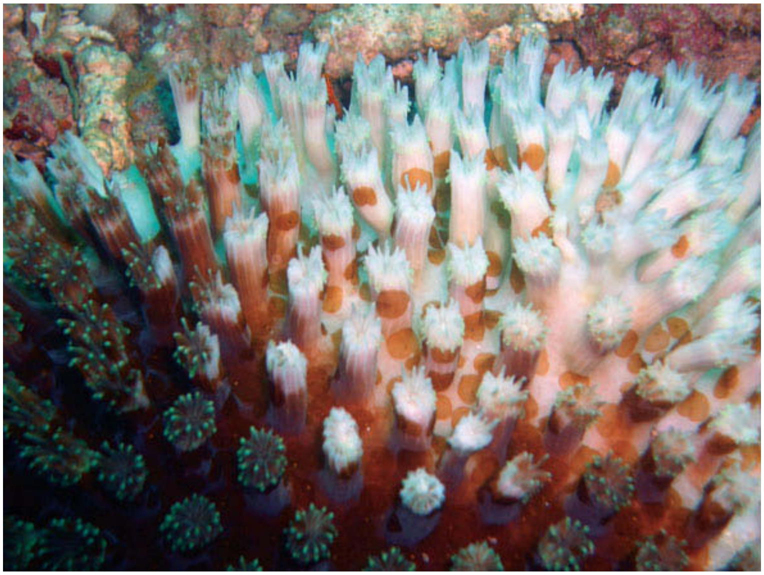


Figure 8.13 When water becomes too warm, corals become stressed and expel their zooxanthelae in a process known as coral bleaching. If the sea temperature does not drop quickly, the expulsion becomes permanent and the coral dies.

The most diverse marine ecosystems are coral reefs, which harbor a quarter of all ocean species. They are under multiple threats from warming (causing bleaching), acidification, and turbidity of the water arising from local pollution. In 25 years from now, the oceans will have warmed so much that the majority of coral reefs could suffer bleaching at least every second year. This is likely to destroy the reef ecosystem as we know it, leading to reefs dying off and being covered in algae. In addition, the ocean waters are turning increasingly sour – reaching an acid level critical for corals by the year 2070, unless we stop the trend of rising CO_2 concentration. Equally threatened are the ancient, slow-growing and fragile cold-water coral reefs. Not many lay people even know about their existence – yet they are as abundant as the well-known warm-water corals and also harbor a rich and distinct biodiversity. Acidification will also threaten the entire Southern Ocean ecosystem, where a critical threshold could be crossed before the end of this century: polar and subpolar waters will be under-saturated with aragonite by then. This means that the many organisms that use aragonite from the water to make their shells will be at risk. These organisms dominate the food web and carbon uptake of the polar ecosystem.

In addition to the eight ecosystem types discussed above, the migratory birds that travel across ecosystems deserve a special mention. They are likely to be even more vulnerable than stationary species. The routes and timing of their travels are highly adapted to certain conditions found at particular times at their breeding or wintering sites or at stopover points. Many have to cross difficult barriers like the Sahara Desert or oceans. Critical stopover habitats could be lost through sea level rise (e.g., Delaware Bay in North America) or suffer a deterioration of vegetation (e.g., the Sahel). A review of 300 migratory bird species found that 84% of them will face some threat from climate change – equal in severity to the threat from all other human activities combined.

Overall, the picture of the expected impacts of global warming on the world's ecosystems is dire. Simulations with global vegetation models support the conclusion that a large fraction of the Earth's surface will be transformed by major shifts in vegetation cover (Figure 8.14). These changes will likely turn the land biosphere from a carbon sink into a carbon source some time in the second half of this century, exacerbating atmospheric CO_2 concentration and global warming.

Food, water, health: how global warming will affect us

We have now discussed the expected impacts of global warming on natural ecosystems, but what about us humans? To what extent is human society vulnerable to climate change? Numerous scientific studies over the past years have collected evidence towards answering this fundamental question.

Let us start with one of the most basic issues: water. In the previous chapter we have discussed how some regions (especially in the subtropics) will become drier, others will become wetter, and the land area affected by drought and the risk of flooding are expected to increase strongly. This is reflected, for example, in the expected changes in river runoff shown in Figure 8.15. In addition, reduced snow pack and vanishing mountain glaciers will reduce the flow in many important rivers especially in the summer months, when water is most needed. These are major hydrological changes, and Figure 8.15 also summarizes their most important impacts on human society. The IPCC report concludes that the number of people living in "severely stressed" river basins will increase drastically, namely by one to two billion people in the 2050s. About two-thirds of the global land area is expected to experience increased water stress, and only less than a third will see a decrease. With high confidence it is concluded that the negative impacts of climate change on fresh

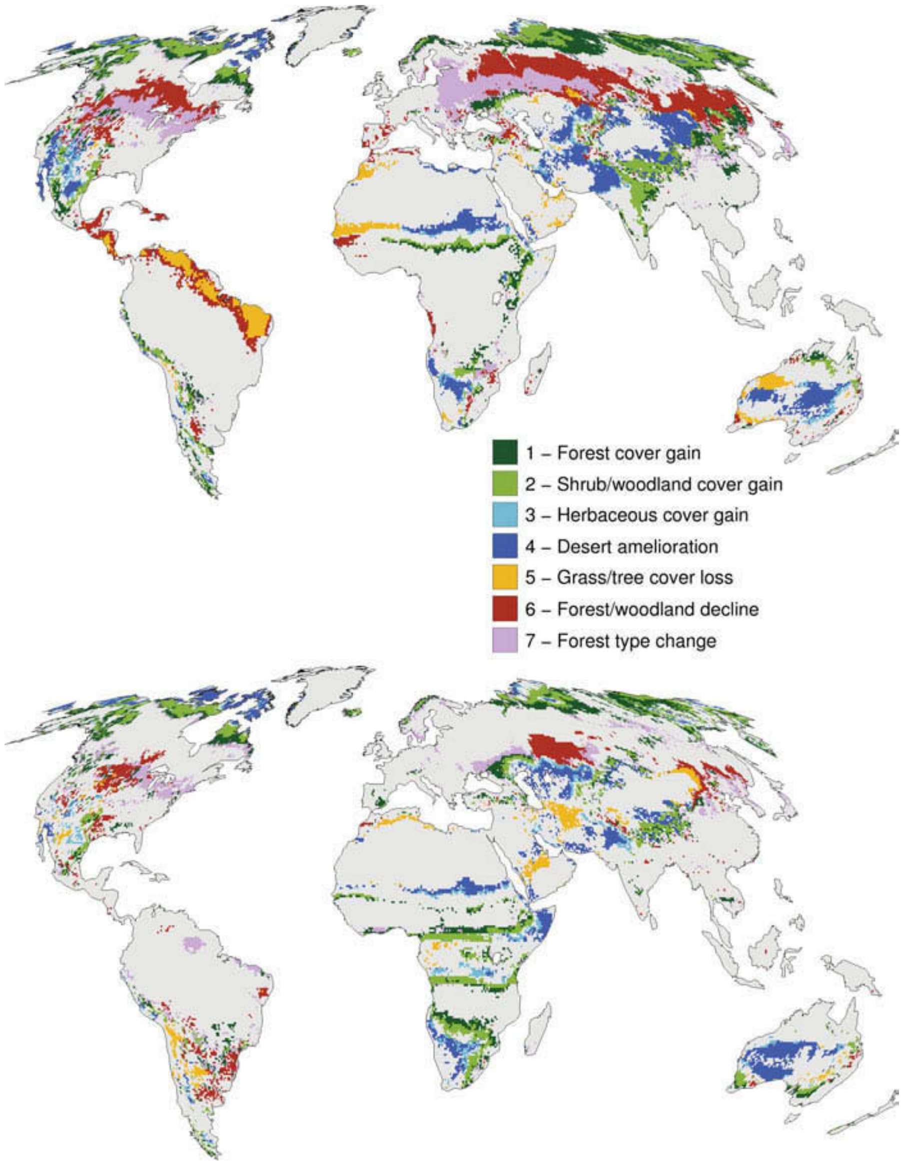


Figure 8.14 Projected changes in terrestrial ecosystems by the year 2100 as simulated by a global vegetation model, driven by two different climate models and emission scenarios (top: HadCM3 model driven by A2 scenario; bottom: ECHAM5 model driven by B1 scenario). Changes are only shown where they exceed 20% of a simulated grid cell.

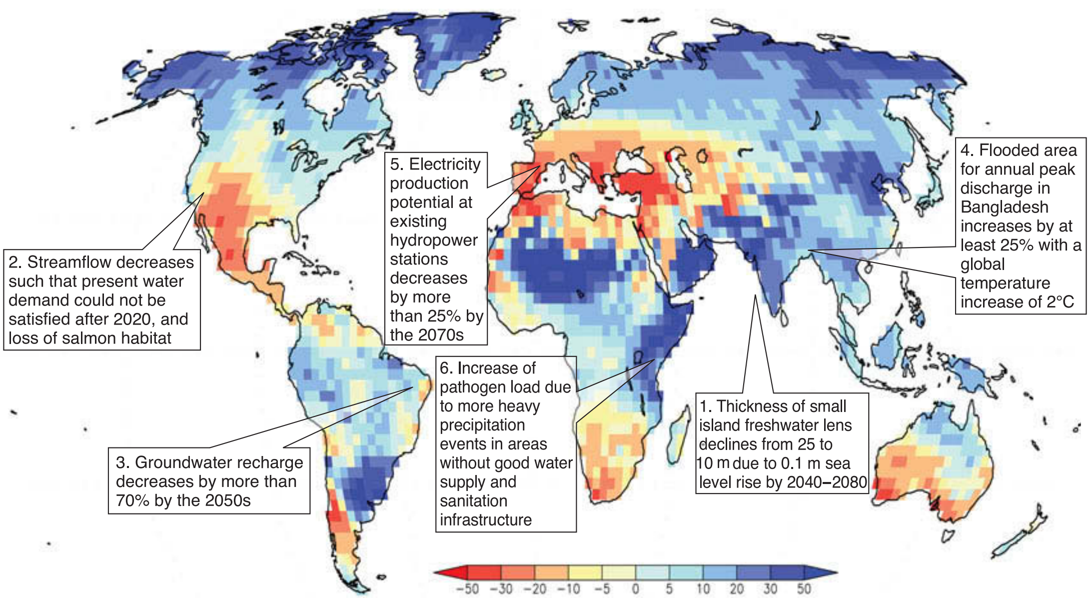


Figure 8.15 Projected changes in runoff by the end of this century, based on a suite of model simulations for the emission scenario A1B. Blues shows increased runoff, red decreased runoff (in %). This map points to serious future drought problems, e.g., in the Mediterranean region, southern Africa, the south-west of the United States and western Australia.

water systems will outweigh the benefits. Among those negative impacts are exacerbated problems with many forms of water pollution and impacts on human health and the reliability and operating costs of water supply systems.

The availability of fresh water is very tightly linked to the issue of agriculture and food supply. How will climate change affect our ability to feed a growing world population? A general answer is impossible; we need to look in some detail at the climate tolerances of specific crops grown in specific regions, and we need to take into account economic developments and the ability of farmers to adapt to a changing climate, e.g., by switching crops or by investing in irrigation. From the studies performed thus far, a pattern emerges. For a moderate climatic warming (up to 3 °C), important crops such as cereals and pasture growing in mid- to high-latitudes will probably benefit to some (small) extent. However, for a greater warming, yields will start to decline below current levels. Suitable adaptation measures can help to maintain high productivity in warmer conditions, but if it gets too warm productivity will eventually drop. In the tropics and in seasonally dry regions, the picture looks different: a decline in yield is expected for most crops even for slight warming, becoming quite drastic for large warming (see Figure 8.16).

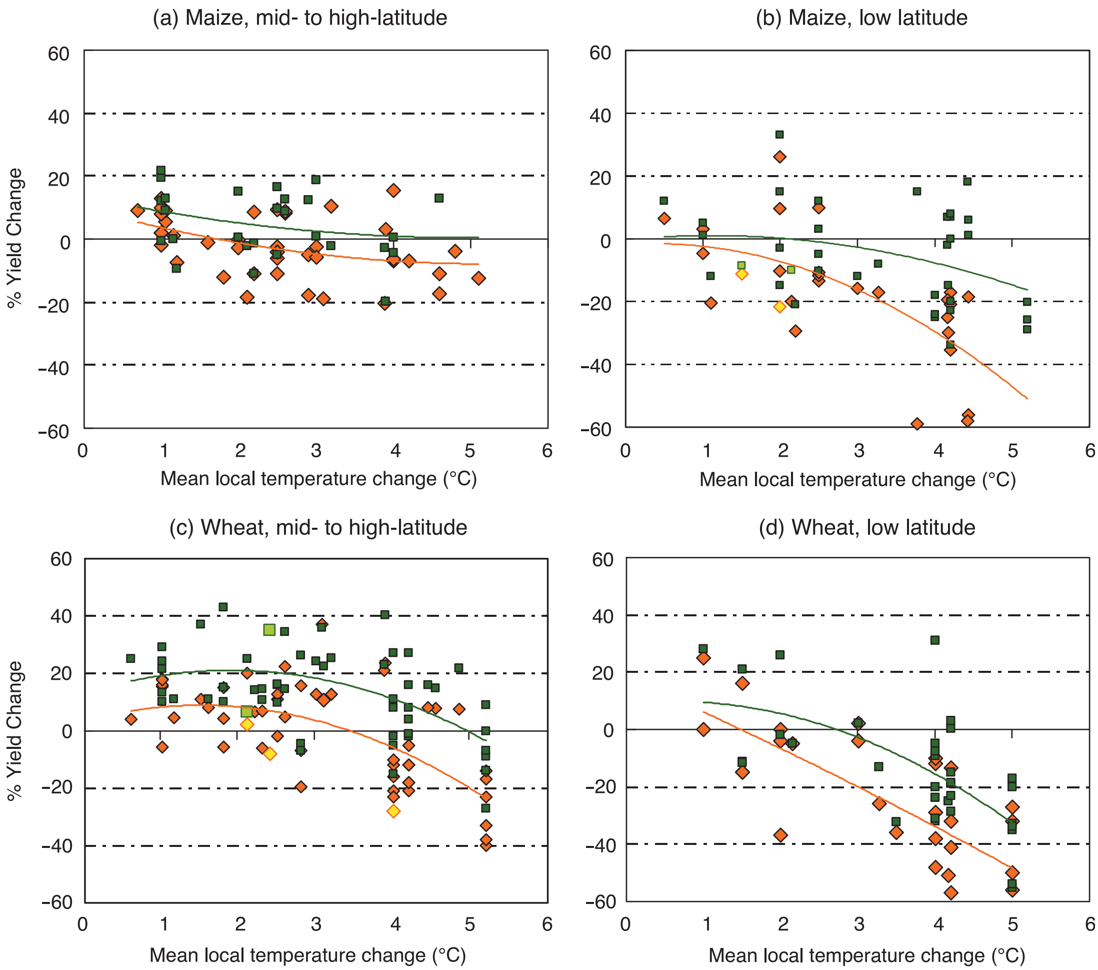


Figure 8.16 Simulation results for future crop yields in a warmer climate vary widely, depending on differences in the models for things such as precipitation and climate variability changes and the CO_2 fertilization effect. Overall they suggest a serious decline in yields especially for larger warming.

In addition, climate warming and elevated CO_2 is expected to reduce fishing yields in many regions. In the North Atlantic, a slow-down of ocean currents (see Chapter 7) could have serious consequences for fisheries.

What does this mean for the risk of hunger in our world? Today, about 820 million people are undernourished. Obviously food shortages are affected strongly by socio-economic and political factors. Without climate change, most of the economic scenarios of the IPCC assume a positive trend where the number of undernourished people will decline strongly over the coming 75 years due to favorable socio-economic development: down to 100–240 million people for the more optimistic scenarios (the A1, B1, and B2 scenarios of SRES, see above). Climate change is expected to prevent a part of these benefits, adding up to 140 million undernourished. However, the social scientists also considered a more pessimistic future world with less international cooperation and trade (A2 scenario). In this case the number of undernourished people is expected to remain almost steady at 770 million even without climate change, rising to up to 1.3 billion through the effects of climate change. These numbers are very uncertain, though, and the IPCC classifies them as "low to medium confidence." They should thus not be taken at face value but rather as an illustration of the fact that, depending on how we act, climate change could substantially increase the risk of hunger.

There is another very important caveat to these numbers: they are based on changes in mean climatic conditions (average temperatures, average rainfall), not on an analysis of extreme events. The rising number of extreme events such as droughts, floods, heat waves, fires, or pest outbreaks will very likely add substantially to the number of people threatened by famine, especially for those depending on subsistence farming who cannot afford to buy food from the world market. Overall, tropical countries are expected to become more and more dependent on international food trade as yields decline in the tropics and increase in higher latitudes. This means that poor people, who have contributed very little to the rise of greenhouse gases in the atmosphere, will suffer most from the effects. These people also can do very little to reduce their vulnerability to extreme climate events.

After the impacts on water and food security, the impact on the coastal zone is perhaps the next most serious effect of global warming for human society. In Chapter 5 we discussed the observed sea level rise, in Chapter 7 we discussed the expected future sea level rise, and here we will consider how sea level rise will affect our coastlines and cities. Climate change impact on the coasts is "virtually certain to be overwhelmingly negative." These impacts include increased risk of flooding, loss of coastal ecosystems such as salt marshes, mangroves (Figure 8.17), and coral reefs (which protect the coast from storm surges and tsunamis), and the degradation of fisheries and fresh water resources (due to salt intrusion). Most of the sandy shorelines of the world have already retreated during the past century, and with increasing sea level this trend will accelerate. A rule of thumb is that for every centimeter of sea level rise in the vertical, the coastline will retreat by 50 to 200 times as much in the horizontal.

Around 120 million people are exposed each year to hazards from tropical cyclones, and these storms caused 250,000 deaths between 1980 and 2000. These storms are becoming more hazardous as the sea level rises, and the intensity of the storms is increasing – see Figure 8.18. In addition, more and

Figure 8.17 Coastal mangrove forests, like this one on the island of Hispaniola, are threatened by sea level rise.

more people are moving to coastal areas. Coastal population could grow from 1.2 billion in 1990 to anywhere between 1.8 and 5.2 billion in the 2080s. "Hot spots" of greatest risk include river deltas, partly because these deltas often suffer from subsiding land, and partly because they are population centers – the seven Asian megadeltas already have a population exceeding 200 million. Figure 8.19 shows some of the most vulnerable deltas. The IPCC concludes that, without action, some islands and low-lying coastal areas (e.g., in deltas) could become uninhabitable by the year 2100.

Despite the large uncertainty about the exact amount and impact of sea level rise, the costs of climate change for coastal regions are "virtually certain to escalate." However, they can be reduced by appropriate adaptation measures such as coastal defenses and early warning systems. In the long run, beyond the year 2100, sea level will continue to rise for many centuries and would rise by several meters if the threshold for a melt-down of the Greenland

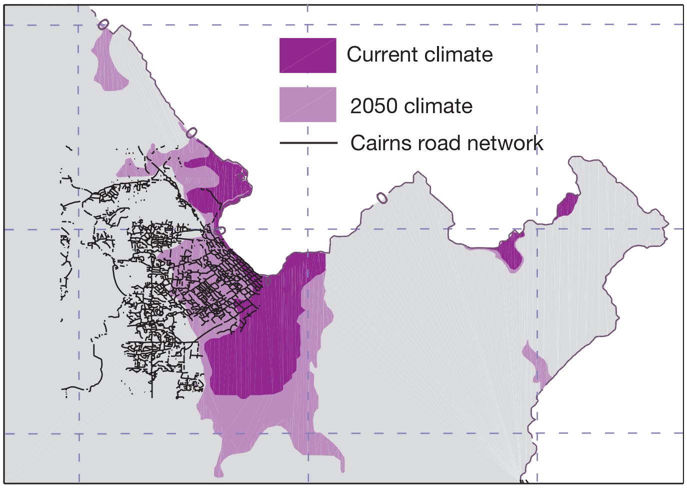


Figure 8.18 The map shows how much of the city of Cairns in Australia would be flooded during a storm surge with a return period of once per century, both for current climate and for the projected climate in the year 2050.

Figure 8.19 Vulnerability of coastal deltas, based on estimates for the population that would be displaced by current sea level trends by the year 2050. "Extreme" vulnerability (large red dots) indicates over 1 million displaced people; "high" vulnerability indicates between 50,000 and 1 million, and "medium" refers to between 5,000 and 50,000 displaced.

ice sheet were crossed. The report notes: "this questions the long-term viability of many coastal settlements and infrastructure (e.g., nuclear power stations) across the globe" (see Figure 8.20). It concludes: "it has become virtually certain that the most appropriate response to sea-level rise for coastal

Figure 8.20 Coastal infrastructure, like the Sizewell B nuclear power station in Great Britain pictured here, is at risk when sea levels rise.

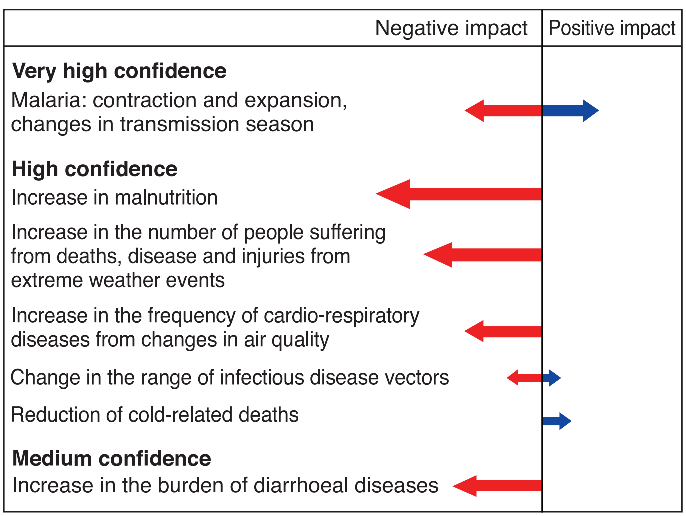


Figure 8.21 Direction and magnitude of selected health impacts of climate change.

areas is a combination of adaptation to deal with the inevitable rise, and mitigation to limit the long-term rise to a manageable level."

Finally, let us take a look at future human health impacts of global warming. Climate change is already contributing today to the burden of disease and premature deaths, and it is expected to have far more serious health impacts in the future. A simple overview is presented in Figure 8.21. Some impacts are positive, like reduced deaths from cold spells, but more will be negative. Many millions of people will suffer from an impairment of their health and well-being. A relatively well-studied issue is malaria. Although in some parts of Africa malaria transmission is likely to decline, the disease will spread into other areas not previously affected, such as highlands. Warming is expected to increase the population at risk by 220 to 400 million people overall. The drought problems and other agricultural impacts discussed above will lead to malnutrition for many people, impairing the healthy development of children. Extreme weather events will cause deaths, injuries, and disease outbreaks.

A hotter climate is also bad for air quality. Many regions in the developing world already suffer serious air pollution problems now, for example from the notorious Asian haze. But even in North America and Europe, summer smog from low-level ozone in cities is expected to increase strongly, worsening respiratory diseases and heart problems. The flip side of this is a "double dividend" of many emission reduction measures. They pay off twice, first in direct health benefits to people and later by limiting global warming.

A score of infectious diseases will spread their range in response to global warming. Incidences of diarrhea and food poisoning are expected to increase. The Lyme disease vector will move north in Canada by 1,000 kilometers over the coming 75 years, and the abundance of ticks may increase two- to four-fold. Tick-borne encephalitis is also expected to make its way northward. By the year 2085, an estimated 3.5 billion people will be at risk from Dengue fever.

Climate impacts by region

Thanks to the improved resolution of global climate models, the development of regional models, and many regional impact studies "on the ground," the fourth IPCC report is able to devote eight full chapters to regional climate change impacts. The compilation of such an enormous amount of information from diverse sources is another example of the power of large assessment exercises. From this wealth of information we can only briefly give a few examples from different parts of the world here.

In *Africa*, agricultural production will likely be "severely compromised." At the same time, Africa is amongst the most vulnerable continents (see Figure 8.22), due to the extreme poverty of many Africans, weak governance structures, frequent natural disasters, and a strong dependence on rain-fed agriculture. Problems with access to safe water, already worsening through other factors, are likely to be further exacerbated by climate change. As soon as the year 2020, up to 250 million people are projected to be suffering

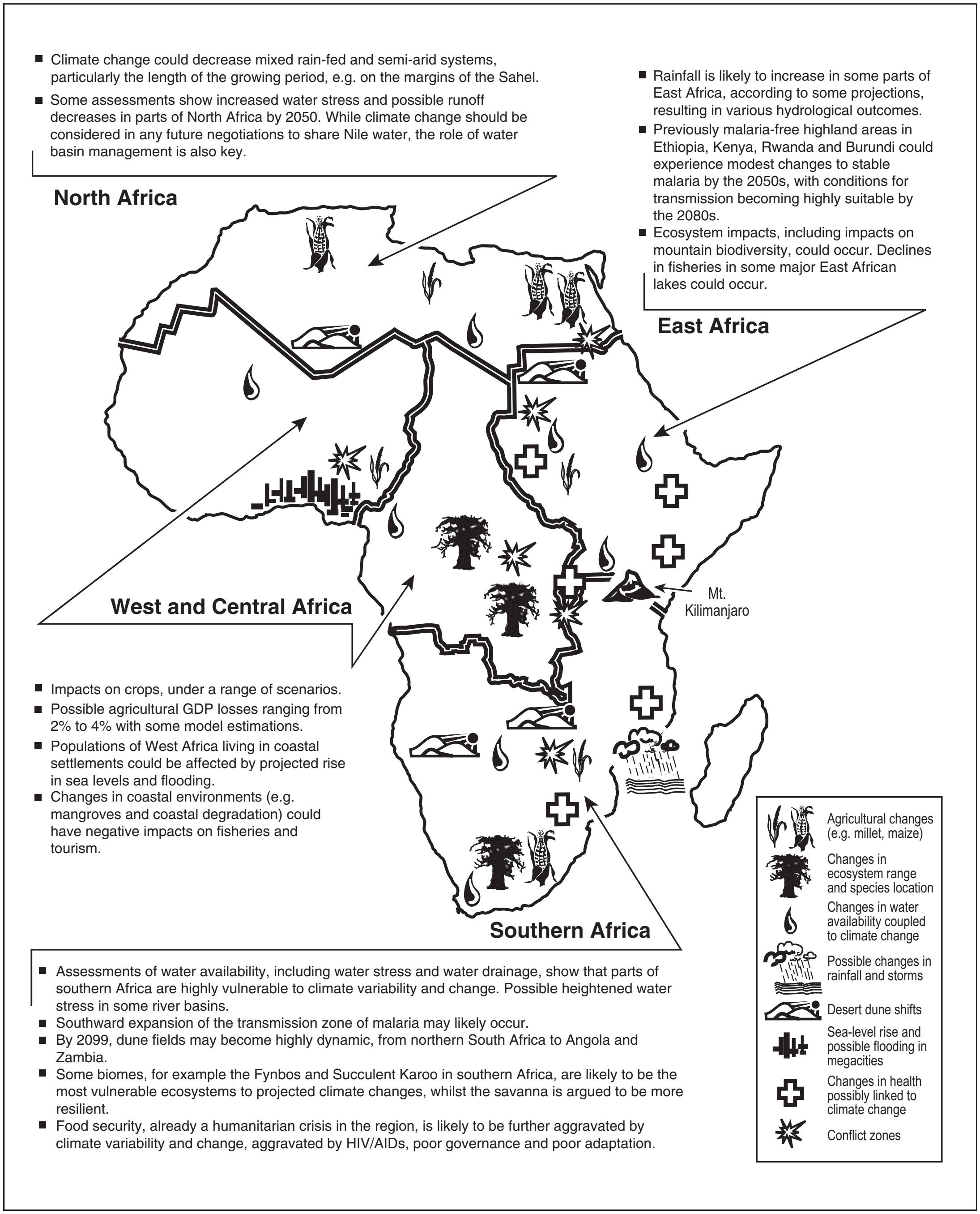


Figure 8.22 Overview of current and possible future climate risks for Africa.

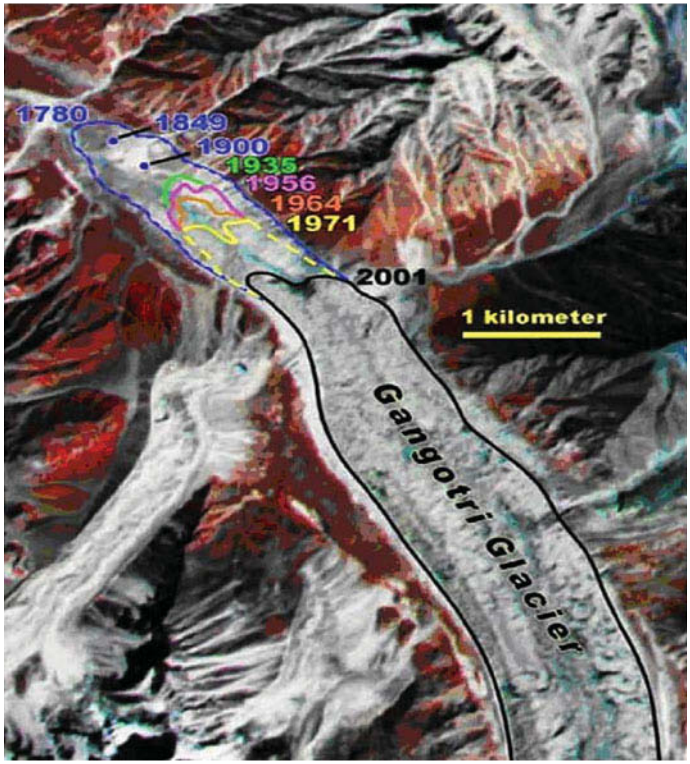


Figure 8.23 Retreat of the Gangotri Glacier in the Himalayas. Historic glacier outline superimposed on satellite images.

from increased water stress due to climate change. One of the most famous landmarks and tourist attractions of the African continent, the ice on Mount Kilimanjaro, is disappearing rapidly.

Asia is likewise suffering from rapid loss of glacier ice (Figure 8.23). Himalayan glaciers are the largest body of ice outside the big polar ice caps, and together with snow melt they contribute to the summer flow of major river systems such as the Indus, Ganges and Brahmaputra. These rivers form the lifeline for many millions of people; their flow initially increases during glacier melt, then is reduced, especially during the dry season, once the glaciers are gone. By 2050, more than a billion people could be adversely affected by water stress arising from climate change. Crop yields in Asia have recently been declining, probably as a consequence of warming. A further decline is expected, up to 30% in Central and South Asia by mid century. In Siberia and the Tibetan Plateau, permafrost is warming up and starting to thaw. South-East Asia hosts the largest area of coral reef in the world (92,000 square kilometers) – of this, only 5% is healthy, 38% is already destroyed and a further 28% is at

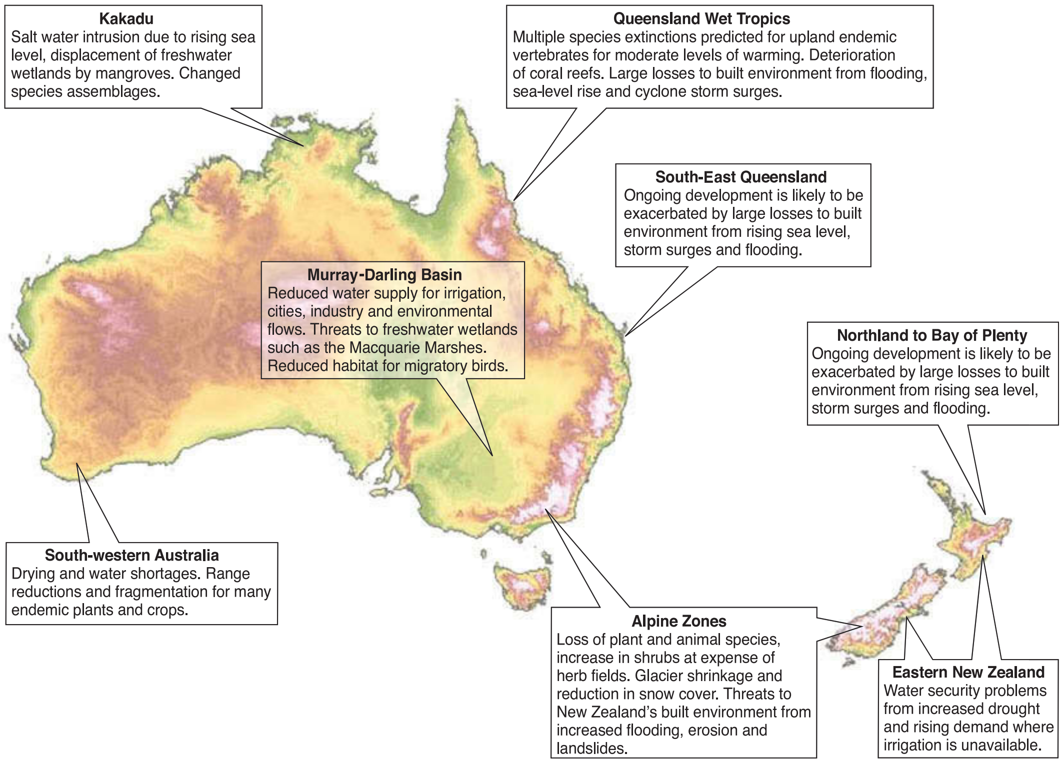


Figure 8.24 Hotspots of climate change in Australia and New Zealand.

a critical stage. In China, the incidence of flooding from extreme rainfall has increased seven-fold since the 1950s. At the coast, China and several other countries are vulnerable to tropical cyclones of increasing intensity combined with increasing sea level. In the 54 years from 1950 to 2004, 21 extreme storm surges hit China, two-thirds of which occurred in the last 18 years.

Australia and New Zealand (Figure 8.24) are already noticing the effects of warming temperatures and rising sea levels, as well as an increase in the intensity of Australian droughts. As early as the year 2020, significant losses of biodiversity are expected in some of the most beautiful and valuable ecosystems: the Great Barrier Reef, the Kakadu Wetlands, some subantarctic islands, and the mountain regions of both countries. Drying and water shortages are expected to be the main future problems for people in large parts of Australia and New Zealand. Forestry in many parts is expected to decline due to drought and fire problems, although initially some forest plantations in New Zealand may benefit from warming.

In *Europe* (see Figure 8.25), climate change impacts are split in a north–south direction: southern Europe will become (and is already becoming) drier,

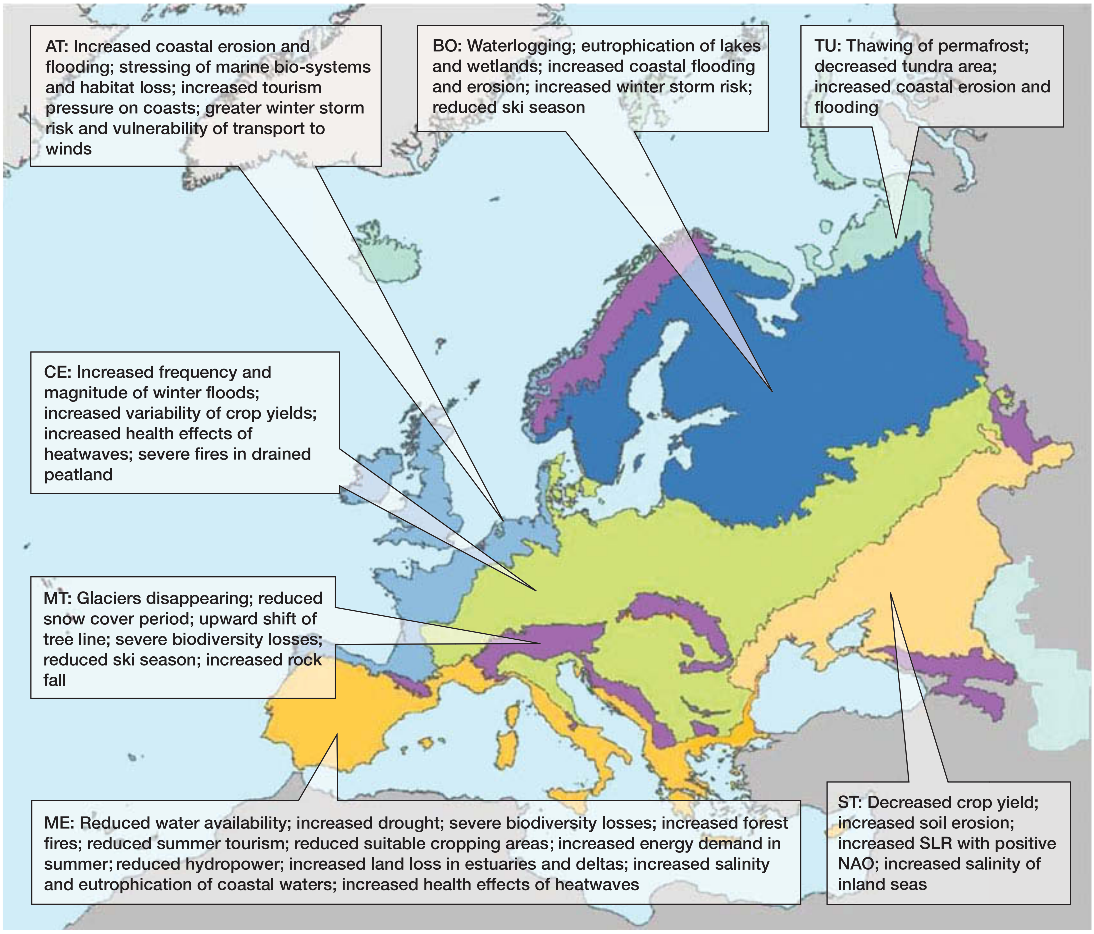


Figure 8.25 Map of key vulnerabilities to twenty-first century climate change in Europe. Different colors indicate different biogeographic regions: TU, Tundra; BO, Boreal; AT, Atlantic; CE, Central; MT, Mountains; ME, Mediterranean including Black Sea; ST, Steppe. SLR stands for sea level rise, and NAO, for North Atlantic Oscillation.

while northern Europe is getting wetter. The increasing water stress in the Mediterranean region raises the fire risk there, as is illustrated by the dramatic fires in Greece in August 2007. It is also expected to reduce the hydropower potential by 20–50% by the 2070s. European mountain glaciers will lose between 30 and 70% of their mass by mid century. The extreme heat wave of 2003 was an unexpected outlier at the time it occurred, but will be a normal summer by the 2040s. The risk of flash floods will increase. In Europe, the “great majority of organisms and ecosystems are likely to have difficulty in adapting to climate change,” and extensive species extinctions are expected.

Latin America has been hit by a series of highly unusual weather extremes in recent years. Hail storms in Bolivia (2002) and the Greater Buenos Aires area (2006), intense rainfall in Venezuela (1999, 2005), flooding in the Argentine Pampas (2000–2) and drought in the Amazon (2005). Then there was the first ever hurricane in the South Atlantic (2004) and the record hurricane season of 2005 in the Caribbean. The loss of mountain glaciers is critical in Bolivia, Peru, Colombia, and Ecuador. Water supplies there are already affected, and the situation is expected to get worse as glaciers in the Andes disappear in coming decades. Water stress, weather extremes, sea level rise, and species extinctions will all affect Latin America, with some of the "hot spots" shown in Figure 8.26. In eastern Amazonia, savanna is expected to gradually replace the existing tropical forest, although a more dramatic collapse of rain forest cannot be ruled out.

In *North America* the aftermath of hurricane Katrina has demonstrated that even a highly advanced and wealthy nation is vulnerable to extreme events, and may be ill prepared despite repeated advance warnings of its scientists.

With rising sea levels and coastal erosion, storm impacts will likely become more severe in the future and coastal ecosystems are under threat. Water supplies in North America are increasingly affected by the diminishing snow pack, leading to more flooding in winter and water shortages in summer. Water levels in the Great Lakes and some major rivers are expected to fall, causing problems, e.g., with shipping and hydropower generation. North Americans in urban centers will be affected by heat waves, rising ozone pollution and pollen stress and the growing risk of respiratory illness or vector-borne diseases. In some areas, like California and Canada, the risk of wildfire is growing (Figure 8.27 and Figure 8.28).

Impacts of warming are already very clear in the *Arctic*, where surface temperatures have warmed at twice the global rate and sea ice cover has shrunk dramatically in recent decades. Polar ecosystems are especially vulnerable, as many species have adapted to harsh conditions and will not be able to compete with intruders when climate warms. They are also vulnerable to pests and parasites. Species richness is low, and loss of keystone species like the lemming could harm entire ecosystems. The Arctic Ocean already shows major changes in its ecosystem, and it will be transformed once the sea ice cover is largely gone in the summer months (Figure 8.29). Traditional ways of life of Arctic communities are being threatened and some communities will need to be relocated.

In the *Antarctic* region, seals, Adelie and Emperor penguins, and krill have all been declining, while shallow-water sponges and their predators are becoming more abundant. Alien species are taking hold on subantarctic islands, harming the unique native ecosystems there.

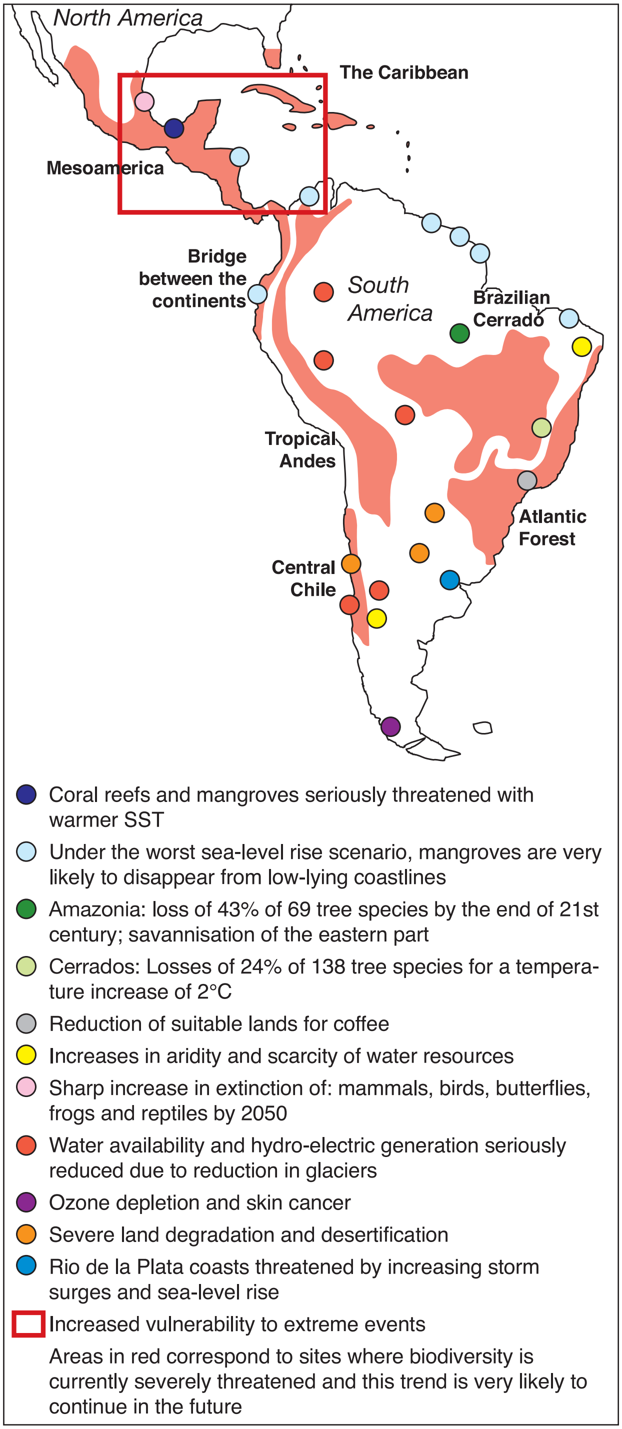


Figure 8.26 Map of key hot spots of particularly severe climate change for Latin America.

Figure 8.27 Satellite view of wild fires in California in summer 2007.

Finally, *small islands* are given a separate chapter in the report, due to their special vulnerability to extreme events and sea level rise. Over half of the population of Caribbean and Pacific islands live within 1.5 kilometers of the shore, and most airports, major roads, and other infrastructure are right by the sea. Therefore, sea level rise and the resulting problems of inundation and erosion are an existential threat to the people living on such islands. Also, the supply of fresh water is often very limited on such islands, and reduced rainfall in some regions and salt water intrusion due to sea level rise are expected to lead to water shortages. The decline in coral reefs, discussed earlier in this chapter, will further compromise the economic viability of small islands, and some may have to be abandoned.

Can we adapt?

When discussing the response of human society to climate change, two fundamental options are usually distinguished: *adaptation* and *mitigation*. Mitigation refers to efforts to reduce the rate and magnitude of climate change

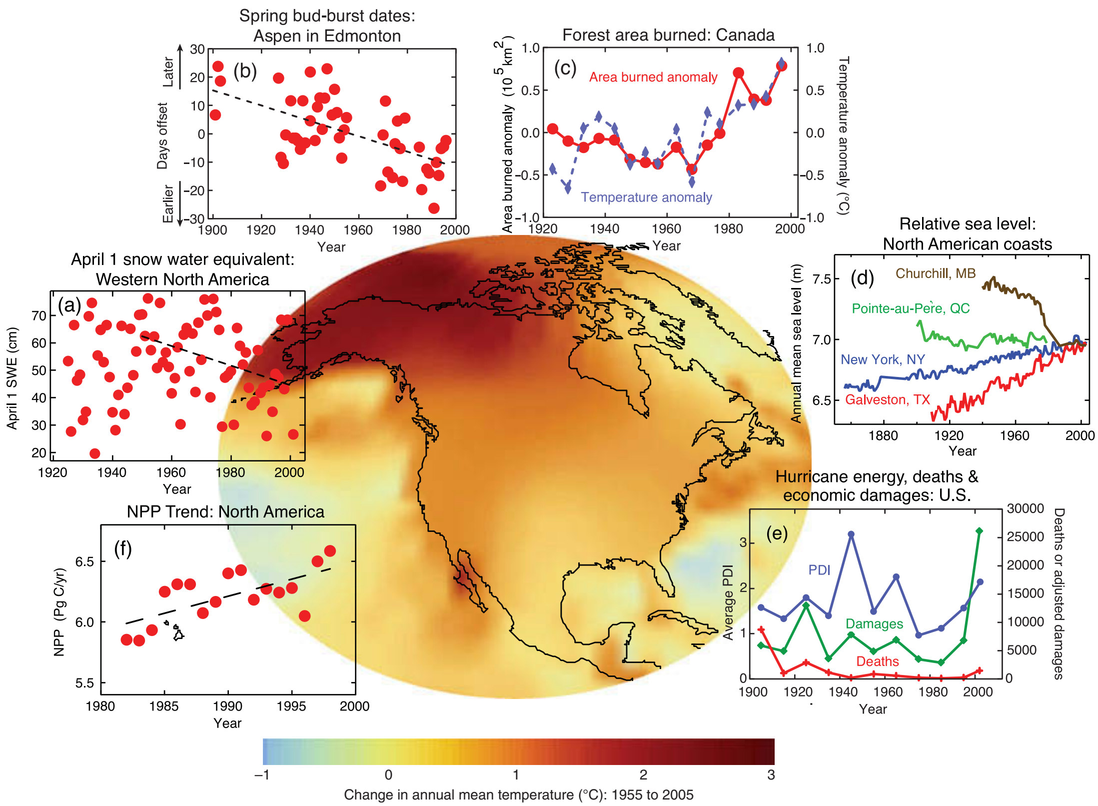


Figure 8.28 Forest area burned in Canada, compared to local temperatures (both shown as 5-year averages).

by reducing the emissions of greenhouse gases – the options for this will be discussed in detail in the next chapter. Adaptation describes efforts to cope better with the consequences of a given climate change. Adaptation and mitigation are not alternatives; rather, there is a wide consensus amongst experts that both are essential. On one hand, climate is already changing and will continue to change for several decades at least, so it is inevitable that we will need to adapt to these changes. On the other hand, if climate change is not limited by mitigation efforts, the ability of human society and ecosystems to adapt to the changes will very likely be outstripped by far.

Politically, there is a fundamental difference between mitigation and adaptation. Concerning mitigation we are all in the same boat: a ton of CO_2 emitted anywhere in the world will be mixed throughout the atmosphere and remain there for decades, and some of it even for millennia, affecting everyone on the planet. Mitigation is therefore a classic “tragedy of the commons” problem; its solution requires people around the world working together for the common good. It is likely to require a level of global cooperation

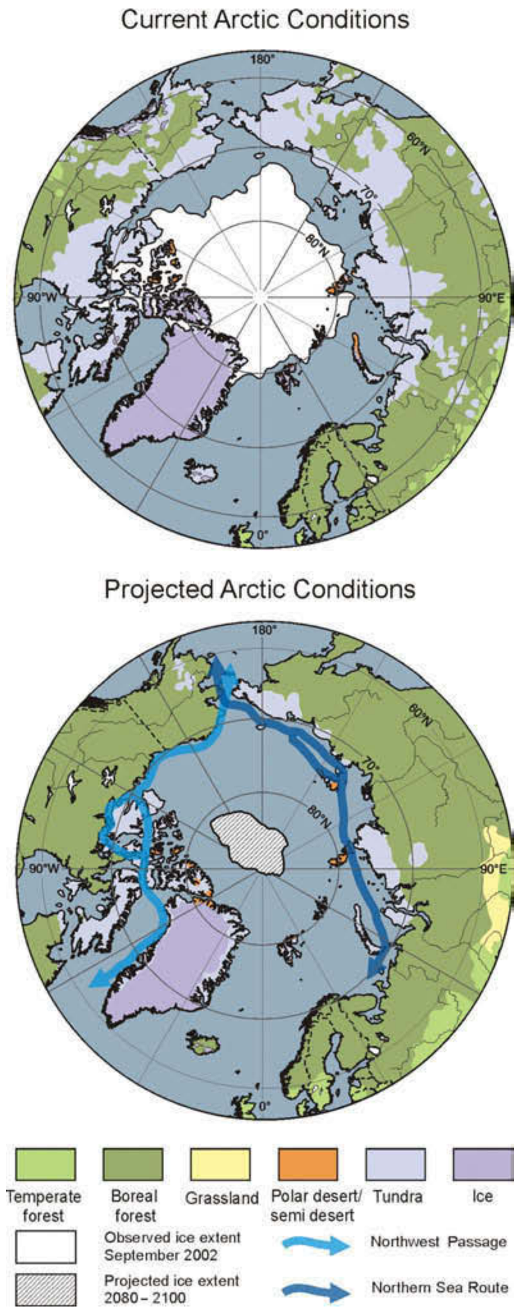


Figure 8.29 Projected changes in the natural conditions in the Arctic until the end of the century. Shown is the summer sea ice extent as well as vegetation changes. Blue lines indicate potential new shipping routes.

Figure 8.30 Malé, capital city of the Maldives in the Indian Ocean. Many small island nations are extremely vulnerable to sea level rise.

unprecedented in the history of mankind. Adaptation, in contrast, is something that everyone can do for their own benefit. For example, the Netherlands can raise its dykes to adapt to rising sea level, and the Dutch people will be the direct beneficiary of that. Mitigation is therefore the far harder problem and requires much more political negotiation. Nevertheless, for reasons of justice, adaptation also needs international collaboration, since many poor countries simply have insufficient resources for proper adaptation measures. At the same time, they are usually only responsible for a very small portion of greenhouse gas emissions and rightly demand help from those countries who have caused the climatic problems they are facing. There is also a difference in time scale: mitigation is a long-term problem, where it will take decades until a tangible success is seen. Adaptation measures are often of immediate benefit. On the other hand, they may only help in the short term unless mitigation is successful.

Some planned adaptation to climate change is already occurring. For example, the coastal defense plans of the Netherlands and Norway are taking climate change and the associated sea level rise explicitly into account. A different example is the controlled drainage of a glacial lake in Nepal to

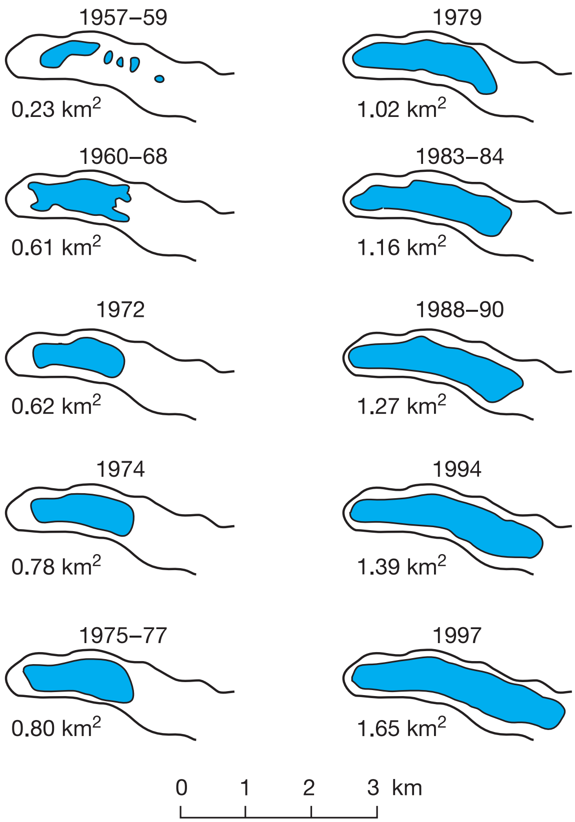


Figure 8.31 The growth of the Tsho Rolpa glacier lake in Nepal. The lake had to be drained in a controlled way to avoid a catastrophic outburst flood.

avoid a catastrophic outburst flood, see Figure 8.31. In many cases, early planning with proper foresight is less risky and cheaper than a "wait-and-see" approach, which would cause the need for costly retro-fitting of dykes and other long-term infrastructure in response to climate change.

Adaptation for water shortages can include water storage and conservation measures, rainwater harvesting, or sea water desalination plants, e.g., for small islands, as well as more efficient drip irrigation techniques. In agriculture, planting times and crop varieties can be adjusted, and land management can be improved to prevent soil erosion, e.g., by planting trees. In coastal zones, sea walls, dykes, and storm surge barriers can be built. Natural barriers against storm surges (e.g. marshlands and wetlands) can be protected. And in some cases a planned retreat from vulnerable coastal areas is advised before a storm surge disaster strikes. The health problems associated with a warmer climate can be alleviated by better health services, improved sanitation and safe water supplies, and access to public "cooling centers" during heat waves. Tourism can adapt, e.g., by shifting ski slopes to higher altitudes and by diversifying attractions to become less dependent on specific weather conditions.

Such adaption measures are vital and beneficial – this was already noted in the previous IPCC report, and it is reaffirmed strongly in the *Fourth Assessment Report*. However, the report also notes that adaptation will never be perfect. Even in affluent and technologically advanced societies, many factors limit successful adaptation. The disastrous 2003 heat wave in Europe or hurricane Katrina in the United States have highlighted that some groups of society, such as the elderly, remain particularly vulnerable. In countries with far more limited resources, it seems all the more likely that some parts of society will suffer much more than others from the effects of climate change – be it the poor, elderly, children, or indigenous populations. And the report makes one thing clear: "Adaptation alone is not expected to cope with all the projected effects of climate change, especially over the long term as most impacts increase in magnitude."

9 Avoiding climate change

The third volume of the IPCC Scientific Assessment Report is an evaluation of what it would take, and how much it would cost, to avoid global climate change. The *Working Group III Report* reviews many industrial processes and economic sectors that will contribute to changing the climate, including projections for future growth and potential for reducing their climate impact.

Carbon dioxide and methane are the most important greenhouse gases to target for emission reduction. Carbon dioxide is the primary target because it contributes more than half of the total greenhouse gas forcing. Methane is the second most important anthropogenic greenhouse gas. A single molecule of methane packs a stronger punch to the climate system than does a molecule of CO_2, by a factor of about 30, but the CO_2 concentration in the atmosphere is rising so quickly that the climate forcing from all the anthropogenic CO_2 is twice as strong as that from methane. Also, the atmospheric lifetime of CO_2 is considerably longer than that for methane. Emissions of CO_2 commit the Earth to warming for centuries and millennia, while most of the warming from methane emissions will be over in a decade or two.

Since 1973, the emission rate of CO_2 has risen by about 50%. This increase can be broken down into a few simple factors as in the following equation:

$$CO_2 \text{ emission} = \text{Population} \times \$/\text{person} \times \text{Watts}/\$ \times \text{Carbon}/\text{watt}.$$

The first is the human population. More people emit more carbon. The next is economic prosperity represented as income per person. Energy production drives economic activity, so economic growth will cause CO_2 emissions to increase. The third factor is the rate of energy use per dollar of economic activity, a measure of efficiency called the energy intensity. Different forms of economic activity also require different amounts of energy: producing steel versus writing software, for example, have different energy intensities. The fourth factor is the emission of CO_2 per watt of energy, which reflects the efficiency and sources of energy generation.

The increase in CO_2 emission since 1973 has been broken down into these four factors in Figure 9.1. Population has risen since 2001 (yellow sections), as has economic prosperity (orange sections). These factors, which tend to push CO_2 emission higher, were offset somewhat by increases in energy efficiency (light blue sections), and until recently by a decrease in the carbon emission per watt of energy (dark blue sections). The carbon per watt factor has diminished in importance in the past few years, to being nearly neutral in the period 1993–2003, because of the scarcity of natural gas. Natural gas contains more energy per carbon atom than coal does, but scarcity and higher prices for natural gas are driving utility companies back to coal.

Projections of future emissions are sensitive to assumptions about future trends that are essentially impossible to forecast with any reliability. The future projections are therefore called "scenarios," and there are many of them, in an attempt to bracket the range of possibilities. Most of these are variations on "business-as-usual," which is intended to project CO_2 emissions in the absence of policies to prevent climate change (Figure 9.2). The emission projection

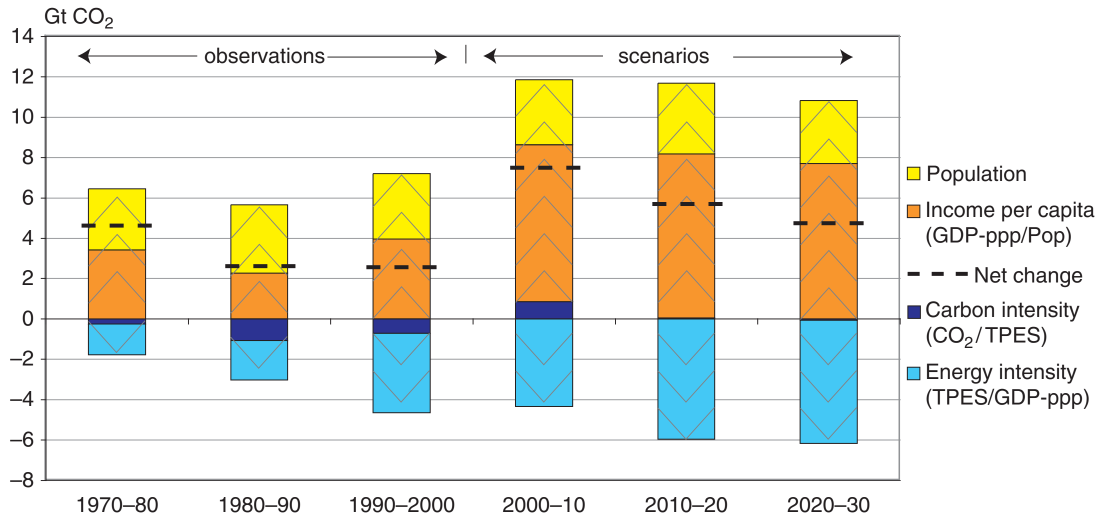


Figure 9.1 Historical trends and future projections of the factors that govern CO_2 emissions.

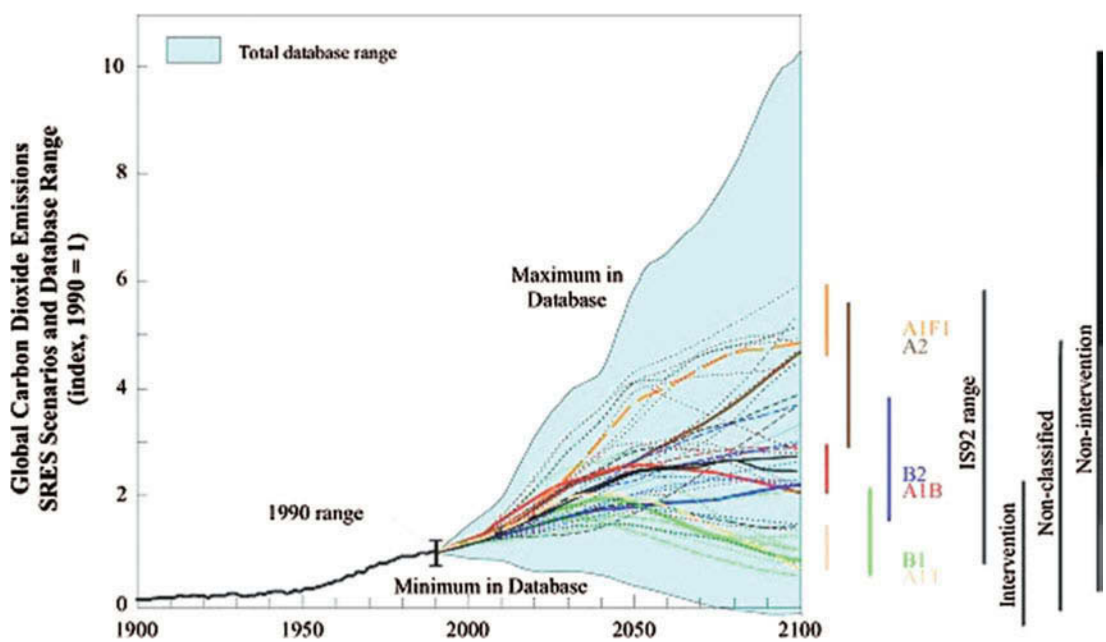


Figure 9.2 Rates of CO_2 emissions in Gton C per year from the various scenarios, from the IPCC *Special Report on Emission Scenarios*, 2000. To obtain values in Gton CO_2, rather than Gton C, the numbers need to be multiplied by 3.7, since a CO_2 molecule is 3.7 times as heavy as the carbon atom it contains, due to the extra weight of the two oxygen atoms.

depends on the scenario, but generally a doubling of CO_2 emissions by 2050 is expected under business-as-usual, with comparable increases for the other greenhouse gases. The Fourth Report concludes, somewhat discouragingly, that policies to avoid climate change, such as the Kyoto Protocol, have done little to alter the CO_2 emissions of the previous five years from the business-as-usual scenarios from the Third Report. In fact, the Montreal Protocol of 1987, limiting freon emission to avoid damaging the stratospheric ozone layer, has arguably done more to avoid climate change than the Kyoto Protocol has done so far, since freons don't just destroy ozone but are also potent greenhouse gases.

As an alternative to looking at business-as-usual, which would cause ever-increasing greenhouse gas concentrations in the atmosphere, the IPCC has also examined what it would take to stabilize those concentrations. Because the atmosphere is not just a bucket that fills up with gases at the rate we add them, it is not entirely straightforward to compute how fast we need to reduce our emissions to reach a certain stable concentration. For CO_2, this depends on how much the oceans and the biosphere absorb, so that carbon cycle models are needed to compute such stabilization scenarios (Figure 9.3). One also needs to consider the changes in other greenhouse gases such as methane, freons, and N_2O (Figure 9.4). To make discussions a little simpler, the total radiative effect of these other gases can be bundled together into an "equivalent" CO_2 concentration. For example, an equivalent CO_2 concentration of 450 ppm might translate to an actual CO_2 concentration of about 400 ppm, with other gases adding as much radiation as another 50 ppm of CO_2 would. For example, the category I stabilization scenarios shown in the first panel would lead to a stabilization between 445–490 ppm equivalent CO_2, or 350–400 actual CO_2. Stabilization in this range would in the long run likely cause a warming between 2.0 and 2.4°C above the preindustrial temperatures. To reach this stabilization, emissions would have to drop throughout this century to practically zero near its end, and would have to be 50–85% below year-2000 levels by 2050.

So there are estimates of expected CO_2 emissions under business-as-usual on the one hand, and estimates of allowable CO_2 emissions from stabilization scenarios on the other. The challenge is not just to reduce CO_2 emissions from their present values, but actually to reduce them as compared to the growing emissions that would normally occur due to growing wealth and population. Although the exact amount of reduction depends on future economic growth and on the CO_2 stabilization target, the challenge roughly is to cut CO_2 emissions substantially between now and 2050, instead of letting them double as forecast under business-as-usual.

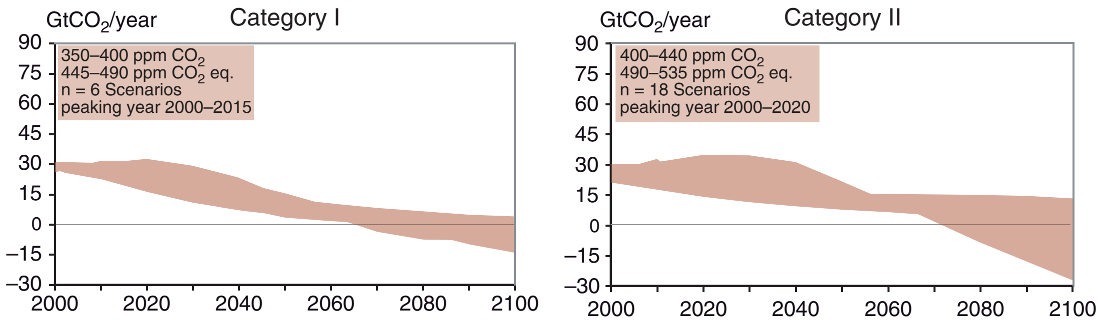


Figure 9.3 A summary of CO_2 stabilization scenarios. Each plot shows model CO_2 emission rates that would achieve the CO_2 concentrations given in the boxes.

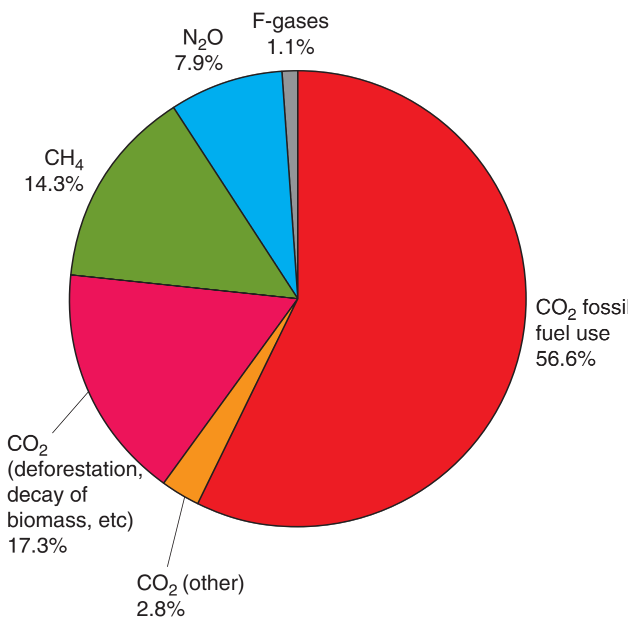


Figure 9.4 Greenhouse gas emissions in 2004. To compare the share of different gases they are weighted by their "global warming potential," i.e., their effect on climate over a 100-year time frame. A rule of thumb that is easy to remember is 60/20/20, i.e., anthropogenic warming is caused by roughly 60% fossil CO_2, 20% land-use CO_2 and 20% other gases.

Much of the WG III report is an analysis, broken down into sectors, of future trends in carbon emissions from various sectors of the economy, and what the potentials are for reducing emissions. Overall, the news is reassuring. The projections are that it would be feasible to stabilize atmospheric CO_2 not through a single technology shift, but rather through a "portfolio" of changes that together sum to reach the required emission reduction. Carbon dioxide arises from many sources, and so it makes sense that reducing CO_2 emissions requires making many changes in business-as-usual. The principle was illustrated in a commentary paper by Pacala and Socolow in 2004, which refers to each of these separate reduction strategies as "wedges", because they wedge up from no CO_2 reduction at the outset to 3.7 Gton CO_2 (1 Gton C) per year reduction by 2050. They list 15 possible strategies, all of which are technically available and scalable today. Further studies for individual countries have fleshed out this principle in more detail since, analyzing dozens of individual measures to reduce emissions, including their costs. The main message is that there is no "silver bullet" to solve the climate problem; it has to be tackled on many fronts.

Three basic and complementary types of strategies exist for avoiding climate change, which will all be covered in turn in the following sections. Changes can be made to the energy supply to decrease its carbon emissions, or to switch from carbon-intensive to carbon-free sources. Changes can also be made in energy use, decreasing demand by increasing efficiency.

The IPCC *Fourth Assessment Report* finds that, for the next few decades, more carbon emission can be avoided by changing energy usage than by changes in energy supply. Also, there are changes in other industries, primarily agriculture, forestry, and waste management, that can help avoid climate change.

Energy supply: the present, the forecast, and what can be changed

Carbon dioxide emissions can be cut at the source of energy production, by switching from one energy source to another, or by increasing the efficiency of producing, say, electricity from coal. Overall, energy production, including fuel for transportation and heating, accounts for 80% of greenhouse gas emissions, with the other 20% resulting from agricultural practices, concrete manufacture, waste treatment, and other niche practices.

The demand for energy is projected to grow 50% by the year 2030 under business-as-usual. Most energy is produced from fossil fuels, and most of that actually comes from oil. Coal and gas lag behind, although all three are increasing (Figure 9.5). The energy content per carbon emission is lower for coal than for the other fossil fuels, so the increase in coal consumption since 2000, driven by an increase in the price of natural gas, tended to increase CO_2 emission.

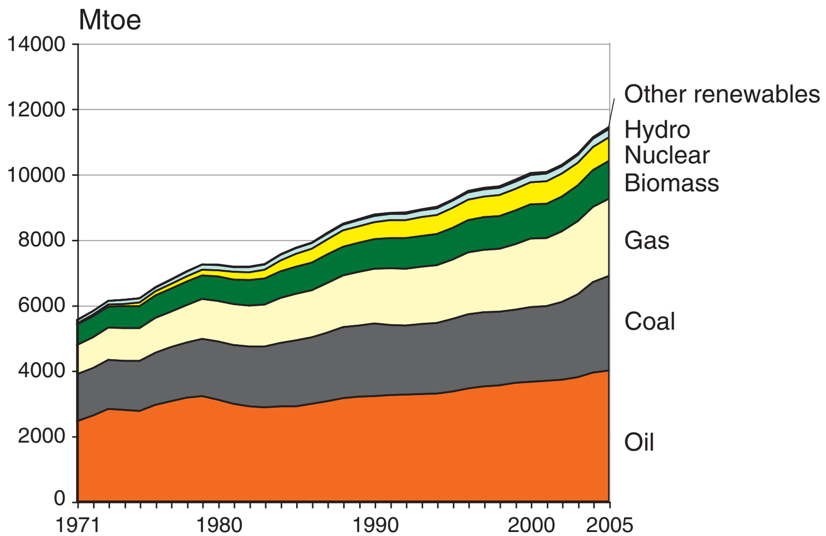


Figure 9.5 World primary energy consumption by fuel type. Data, in millions of tons of oil equivalent (1 Mtoe = 42 EJ) from IEA. Note that the efficiency of using this energy differs between sources. Nuclear and fossil fuel power plants are typically 33% efficient at converting "primary energy," the quantity plotted here, into usable energy (electricity). The efficiency of hydroelectric power is closer to 100%, so in fact hydropower contributes more to global electricity supply than nuclear power. This way of accounting is thus biased against highly efficient electricity sources like hydro and wind. In an alternative accounting method, the substitution method, 1 kWh of hydro or wind electricity is counted as 3 kWh of "primary energy," since this is the amount of conventional power it replaces. With this method, the current global share of nuclear power is 5.2%, that of renewables (including biomass and hydro) is 16.2%, while fossil fuels make up the rest.

Coal

Coal is the world's most abundant form of fossil carbon fuel. Coal currently supplies 27% of the world's energy. Coal is also the fastest-growing source of fossil energy production, growing at a rate of 6% in 2007. A recent uptick in coal consumption (dark brown region, Figure 9.5) was driven by the rising price of natural gas. The prognosis is for gas to get more expensive as supplies are depleted in the coming decades. This would leave coal to become even more important as a global energy source under business-as-usual.

There is tremendous potential for cutting CO_2 emissions from coal combustion. Traditional coal combustion generates electricity by boiling water to drive a steam turbine. Improvements can be made in traditional

Figure 9.6 The coal plant Scherer in Georgia, USA, the largest in the western hemisphere.

coal-burning power plants to increase efficiency and reduce emissions of by-products such as sulfur, nitrogen oxides, and mercury.

Larger efficiency improvements can be had by extracting energy chemically from the coal, rather than burning it directly. Coal can be treated in chemical reactors to produce combustible gases called syngas, a mixture of carbon monoxide (CO) and hydrogen (H_2). Unlike powdered coal, the combustible gases can be burned directly in a turbine to produce electricity. After the gases have run through the turbine, the heat can still be used to boil water in a second-stage steam turbine. The two-stage electricity generators increase the efficiency of energy extraction from coal, and reduce the emission of mercury, sulfur (acid rain), and particulates. The technology to extract syngas from coal has been commonplace for over a century, used for example to produce gas for lighting in Victorian London. Syngas extraction is the first stage for much of our industrial chemical synthesis, including the production of nitrogen fertilizer from atmospheric nitrogen gas. Coal gasification produces CO_2 in a pure stream, which can be captured more easily than it can from the mixture of gases coming out of a coal burning power plant. Coal could in principle be burned in pure O_2, producing pure CO_2, but the combustion temperature of coal in pure O_2 is impractically high, so coal is burned in air, producing a CO_2/N_2 mixture.

Pure CO_2 can be sequestered in the Earth, a technology that is called carbon capture and storage (CSS). There wasn't much discussion of carbon sequestration in the 2007 IPCC report, but there was an entire IPCC report on carbon sequestration published in 2005. The largest potential repository for CO_2 beneath the land surface is a type of geological deposit called saline aquifers, porous rocks filled with salty water. Since the water has salt in it, it will never be useful for irrigation or human use, so filling them with CO_2 is thought to be no loss. Their high permeability would allow the CO_2 to spread laterally from the injection site, allowing more CO_2 storage. Alternatives to saline aquifers include old oil reservoirs and sediments of the deep sea.

The IPCC sequestration report concluded that carbon sequestration could make up 15–55% of the global carbon emission abatement effort to the year 2100, at costs between \$10 and \$100 per ton of CO_2 avoided (comparable to the other emission abatement strategies discussed in WG III and this chapter). The total cost of a coal gasification plant including carbon sequestration is cheaper than the total cost of a traditional coal-fired power plant, retrofitted for carbon sequestration. If we want to stop global warming, it would be cheaper in the long run to stop building coal-fired power plants now, and start developing coal gasification technology with carbon sequestration.

Oil

The liquid form of oil renders it particularly suited for transportation uses. For airplanes there is no available substitute for liquid fuels. Improvements in energy efficiency of transportation will be covered below.

The question about oil is how long it will last. There is enough coal available to last for several centuries, but for oil and gas the amount of time left at current extraction rates is measured in decades. The IPCC quotes a variety of estimates of the amount of oil that has already been extracted, and the amount remaining. The extracted and remaining oil reserves are each estimated to be close to 100 Gton, for a total original oil supply of 200 Gton C, half of which is

Figure 9.7 At the Sleipner gas field in the North Sea, the Norwegian company Statoil pumps CO_2 that arises during gas production into a saline aquifer 800 meters below the sea bed. This is economically interesting since Statoil avoids paying the Norwegian government's CO_2 emission tax in this way. The project also serves as a test bed for CO_2 sequestration technology.

gone now. At current rates of usage, the 100 Gton left could last for 70 years, but projecting continued growth in oil demand leaves us with about 40 years until this hypothetical last drop is extracted. More than half of the oil is typically left in the ground using current extraction technology, so improvements in extraction techniques could increase the total amount of available oil.

Alternatively, one can view oil extraction through the lens of "peak oil" theory, first expounded by M. King Hubbert in 1956. Hubbert argued that oil extraction from a given field typically follows a bell curve trajectory, where the maximum rate of extraction occurs when the resource is about half depleted. Before the peak, the extraction rate increases with time, so that it would be able to keep up with exponentially rising demand. The shortage comes at the peak, when the exponentially rising demand begins to diverge from the plateauing and ultimately declining production rate. Of course, the global rate of oil extraction depends on social, economic, and logistic factors, such as corporate investment in oil refineries, none of which are explicitly included in the peak oil model, if it can be called a model. Hubbert's peak is an observation, a sort of a rule of thumb, rather than a rigorous theoretical prediction. The salient point of the peak oil perspective is that the shortage will be perceived well before the last drop of oil is extracted from the ground. Given the amount of oil that is estimated to remain in the ground, the rate of oil extraction is arguably at its peak today, or will be in the next few years.

When oil starts getting scarce, liquid fuels could be synthesized from coal, or extracted from non-traditional fuel sources such as oil shales, tar sands, and heavy oils. The extra processing involved tends to decrease the efficiency, resulting in higher rates of carbon emission and other environmental impacts per yield of energy. Alternatively, liquid fuel could be generated biologically (see below).

Gas

Natural gas burns cleaner than oil or coal, and because it has a high hydrogen-to-carbon ratio it delivers more energy per carbon released than oil or coal. Natural gas is a limited resource comparable to oil with about 150 Gton C left. This is enough to last for some decades. In spite of the growing scarcity of gas, its use for generating electricity is projected to increase in the coming decades. Ultimately, because oil and gas supplies are limited, the most important factor for avoiding serious climate change is coal.

Nuclear

Nuclear energy is a large source of energy that hardly releases CO_2 to the atmosphere, accounting for about 5% of global energy production. The downsides of nuclear energy generation are that it produces radioactive waste, which is toxic and dangerous for centuries to millennia in the future, and that nuclear material can be used to make weapons. In spite of these problems, many advocate an increase of nuclear power production, as a lesser environmental impact than global warming. The prognosis for future nuclear energy production is limited by the availability of uranium fuel, just as it is for oil and natural gas. Using present-day technology and at present-day rates of uranium use, we have enough to last about 85 years. If nuclear power production were accelerated in the future, as part of a shift away from carbon-based energy production, that lifetime would decrease.

To get around this uranium shortage, one would have to shift to breeder reactors. Nuclear reactors in use today derive energy from a minor isotope of natural uranium, U-235. The major isotope, U-238, makes up 99.3% of natural uranium ores, but it is useless for energy production because it doesn't participate in the energy-producing nuclear chain reaction. Breeder reactors bombard U-238 with neutrons to produce plutonium Pu-239, which does undergo chain reaction. Breeder reactors could extend the life of our uranium stock by a factor of 50 to 150. An added benefit is that the waste from this type of reactor tends to be burned out of the long-lived isotopes, and so it doesn't last as long. The disadvantage of breeder reactors is a serious one. It is much easier to produce nuclear weapons using plutonium rather than uranium, because plutonium can be separated from uranium chemically, whereas uranium must be enriched by separating the two uranium isotopes which have nearly the same chemistry. For this reason, breeder technology is not really used today for nuclear power production.

In order to double the share of nuclear power over the next 30 years, from its current 5%, around 1,000 new nuclear power stations would have to be built over this time.

Renewables

The dominant renewable forms of energy today are traditional biomass (wood-burning) for 9% of global energy production, and hydroelectric power, 6% (Figure 9.5). Other forms of renewable energy, such as wind, solar, and non-traditional biomass, are much smaller but growing quickly, with the potential for significant expansion in the future. Most of the potential locations for new hydroelectric dams are in the developing world, and many of these are located in environmentally or culturally sensitive areas, such as the Yellow River in China. For these reasons the potential for generating power by building new dams is limited. Hydroelectric power has an impact on the carbon cycle, in that when a reservoir fills, it produces CO_2 and methane from decomposition of the flooded vegetation. For small dams, the IPCC analysis finds that this greenhouse gas source makes hydroelectric power comparable to natural gas power in terms of CO_2 produced per kW hour of electricity. One way to expand hydroelectric power without this problem is to fit generators on dams that currently don't have them. Only 25% of reservoirs generate power, because most of the small dams in the world were built for water management for irrigation or flood control.

Wind energy has the potential to supply a much greater fraction of our power than it currently does (about 0.6% globally). The highest utilization of wind is in

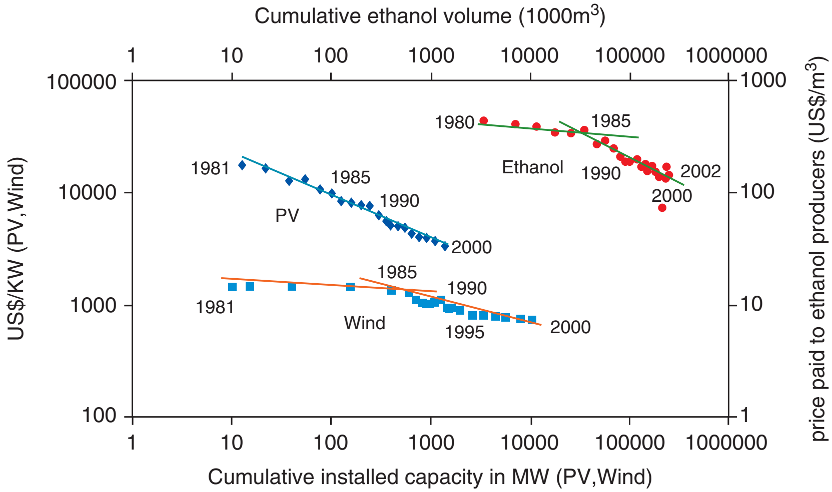


Figure 9.8 Costs and installed capacity for photovoltaic (PV) and wind energy (left hand axis). The right hand axis shows the cost and production rate of ethanol.

Denmark, which produces about 18% of its electricity use as wind. The difficulty with both wind and solar power is that they are intermittent. Denmark actually exports most of its wind power, and uses wind for only about 7% of its internal consumption, using electricity import and export as a sort of storage cell. Wind power is currently much cheaper than solar photovoltaic power, and provides a much larger energy source than solar photovoltaic (Figure 9.8).

There is enough sunlight hitting the Earth to cover our current energy demand 10,000 times over. There are two basic strategies for harvesting energy from sunlight. One is to heat water, either for local use or to generate electricity from steam. This so-called solar thermal power is much closer to cost-competitive than solar photovoltaic. A further advantage of solar thermal is that energy can be stored in the form of heat, for example in the form of melted salt, which can then be harvested to produce electricity through the night or a series of cloudy days. Solar thermal is best suited to low-latitude desert areas. Theoretically, just 1% of the low-latitude desert area could supply the global electricity demand forecast to the year 2030.

The other form of solar energy is photovoltaic, using solar cells to generate electricity directly. The cost of solar PV energy currently exceeds that of wind energy (Figure 9.8); for this reason PV is only a small source of energy globally.

Wind and solar power share the technical problem of intermittency. Traditional power plants can be used as backup energy sources, but this adds to the effective cost of wind or solar power, if you have to also build a traditional plant to go along with it. Another solution to the storage problem would be to improve the electrical grid, such that power could be efficiently transported around the world. A third is to develop better means of storing power than are available at present, but this too adds to the cost and the technical challenge.

Plants extract energy from the sun, and we can extract energy from the biomass of the plants. Traditional wood-burning is a form of biomass energy production, in fact the largest, contributing about 9% of global energy production. On an industrial scale, plant material can be mixed with coal for combustion in traditional coal-fired power plants. Biomass could also be "gasified," producing the same syngas (CO plus H_2) that was discussed for IGCC coal processing. Syngas can be burned in turbines to generate electricity.

Biomass energy is also used in the form of ethanol, a liquid fuel that is mixed with gasoline to increase its combustion efficiency. Ethanol production is attractive because ethanol is well suited for transportation uses. Currently, ethanol is produced from corn in the USA, and from sugar cane in Brazil. Sugar cane is a more efficient source of ethanol than corn is, but sugar cane can only be grown in the tropics. From corn, it takes almost as much fossil fuel to produce ethanol as the ethanol replaces.

Both of these sources of ethanol are derived from starches and sugars (carbohydrates). There is much more energy to be had in other forms of carbon such as cellulose and lignin. New technologies might make it possible to produce ethanol from agricultural biomass products such as fast-growing grasses or agricultural by-products. Cellulose could supply much more ethanol than corn ever could.

Biomass energy production is limited by competition with food production and wildlife preservation for available land. Therefore, the focus should be on bio-energy derived from agricultural wastes, such as rice husks or stalks from grain crops, as well as on plants grown on wastelands not suitable for food production. And bio-energy should be used in the most efficient way to reduce CO_2 emissions. Conversion to a liquid fuel wastes over half of the energy content of the biomass, so from a climate mitigation point of view it is not an efficient use of biomass.

Overall, the report concludes that, in the energy sector between now and 2030, an investment in avoiding carbon emissions equal to about \$100 per ton of CO_2 avoided could reduce annual emissions by about 3.7 Gton of CO_2 equivalent (Table 9.1). The total rate of CO_2 emission today is about 26 Gton CO_2 (7 Gton C) per year. What this says is that the way our appetite for energy is growing, building new power plants is not going to be sufficient by itself to solve the climate problem. However, the report also identified half a dozen potential changes in energy consumption, discussed next, which can all make

Table 9.1. **Potential cuts in CO_2-equivalent emissions between now and the year 2030, available at a cost of $100/ton of CO_2-equivalent. The other greenhouse gases are included in this total, converted into their CO_2-equivalent emissions based on their relative potency as greenhouse gases. The numbers are from table TS.17 in the IPCC *Working Group III Report*. Where there was a range of uncertainty in the original table, we have averaged to the middle value.**

Sector	Carbon-equivalent emissions savings (Gton CO_2 per year)	
Energy supply	3.7	Shifting to carbon-free renewable energy, and capturing CO_2 from coal
Transportation	2.9	Major improvements in efficiency are possible at low cost
Buildings	4.0	Large savings possible which would pay for themselves
Industry	4.0	This slow-growing sector could be more efficient
Agriculture	3.3	No-till agriculture could capture carbon from the atmosphere
Forestry	2.6	Reforestation
Waste treatment	1.0	Smaller emissions savings, mostly methane and N_2O
Total	21.6	

comparable contributions to stabilizing CO_2. In addition, some energy experts find the IPCC too pessimistic on the renewable energy potential – their views will be discussed near the end of this chapter.

Energy consumption

Transportation

Transportation uses 24% of our energy production, and it is the fastest-growing sector of energy use. Internal combustion of fossil fuels supplies 96% of all transportation energy. Oil is the most convenient form of fossil fuel for transportation, because its liquid form is easily transportable. Oil will become scarce at some point in the coming decades, but liquid fuels could be baked out of carbon-rich rocks such as oil shales and tar sands. Liquid fuels could be

Figure 9.9 Morning rush hour traffic in Hyderabad, India.

synthesized chemically from coal, natural gas, or biomass. Except for biomass, these alternative energy sources are less efficient than petroleum in terms of carbon emissions.

Automobile ownership is strongly correlated with income (Figure 9.10), and globally, automobile ownership and use is projected to increase. If it were not for environmental and fuel limitations, one estimate has 80% more cars in the world in the year 2030. Free markets have a mixed record at optimizing for fuel efficiency, regardless of the price of fuels. In many markets people prefer large, powerful vehicles if they are available. Fuel economy regulations in contrast have been nearly universally effective at steering technological development toward higher efficiency (Figure 9.11).

There have been technical improvements in the efficiency of automotive transport, for example hybrid vehicles (40% more efficient than traditional gasoline engines) and turbo diesel (30% more efficient). Biofuels, for example ethanol, can be used for transportation. As described above, the potential for ethanol will be greatly expanded when techniques for generating ethanol from cellulose are developed. There has been progress in hydrogen fuel cell technology, but hydrogen cars are still a "demonstration project" technology. Hydrogen cars could be 50–60% more efficient than internal combustion of

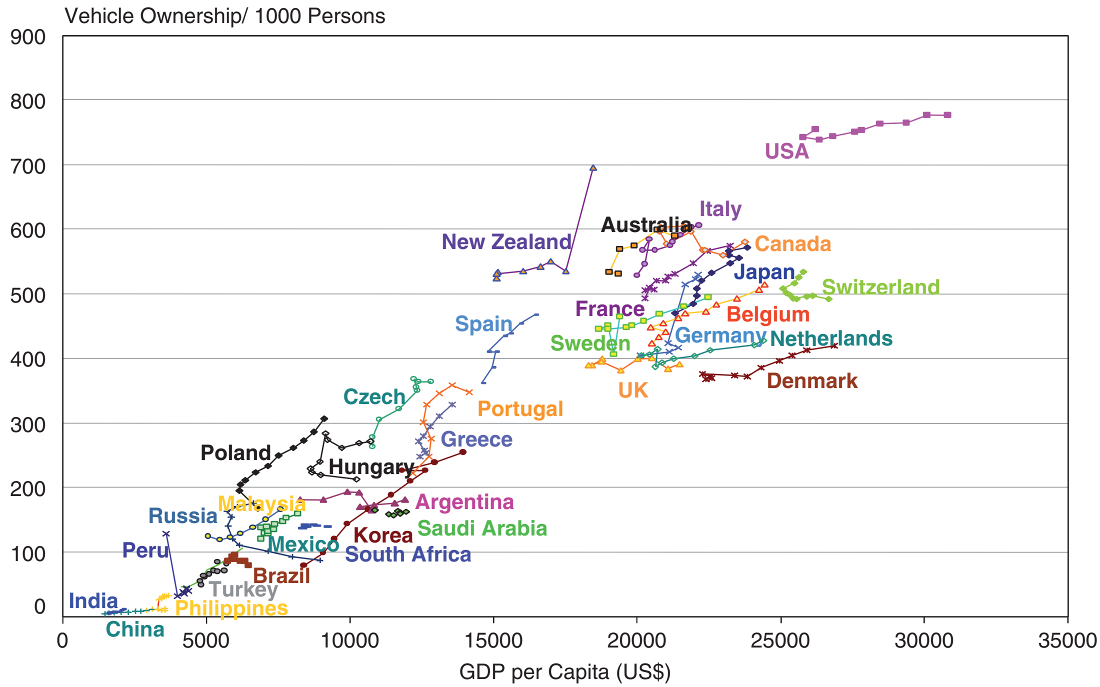


Figure 9.10 Car ownership as a function of income.

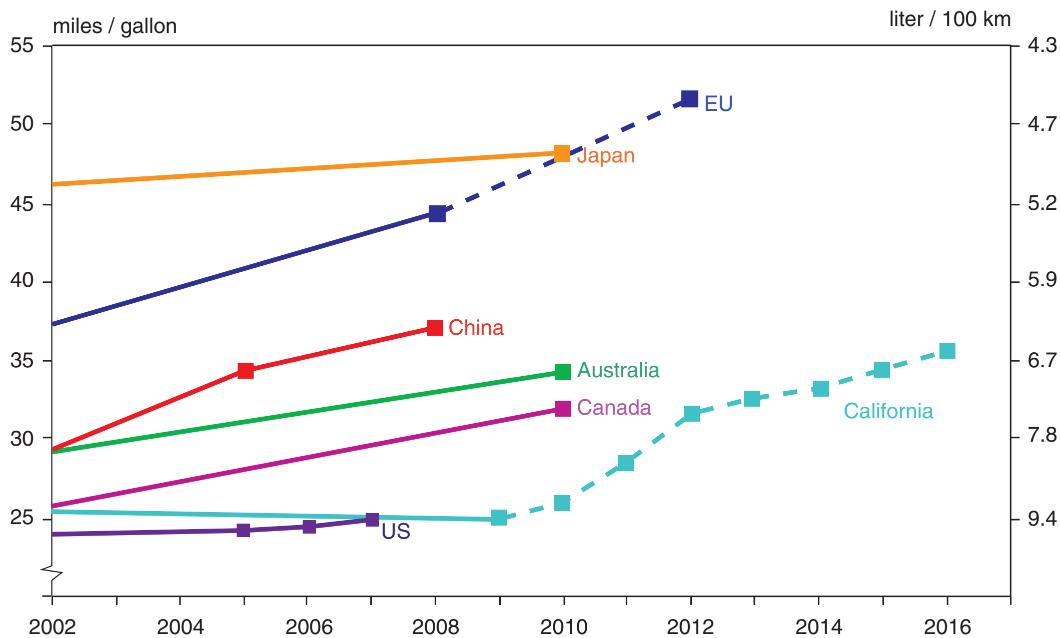


Figure 9.11 Fuel economy standards for various countries.

gasoline, or even more if the hydrogen were produced from some carbon-free energy source.

The *Fourth Assessment Report* estimates that improvements in the transportation sector could reduce CO_2-equivalent emissions by 2.9 Gton CO_2/year at a cost of less than \$100/ton of CO_2 (Table 9.1). As we shall see as we continue our survey of the energy landscape, there are numerous sectors that could all cut CO_2-equivalent emissions by about this same amount.

Buildings

The outlook for cutting CO_2 emissions by changing energy use in buildings is similar to that for transportation. Buildings use about a third of our global energy production, also similar to transportation. The rate of growth of building energy use has been 1.8%/year, somewhat slower than that for transportation, but not wildly slower. And there appears to be a lot of easily trimmed fat that could bring CO_2 emissions from the building sector down at relatively low cost. In fact, many energy-saving efficiency measures in the building sector could actually pay for themselves.

The *Fourth Assessment Report* summarizes a suite of 11 studies to conclude that cuts of about 25% could be made in the industrial world, and 60% in the developing world, all of which would eventually pay for themselves. Investment in CO_2 emission reduction of up to \$20/ton could buy even further reductions. Surveys of domestic energy use show factor-of-two variations or more between houses and families of comparable size, just based on differences in energy use habits.

The three main types of energy use in buildings are heating, cooling, and lighting. Heat efficiency can be improved by insulating the building and sealing up the leaks. In cold climates, heating costs can be reduced by 80–90% below standard practice using twice the insulation called for by code, taking care to seal air leaks, and using the best available windows. Windows are available that cut heat loss by a factor of three to four below standard double-pane non-coated windows.

Conversion of heat energy from fossil fuel combustion into electrical energy is only about 30% efficient. The lost energy is called waste heat. This heat can be used to heat buildings in a strategy called cogeneration. With cogeneration, the efficiency of energy extraction from fossil fuels doubles, to around 60%. The benefits of cogeneration have been demonstrated in a few projects, but are not used extensively in practice.

Cooling costs can be reduced by architectural design, for example shading and ventilation. Air conditioning is often used as a means of dehumidifying air, by cooling and re-warming it, but dehumidification can be done more efficiently by other means. Air conditioning systems are also used in practice for blowing air around, which fans can do more economically.

Lighting costs can be reduced by a factor of four by switching from incandescent to fluorescent light bulbs. Compact fluorescent bulbs have already made significant inroads into commercial buildings, but not so much into residential buildings.

The building sector has an amount of CO_2 emission reduction to offer which is comparable to that from the transportation sector (Table 9.1). However, abatement from the building sector would be much cheaper than that from transportation.

Industry

The third major type of energy use is industrial. Industrial activity is responsible for about 8.4 Gton CO_2 emission today, but it is growing only 0.6%/year, so industrial CO_2 emissions have lagged behind, from about 40% of emissions in 1971 to 36% today. Most of the CO_2 emission from industrial activity comes from metal production, such as iron, steel, aluminum, and magnesium; chemical production such as plastics, fertilizers, and petroleum refining; cement; and forest products. These energy-intensive industries account for 85% of industrial CO_2 emission. The growth rate of CO_2 emissions has been slower than the growth rate of the other sectors of energy use, because of improvements in efficiency. Another trend in industrial energy consumption is a migration to the developing world, which accounts for just over half of industrial CO_2 emissions today.

A significant fraction of industrial CO_2 emission is due to chemical uses of carbon, rather than energy uses. Steel, aluminum, and other metals make use of carbon from coke (a derivative of coal) to "un-rust" the metal ores to produce pure metals. Carbon dioxide is also produced as a by-product of cement manufacture. The process begins with calcium carbonate, $CaCO_3$, from which the CO_2 is released by heating. The result, called clinker, contains calcium oxide (CaO), which reacts with water to form cement. Cement manufacture accounts for 5% of global CO_2 emissions, about half of which is chemical, the other half is for energy. Reduction in cement CO_2 emission is mostly based on improvements in the energy release.

The most significant CO_2 sources in the chemical synthesis industry include ethylene manufacture, an ingredient for plastics, and the manufacture of ammonia for fertilizer. Ethylene could be made more efficiently, but ammonia production in new plants is approaching the thermodynamic efficiency limit, so the prospect for further efficiency gains is not promising.

Most of the potential reduction in CO_2 emissions can be found in the steel, cement, and petroleum industries, and by reduction of non-greenhouse gases like methane and halocarbons. Many of the industrial CO_2 emission sources could be candidates for carbon capture and sequestration; examples include the steel, fertilizer, and chemical synthesis industries.

Overall, the AR4 concludes that CO_2 emission cuts of 14–40% could be possible at a cost of $20/ton of CO_2 or less. For $100/ton of CO_2, the potential cuts are comparable to those from the transportation and building sectors we've seen so far (Table 9.1).

Other mitigation strategies

Agriculture

Agriculture releases most of the anthropogenic N_2O source to the atmosphere, about half of the methane (CH_4), and less than 1% of the CO_2. However, the largest potential fix for global warming from agriculture involves CO_2, by changing land use practices to encourage the build-up of carbon in the soils. To date, agricultural practices have resulted in the transfer of about 180 Gton CO_2 to the atmosphere, about one-sixth of the fossil fuel and cement CO_2 sources. Adoption of no-till agriculture, careful management of grazing lands, rotation of crops, and even setting aside agricultural land for reforestation, all have significant impact on future carbon fluxes.

Reduction of fertilizer use decreases the fossil fuel energy required to produce the fertilizer, and may also decrease N_2O emissions, but Figure 9.12 indicates that the IPCC does not find easy ways to reduce N_2O emissions. The agricultural sector may also contribute biofuels, which can displace the combustion of fossil fuels. The IPCC concludes that we have enough excess agricultural capacity today to eliminate about 1.8 Gton CO_2 using biofuels.

Overall, the CO_2-equivalent emission cuts in the agriculture sector, at costs below $100/ton of CO_2, are comparable to all the others so far: transportation, building, and industry (Table 9.1).

Forestry

Forests store carbon in trees, and in the organic carbon in soils. Deforestation releases carbon to the atmosphere as the wood from the trees

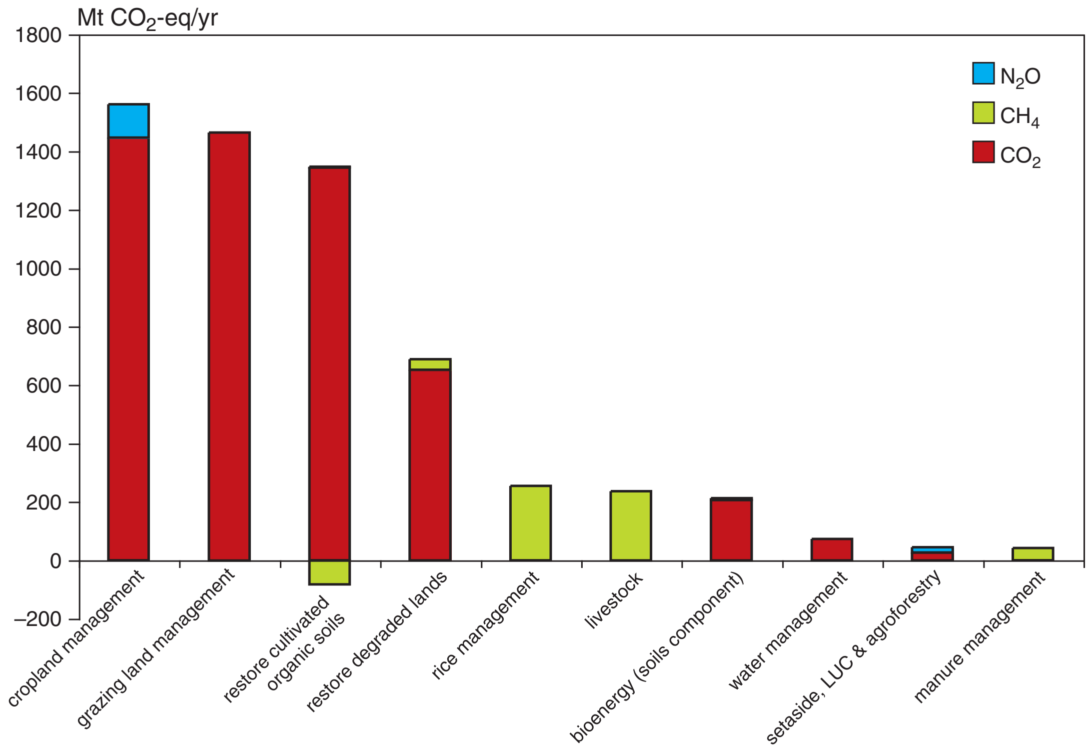


Figure 9.12 Estimated potential for cutting greenhouse gas emissions (expressed as CO_2 equivalent), resulting from various agricultural practices.

decomposes or is burned. Deforestation is largely a tropical phenomenon. Projections for the Amazon forest range from 17% to 40% depletion by the year 2050, releasing 55–110 Gton CO_2 by that time. Forests in temperate latitudes were mostly cut centuries ago, and are now holding more or less steady (Figure 9.13). Huge gains in agricultural efficiency in the past decades have allowed food production to increase without an expansion of land devoted to agriculture.

Wood provides a primary heating fuel throughout large regions of the world, accounting for 40% or more of the total wood harvest, and nearly 100% in Africa, and parts of Asia and South America. Two billion people today depend on wood for heating and cooking fuel. This number is likely to increase with population growth.

Modeling studies find that the forest sector globally could absorb 1.8–4.8 Gton CO_2/year at a cost of less than \$20/ton of CO_2. At a cost of \$100/ton of CO_2 or less, the total amount of CO_2-equivalent abatement from the forestry sector is comparable to all the others so far (Table 9.1).

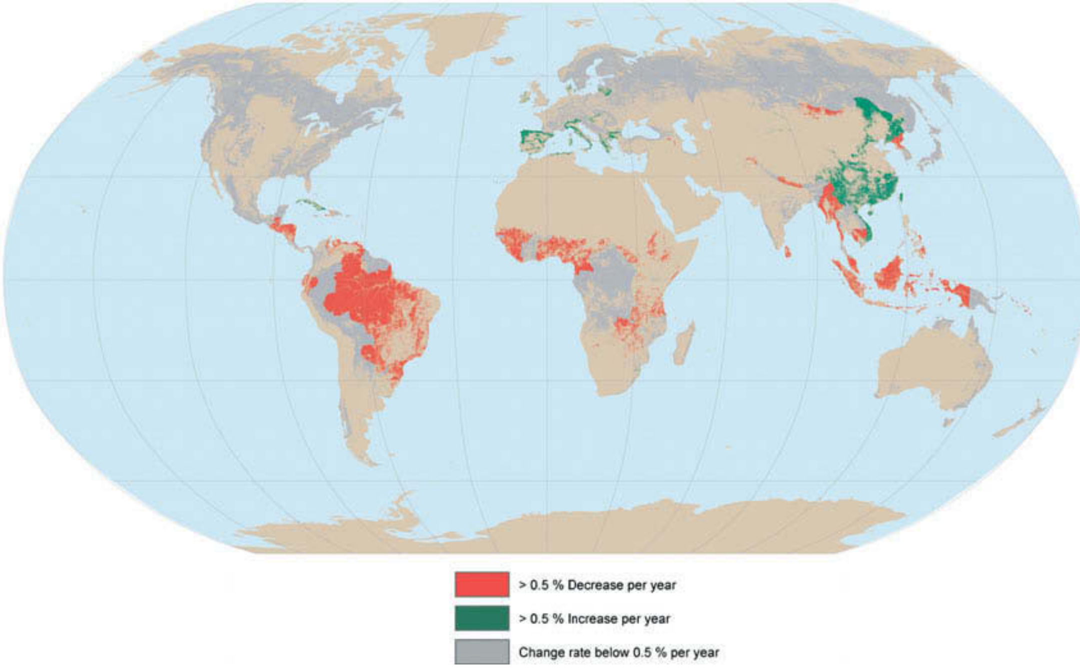


Figure 9.13 Net change in forest area between 2000 and 2005.

Waste management

Solid waste is either buried or burned. Burying it has an advantage of sequestering the carbon, rather than releasing it to the atmosphere as CO_2 the way combustion does. Landfills emit methane, which can usually be converted to CO_2 quite inexpensively by covering the waste with soil. Or the methane can be captured; landfill methane capture has been a commercial source of energy since 1975. Waste incineration can also be used to generate energy, by mixing waste with coal for example.

Solid waste production has been ramping up steadily since 1975. Much of this material, newspapers and packaging and so on, required energy to produce, and may release greenhouse gases when disposed of. There is a large but not very well quantified potential to reduce solid waste production by reducing unnecessary production, and by recycling.

Liquid waste can affect climate by emitting methane and N_2O. Treated wastewater does not emit much of either gas, but anoxic sewage can emit a large fraction of the waste carbon it contains in the form of methane. Only 58% of the world population treats their sewage, the rest do not, using instead latrines and septic tanks.

The potential greenhouse gas emission reductions from the waste sector, expressed as equivalent CO_2, are smaller than the other sectors, by about a factor of three. The IPCC found potential cuts of about 1 Gton CO_2 at a cost of less than $100/ton (Table 9.1).

A more optimistic vision

The job of the IPCC is to provide a widely supported consensus view, and when discussing future technology options this is naturally more difficult than in climate science. Also, this is a rapidly advancing field. So it is not surprising that some energy experts and engineers find the IPCC assessment of mitigation options too limited and conservative. Governments have in fact recognized that there is much more to explore in this area than the IPCC AR4 has done, and it has been decided recently that the IPCC will produce a special report on renewable energies. To stimulate discussion, in this section we provide a somewhat more visionary perspective on our possible energy future, based on renewables, cogeneration, smart grids, heat pumps and electromobility.

Our current use of energy is vastly inefficient, due to the fact that fossil energy sources have been cheap and abundant until now, and we have "locked in" to century-old inefficient technologies. This is good news, since it means that the potential for improvement due to technological innovation is huge. Let us have a brief look at the three main energy needs: electricity, heat, and transport.

Electricity generation today occurs with an average efficiency of about 33%, so that two-thirds of the energy input is simply wasted in the form of heat. This waste and the emissions can be slashed through two technologies. The first is cogeneration, which uses the heat from power stations for household heating purposes and process heat in industry. The second is the generation of electricity from renewable sources such as wind, hydro and biological matter, and, as technology advances, increasingly from solar power.

Wind power has been a surprise success story. Over the past two decades it has grown at 20% per year, thanks to government support in just a few countries. At the same time, wind generation costs have halved within a decade and at good wind sites are now competitive with conventional electricity. If the growth rate of wind power is sustained, it will supply 20% of global electricity by 2025. Combine this with the existing hydropower (currently 17.5%, by 2025 about 16%), bio-energy (mostly based on using agricultural waste in power stations) and solar thermal power plants

Figure 9.14 Wind turbine on farm land near the Baltic coast in northern Germany. In Germany wind power supplied 6.5% of the electricity used in 2008, almost twice that of hydropower and up from next to nothing ten years earlier. Mass-produced small units, which can be rapidly installed (or removed), are one of the key advantages of wind power.

(new commercial plants opened in Seville in Spain and White Cliffs in Australia in 2007, see Figure 9.15), and by 2025 more than half of the world's electricity needs could be supplied from renewable sources.

German scientists from the Institute for Solar Energy Research in Kassel have shown that Europe could even be supplied completely with renewable electricity at current cost and with current technologies, with wind power taking about 60% of the share. With a high-capacity, pan-European electricity grid (the "super-grid") and wind power fed in from different regions, this share would not cause problems with fluctuations in supply, as simulations with hourly weather data have shown. Existing hydropower capacity and a small biomass contingent would tide us over times of lull, in combination with the load management that is made possible by "smart grids." No doubt similar schemes are possible in other parts of the world as well.

Later in this century, solar power could easily supply most of our energy needs. Solar energy supply is practically unlimited, and photovoltaic cells

Figure 9.15 Solar thermal power plant in Seville, Spain. An array of 624 mirrors focuses the sunbeams to a receiver on top of the tower, to produce 11 MW of electricity. Further, larger plants like this are being planned.

already harvest solar power many times more efficiently than plants can with photosynthesis, so that this high-tech approach to harvesting the sun is far superior to the traditional low-tech approach of burning wood. All we need is the costs for harvesting solar power to come down further, and strong electrical grids to transport the power, e.g. from the desert to consumers. Prices are already falling steeply (Figure 9.8), and many promising technologies are being developed, such as polymer solar cells that can be printed on a roll of plastic sheeting. A massive investment in technology research could accelerate the transition from the fossil fuel age to the solar age.

Now turning to *heating* needs, three major technological building blocks – all available now – are insulation, cogeneration, and heat pumps. The large potential of cogeneration and insulation has already been discussed above; up to 90% of the heat currently wasted could be used in an intelligent manner. Even in colder parts of the world, "passive houses" that need no heat input can be built, and at more modest cost heating needs can be reduced by 80% compared to conventional houses. Heating needs for older buildings cannot be reduced quite so much, but heat pump technology can be used, which takes heat energy from the surroundings through a thermodynamic machine run on electricity. Current commercial heat pumps provide three times the energy in heat that they use in electricity. This is why they have no real reduction potential in the current electricity generation mix with its 33% efficiency, and are not very widely used. (Multiply those 33% by 3 and you get back to 100%, i.e. the same as burning fossil fuel directly for heating.) But in a future system running increasingly on directly generated, renewable electricity, heat pumps become an ever better option to cut down fossil fuel use.

Finally, in the *transport* sector, we are currently largely stuck with a nineteenth-century device, the internal combustion engine, which in cars runs with an average efficiency of about 20% and with no hope for much improvement. This means that our car fleet wastes 80% of the petrol and diesel it guzzles up, to produce waste heat. Electric cars, in contrast, perform with a "tank-to-wheel" efficiency already up to 80%. Now that the battery problem is as good as solved with lithium-ion battery technology, we cannot afford to leave this factor of four efficiency gain untapped – also considering the co-benefits of quieter cars that accelerate better and don't cause local air pollution. Hybrid cars, which include a small electric motor, are now conquering our roads, and the next step will be plug-in hybrids. In China, and also increasingly in Europe, bicycles with a small electric support motor are proving to be a serious transport alternative for faster, effortless riding. And a fully electric sports car, the Tesla, is on sale as of 2008 (Figure 9.16).

As with heat pumps, the benefits of electric mobility are not so large while we are stuck with a wasteful fossil electricity generation system. But as part of an overall energy transition towards efficient renewable electricity, the savings potential is huge. And millions of car batteries hooked up to a smart electricity grid provide an excellent buffer to stabilize the grid against supply fluctuations, e.g. from wind variability. They can be programmed to fully charge preferentially while power is cheap during windy hours, and car owners could even be automatically selling back electricity to the grid at a premium during lulls, thereby making money.

Overall, the options discussed above, combined with improved efficiency of consumer devices like refrigerators, lighting, or television, would be able to reduce greenhouse gas emissions by 80% by 2050 in industrial countries without any loss of comfort or well-being. Once solar power generation becomes cheap and ubiquitous in the second half of the century, the transition to a decarbonized, solar-based energy system with near-zero CO_2 emissions will be within reach. At the same time energy poverty, which currently hampers development in many parts of the world, should be a thing of the past.

In our view, even rising fossil fuel prices will not suffice to bring these new technologies into the market sufficiently fast to prevent dangerous climate

Figure 9.16 The electric car produced and sold by Tesla Motors, a Californian company. Its electric motor is still powered by a large number of laptop batteries, but bigger lithium-ion batteries built for use in cars are now starting to come on the market.

change. Concerted action by governments is therefore needed, not only in the form of a massive investment in research: a kind of "Apollo program" for alternative energy systems. Further government measures include standards for allowable emissions, pricing of carbon emissions (like the emissions trading system operating in the EU), targeted support to help certain technologies into the market (like the highly successful German renewable energy law, now copied by China and several other countries), and infrastructure investments (like the provision of high-capacity electricity grids needed to distribute renewable power). Subsidies and investment in this area are still surprisingly small, when measured either against the importance and scale of the challenge ahead, or even against the support still enjoyed by the fossil fuel or nuclear industries.

What it will cost

Working Group III projects that in the next 25 years, for a reduction of annual CO_2 emissions by 11 Gton CO_2, the cost would be about US$20 per ton of CO_2, while reduction by 22 Gton CO_2 would cost $100 per ton of CO_2. These are prices of CO_2 that would arise in a global trading market of emission allowances, as exists already within the European Union (where the price of a ton of CO_2 varies between €20 and €30 in mid 2008, i.e. about between US$30 and $45). Such prices are not a net cost to the economy (or the consumer), since they lead to greater efficiency in the economy and are to a substantial degree offset by savings. For example, if a price for emitting CO_2 of $40 per ton were to be passed on to the consumer, this would add US$0.40 per gallon ($0.1 per liter) to the cost of petrol (a fraction of the petrol price increase seen over the past years for other reasons). But by using a more fuel-efficient car, the consumer can easily avoid this extra cost.

Overall, the report concludes that dealing with climate change could cost at most a small percentage of global GDP. To stabilize at 650 ppm would cost around 0.2% of GDP to the year 2030, while a 550 ppm stabilization might cost 0.6% of GDP.

These cost estimates are rather uncertain and dependent on underlying assumptions. To analyse these in detail, an international project (the Innovation Modeling Comparison Project) has recently compared ten leading economic models of different research groups. It found that even for stabilization at 450 ppm CO_2, most of the models estimate mitigation costs below 1% of GDP. Two models even have negative costs – that is, the climate protection measures overall save money, compared to continuing business-as-usual. Figure 9.17 illustrates what 1% mitigation cost means for global GDP in a simple but typical economic scenario. The mitigation costs are given as aggregated values, discounted in the future with a given rate of social time preference (which expresses that we dislike costs upfront more than costs that we have to pay at some future time). Note that such a scenario implies that in the year 2100 the world will be about seven times wealthier than now – with or without climate policy. Without efforts to limit global warming (and assuming no damages from climate change occur!) GDP would be 724% of that in the year 2000, while after subtracting the costs of emissions reductions it would be 711%. While the exact numbers depend of course on the parameter choices, it is generally true that the economic growth curves with and without climate policy measures are very close together, and a given level of wealth in the year 2100 will typically be reached less than one year later due to the costs of emission reductions. We need to invest just a very small fraction of the expected increase in wealth to insure us against the dangers of global warming. There is thus a huge discrepancy between public fears that climate policies could hamper economic growth, and the actual costs discussed amongst economists. Part of the confusion may result from the fact that the mitigation costs of, say, 1% of GDP, sound huge to a lay person when expressed in absolute dollar terms. But as the Stern Report notes: a 1% GDP loss

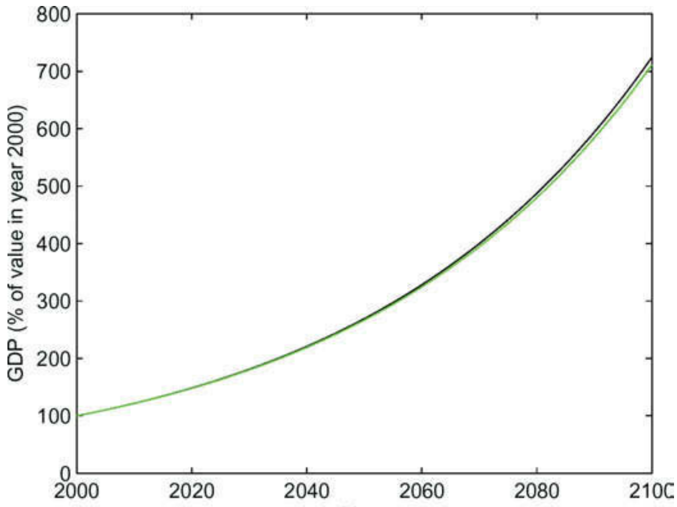


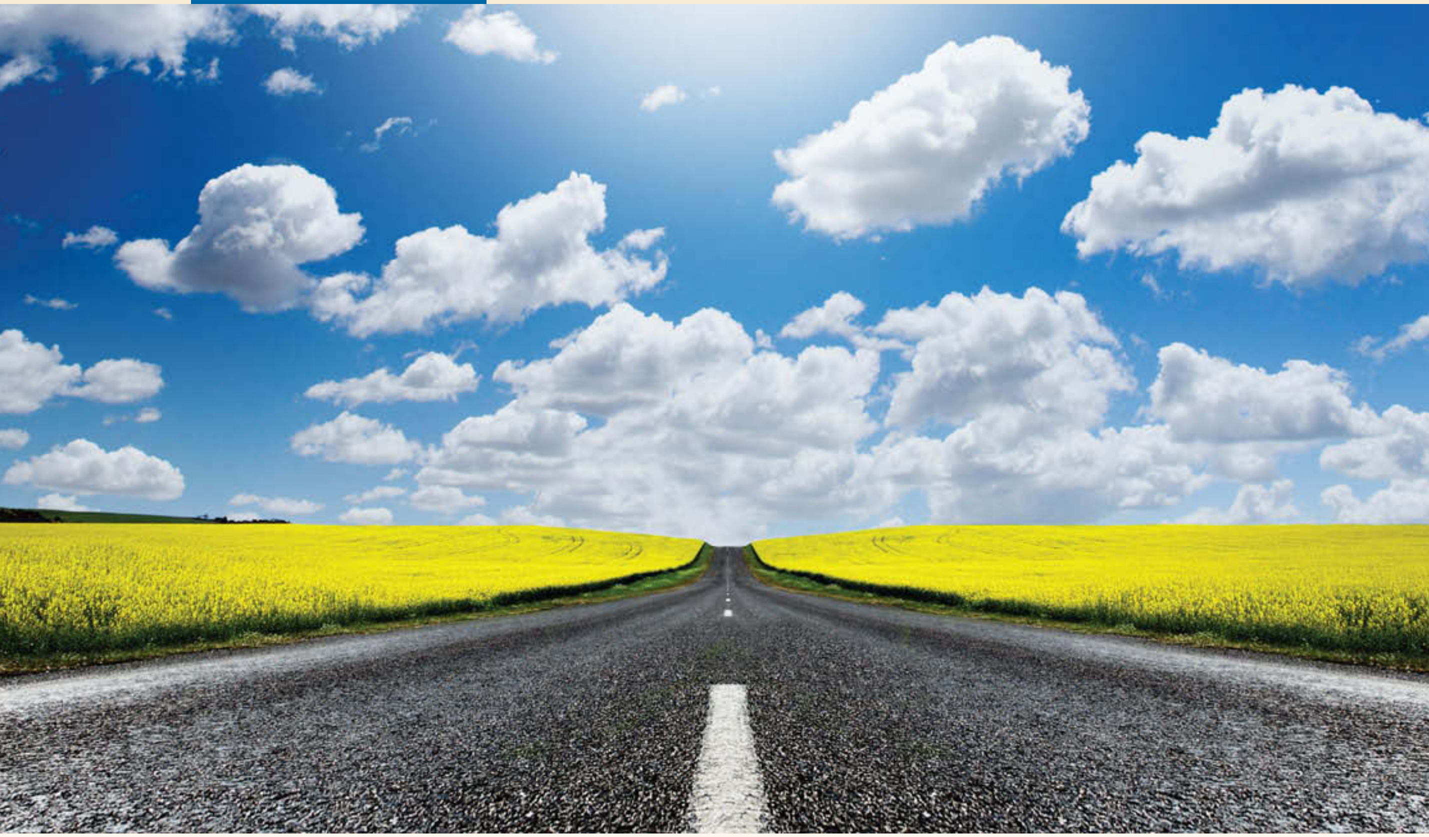
Figure 9.17 Illustrative economic scenarios with and without climate mitigation efforts. The black curve shows a simple scenario with 2% economic growth per year. The green curve shows the same, but with slightly reduced economic growth due to emission reduction efforts. The aggregated costs of the green scenario (with 1% social discount rate) amount to 1% of global GDP; this is more than most economic models estimate for climate stabilization.

is to the consumer roughly equivalent to a 1% tax on consumption – hardly anything to get excited about.

The costs of adapting to or enduring climate change are even more difficult to gauge, but they have the potential to be much larger than the costs of limiting CO_2 emissions would be. The most comprehensive assessment of the economics of climate change was published in 2006 as the *Stern Review of the Economics of Climate Change*. They conclude that the economic impacts of unfettered climate change could be comparable to that of the Great Depression or the World Wars of the last century. In economic terms these are expressed in decreases in GDP of around 20%. The Stern Review differed from much of the economic analysis preceding it by taking into account damages that come far in the future. Typically, costs in the future are "discounted," as justified by the idea that an investment made today at some economic growth rate could be used to pay the cost in the future. The future cost shrinks down in our current time according to the economic growth rate. Discounting makes sense if we are relating costs across a few years, where the same person has to pay either now or later. But when considering costs a century from now, the use of discounting seems rather like a cavalier way to dismiss the interests of people in the next century. If they are forced to live in a degraded world, they probably won't be consoled that people of our era enjoyed comfort and prosperity by using fossil energy at their expense.

At any rate, the costs of paths not taken will always be largely theoretical, because we can never know exactly how the economy would have evolved along such a path. For example, the surprisingly large hike in oil and gas prices since the IPCC analyses were done would significantly reduce the price tag for emissions reductions, since it makes business-as-usual more expensive and increases the savings when replacing fossil fuels. One thing that can be said with some certainty is that, given the 50-year useful lifetime of a power plant, the costs of CO_2 emission abatement will be much lower if the transition is undertaken gradually, beginning now, rather than having to do it more hastily in a decade or two.

10 Climate policy



The mandate of the IPCC is to be neutral with respect to policy, so its assessment reports do not recommend any policies. This is different from scientific advisory bodies to governments, which are often asked to provide specific policy recommendations. Although this is sometimes misreported in the media, the IPCC does *not* recommend limiting global warming to a specific target (such as 2°C) or stabilizing greenhouse gas concentrations at a certain level (such as 450 ppm). Likewise the IPCC does not recommend any mitigation options, such as renewable energy or nuclear power – the report merely lays out a range of available options and tries to evaluate how much they could reduce emissions and at what cost. The IPCC reports provide the scientific background information needed by policy makers and society at large to make well-informed decisions as to which policy they would like to follow. The IPCC mantra is to provide scientific information that is policy relevant, but not policy prescriptive.

But climate scientists are also citizens who care about the world, about their own future and that of their children and grandchildren, or about the fate of people living in other parts of the world affected by climate change. Many of us therefore follow the climate policy debate very closely, simply because climate change and its effects on human society are something we think about almost every day. A few of us also do this on a professional basis, because of involvement in scientific advisory bodies with the mandate to evaluate and recommend policies (e.g., the German Advisory Council for Global Change, of which S.R. is a member). In any case we feel that this book would not be complete without some discussion of where we stand with climate policy. Our readers should be aware that this goes beyond our reporting of the main contents of the IPCC report and presents our personal view on some of the salient issues.

Do we need a climate policy?

In 1992, at the Earth Summit in Rio de Janeiro, almost all nations of the world (including the United States) signed an agreement unique in the history of mankind: the United Nations Framework Convention on Climate Change (UNFCCC). Its famous Article 2 calls for:

> stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Five years later the Kyoto Protocol was signed, in which industrialized nations agreed to cut their greenhouse gas emissions on average by an initial 5% below 1990 levels before 2012. This was to be the first of a series of international agreements made to reach the goal of the UNFCCC quoted above. A mandate for negotiating the second, "post-Kyoto" agreement, covering the period starting in 2012, was decided by the parties to the UNFCCC in December 2007 in Bali, and negotiations on this agreement are underway as we write.

It is thus clear that the global political community had officially recognized in the early 1990s – not long after the first IPCC report had been published in 1991 – the need to stabilize greenhouse gas concentrations in the atmosphere and thus to cut global emissions. Since then, climate has warmed as predicted and the scientific evidence for human-caused global warming has become overwhelming. The negative consequences of warming are starting to be felt very clearly (as discussed in Chapter 8), and we are moving ever closer to the point of "dangerous anthropogenic interference" – some of our colleagues even think we have reached it. At the same time, technology has advanced, renewable energies have developed faster than even optimists had hoped, and economic analyses show ever more clearly that large emissions reductions would not significantly interfere with economic growth. Despite this, climate policy has moved at a glacial pace since 1992, emissions keep increasing unabatedly, and many in the political and business worlds still fundamentally question the need for emissions reductions and are resisting any effective climate policy.

One major obstacle to a successful climate policy is the widespread perception among non-scientists that the prospects for human-induced climate change remain controversial within the climate science community. This perception is fed by the common journalistic practice of trying to find a voice on each side of any issue, as a misguided attempt at finding balance, and by deliberate voicing of skeptical opinions by news media with a political agenda. When we actually survey the peer-reviewed scientific literature on climate change, however, there does not appear to be much controversy. There simply are no competing theories or models of climate in which continued emission of CO_2 into the atmosphere would *not* lead to significant changes in Earth's climate. None of the twenty climate models submitted to the *Fourth Assessment Report* from research groups around the world predict warming of less than 1.5 °C by the end of the century.

Neither does there appear to be any credible reason from examination of natural climate changes in the past to doubt the sensitivity of climate to changes in CO_2. If anything, the abrupt transitions between climate states in the past, which are still not understood in detail, lead us to fear that the real climate may even be "tippier" than the models are, perhaps due to feedbacks between parts of the climate system which may be stronger in reality than they are in the models. There have been a few research articles published in the scientific literature purporting to discount or disprove the reality of human-induced climate change, but these are generally found to be either erroneous, as was the case for early satellite measurements of the near-surface temperature, for example, or the result of deliberate deceptive manipulation of the data or the interpretation. The fact of the matter, in spite of how it may be represented in the popular press, is that there simply isn't any wiggle room in the scientific literature on whether humankind is changing Earth's climate.

One theme that comes up in the media again and again is the idea that global warming could be caused by changes in solar activity, either directly or through its influence on cosmic rays. This is ruled out by the fact that both solar activity and cosmic rays have been monitored for at least the past half-century and show no significant trend over this time, hence could not explain any trend in climate. Over the past 20 years, solar activity has even gone down somewhat (Figure 2.13), recently reaching its all-time low since the beginning of satellite measurements in the 1970s. By far the largest variations seen in solar activity and cosmic rays come in the form of an 11-year cycle that hardly has any noticeable effect on climate – which shows that solar effects are weak. No empirically documented physical mechanism exists by which solar activity could explain any appreciable amount of global warming over the past 50 years. And even if it did, this would not call into question the physically well-understood effect of CO_2 on climate: it would simply be an additional factor.

Numerous similar "red herring" arguments against anthropogenic global warming float around the Internet, repeated by gullible newspaper editors and systematically promoted by lobbyist organizations. It doesn't stop the show if the arguments can be demonstrated to be false; they can be effective tools of persuasion regardless. No month passes without the media repeating claims that have been scientifically discounted long ago.

We would personally be very relieved if anthropogenic global warming were to be disproven by some new scientific findings – we certainly do not "like" global warming. But at this point, the body of scientific evidence is so strong that the hope that this problem will go away by itself looks exceedingly remote. We will have to face this problem and live up to one of the greatest challenges humanity has ever been confronted with. The good news is: we have the technological and economic capacity to meet this challenge.

What global policy targets?

The language of the Framework Convention on Climate Change, the agreement that eventually spawned the Kyoto Protocol, was that greenhouse gas concentrations should be limited to "avoid dangerous interference in the climate system." The FCCC left it open for future deliberations to define what dangerous climate change is.

Ultimately the choice of targets for climate policy depends on how soon, or at what level, we want to stop global warming. The global average temperature has risen about 0.7°C already in response to rising greenhouse gas concentrations, and we have committed to another 0.5°C even if greenhouse gas concentrations remained constant at their year 2000 level (see Figure 7.1). In fact concentrations have gone up further since, and short of a war-like effort it looks almost impossible to prevent an eventual warming of at least 1.5°C above preindustrial temperatures.

We are already feeling the impacts of the very modest global warming experienced so far. As temperatures rise further than this, the expected impacts get stronger and more clearly harmful. As the temperature change rises to 2°C or more, we run the risk of interfering with the monsoonal rain patterns in India and other parts of Asia, with strong potential impacts on rice farming. The rain forest in the Amazon could collapse at some warming threshold, leading to further changes in the climate through changes in evaporation and release of biomass carbon. And we could trigger a dynamic ice loss in Greenland and West Antarctica that could cause several meters of sea level rise in the next two or three centuries, inundating many coastal cities. These are just a few examples. Even if many of the impacts cannot be predicted with certainty, the risks are so numerous that it would be foolhardy to simply ignore them.

It thus seems almost impossible to limit global warming below 1.5°C, while it seems very risky (and thus a clear case of "dangerous interference" as in Article 2 of the climate convention) to exceed the 2°C level. It appears that humanity only has a rather narrow "landing strip" for the climate of our home planet, which we must not miss. Based on this reasoning, many countries have adopted stopping global warming at a maximum of 2°C above the preindustrial temperature level as their climate policy goal. Most notably, the European Union has adopted the 2-degree-limit in its Council decision of 1996 and reaffirmed it several times since. Increasingly, other countries are following this lead: at current count, over 130 countries support this or a lower goal.

Warming by 2°C would make the Earth warmer than it has been in several million years, and push it outside of the range of variability through the glacial cycles of Earth's recent history – so as climatologists we cannot say that this much warming is safe. But it is at least an achievable target. The United States endorsed this target at the G8 summit in July 2009, and important nations such as China, India, and Brazil have also officially recognized its importance. Note that the business-as-usual scenarios without effective climate policy shown in Figure 7.1 all exceed this limit by 2100.

Setting such a limit is of course not simply a scientific question – it also depends on what level of risk society is prepared to take, how many victims to extreme weather events we think are acceptable, and what value society attaches for example to the survival of the polar bear and many other species. It is thus a political and ethical question as much as a scientific one. Setting a specific target after a broad discussion is a sensible way of dealing with a collective risk – very similar to the way a speed limit on a road is set.

While the 2°C guard rail is a policy choice made by society, it is a question of science what emissions reductions are needed to reach this goal. This depends both on the carbon cycle (which determines what CO_2 concentration we get from a given amount of emitted CO_2) and on the climate response (most notably the "climate sensitivity" discussed in Chapter 6). It also depends on the non-CO_2 climate gases and aerosols. The answer therefore comes with a scientific uncertainty range. The IPCC analysed a number of scenarios for the stabilization of greenhouse gas levels in the atmosphere, as discussed in Chapter 9. They were at the center of a battle in the global climate negotiations in Bali in December 2007, when the European Union and other countries called for a goal of reducing emissions by 25–40% below 1990 levels for industrial nations by the year 2020, based on the IPCC category I stabilization scenario that comes closest to its 2°C guard rail (see Figure 9.4). Some countries, led by the United States, did not want these numbers mentioned in the Bali decision. The issue was resolved by the Bali document referring to the "urgency to address climate change" with an attached footnote pointing to the IPCC pages where these numbers could be found. This compromise allowed the EU-led majority to refer to the emissions reductions required for staying below the 2°C limit, without the United States actually endorsing this limit. It is symptomatic of the kind of wrestling that goes on during the international climate policy negotiations.

Climate policy targets will no doubt continue to be debated and adjusted in coming decades as more data come in. But regardless of the exact numbers, it is clear that as soon as possible we need to reach a turning point where emissions are actually starting to fall – waiting for another decade while emissions are growing further will make it extremely hard to stay below 2°C without draconian and costly measures. And it is clear that the emission cuts needed by mid century, with a growing world population and economic development, will require a fundamental transformation of our energy system, as well as a transition to sustainable land use practices (i.e., mainly a halt to deforestation). Reaching a target of 50–85% cuts by 2050, as will be needed to stay below the 2 °C limit, will require that we start now, so that the transition can be made gradually at a rate of about 2% reduction per year. This makes it cost-effective, using the normal replacement cycles of equipment such as motor cars, power stations or refrigerators.

Global conflict, or unprecedented global cooperation?

Roughly three-quarters of the greenhouse gases added to the atmosphere since industrialization have been emitted by the industrial nations, which are therefore responsible for most of the climate change so far (see Figure 10.1). On the other hand, it is poor nations that are most vulnerable to climate change. In many of these the majority of people live on subsistence farming, and a failed harvest due to drought or other weather extremes presents an existential threat. The UN estimates that all but one of its emergency appeals for humanitarian aid in 2007 were climate-related.

A global map of countries with high per capita emissions and countries with high vulnerability to climate threats shows only little overlap between the two groups. In this sense, the world is divided into a mostly wealthy part of the population causing most of the climate crisis, and a mostly poor part of the population suffering most of the consequences. An ethicist would therefore conclude that continued fossil energy use is simply unjustifiable.

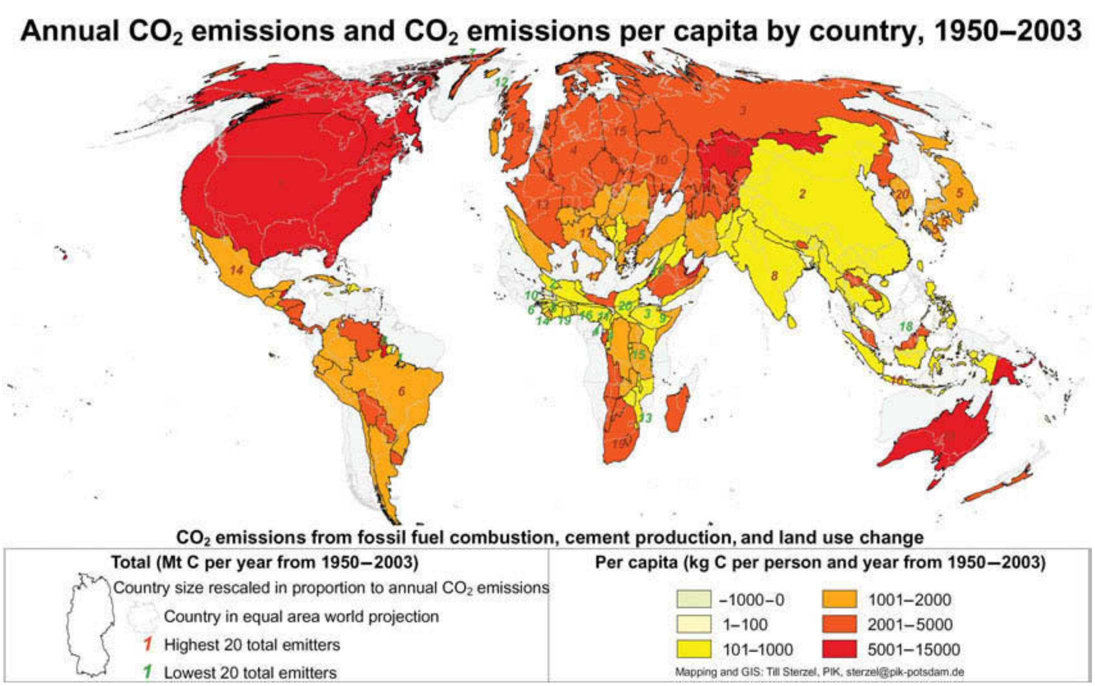


Figure 10.1 Map of total and per capita emissions by country for the period 1950–2003. The size of each country is scaled in proportion to its total emissions.

The fundamental principle of civilized society is to protect people from harm done by others. If we are to call ourselves a civilized species, there is nothing for it but to change the way we produce and consume energy.

This equity problem is one reason why it is not very useful to try and find “optimal emissions” by a global cost-benefit analysis, as some economists (mainly from the United States) have advocated. Imagine that by emitting some CO_2 I can make $1,000 extra profit in the industrial world, while causing $900 in damages to poor people in Africa. The cost-benefit analysis argues for doing this, since the benefits exceed the cost, but most people would find this unethical. The economist would argue that this is still optimal, since I could compensate the victims with $950 and keep $50 to myself, so both parties would profit overall. Non-economists know that the real world does not quite work like that – as can be seen by how sticky the negotiations about support for developing countries to cope with climate impacts are within the UNFCCC talks.

Another problem with the cost-benefit approach is how to value non-monetary damages, such as loss of lives and species extinctions. It is difficult to compensate a farmer in Bangladesh who has lost his family in a cyclone, or to argue that my extra pleasure in driving a bigger car somehow outweighs his loss. Finally, a simple practical problem with the application of cost-benefit analysis to the climate problem is that it is a very ill-constrained optimization problem: the mitigation cost and damage cost numbers are sufficiently uncertain to obtain almost any result one wants, depending on the assumptions made.

A variety of the cost-benefit approach is to play off climate mitigation costs against other “ethical” investments, such as fighting poverty or HIV, and claiming we should prioritize the latter. This argument was put forward by the Danish political scientist Björn Lomborg and promoted as the “Copenhagen consensus,” as if it were a consensus view. Lomborg began his career as a climate skeptic, using deceptive or discredited science to deny the reality of climate change, and while he now accepts the reality of anthropogenic climate change, he still confuses readers of his newspaper columns about the reality of measured climatic trends like sea level rise, by pointing to short-term variations. The idea that there is a fixed pool of “ethical spending money” that is divided up between various good causes, is no more than a clever framing trick. In reality, nobody is suggesting that we take the money for building a renewable energy infrastructure by raiding the poverty alleviation budget. Typically in politics, the people who would be opposed to one would also be opposed to the other. One could equally well frame the issue as if the climate remediation money comes from military budgets, which are many times larger. This might even make sense, in that a world that does not depend on fossil fuels may reap a peace dividend. But reality is more complex, of course: the energy system transformation sketched in Chapter 9 will produce winners and losers – the latter to be found amongst those who have benefitted most from the existing fossil fuel system and who are not flexible enough to adapt to the new reality (perhaps not surprisingly, we have heard Lomborg's argument made most frequently by executives from fossil energy companies rather than by people whose primary concern is poverty in Africa). Perhaps the best approximation is that made in the Stern Report: that the costs to society are somewhat like an extra 1% tax on consumption for all of us.

In any case, climate mitigation efforts should in no way compromise the fight against poverty and HIV. To the contrary: both the dependence on ever costlier fossil fuels and unmitigated climate change, through droughts or extreme weather events, are major obstacles to development in poor countries and could overtax their capacity to cope. In March 2008, the European Commission (the "government" of the EU) and the EU Secretary General Javier Solana issued a remarkable report, which concludes: "climate change, if unmitigated, may well wipe out years of development efforts." Titled *Climate Change and International Security*, this report identifies seven major threats of conflict driven by climate change, including conflicts over resources like water and land and tensions over energy supply, economic damage and risk to coastal cities and critical infrastructure, instability in weak or failing states and environmentally induced migration. It concludes: "Climate change impacts will fuel the politics of resentment between those most responsible for climate change and those most affected by it. . . . The already burdened international security architecture will be put under increasing pressure."

The climate crisis unfolds against a background of major political changes. With the rise of powers like China and India, we are now moving from a world dominated by one super-power to a multi-polar world order, a transition likely to bring some turbulence into international relations. At the same time, with ever increasing economic globalization, the interdependence of all nations has reached a level unprecedented in the history of mankind. Not only do our emissions in one country affect everyone else on the planet – investment decisions, financial crises or natural disasters can do the same. The question is how global politics will evolve under these conditions. We may either move into a phase of growing international tensions and conflicts over increasingly scarce resources, management of migration or compensation payments to countries affected by climate change. Or, recognizing we are all on the same planet, we may develop an unprecedented level of international cooperation to manage the climate crisis by a concerted effort of mitigation and adaptation policies.

The industrial nations will need to lead this effort, since they have the wealth, the technology, and the moral obligation. But other countries, especially the rapidly growing economies like China, India, or Brazil, will also need to take responsibility. They are likely to join the effort if it occurs within a framework that is fair and just, and if the wealthy nations show by practical example that it is possible to reduce emissions without compromising their economic well-being.

The challenge is huge – perhaps the biggest challenge that human civilization has ever faced. If we bury our heads in the sand and ignore this problem, the consequences even in our own lifetime, let alone that of our children and grandchildren, will very likely be dramatic and detrimental. We would not recognize this planet in a hundred years if we continue on our current path of growing greenhouse gas emissions. Accepting the challenge, on the other hand, requires overcoming inertia and doing many things differently. But for all we know it will not seriously hamper our economic well-being. And it will accelerate a number of exciting technological developments that will put our energy system on a truly sustainable footing while reducing pollution and energy poverty.

To us, there is thus no question that we must face up to this challenge, acting wisely and decisively. Just giving up is not an option: that much we owe to our self-respect and to our children.

Epilogue

We would like to end this book with a quote by the British writer Ian McEwan, who has described our current situation thus:

> The sheer pressure of our numbers, the abundance of our inventions, the blind forces of our desires and needs, appear unstoppable and are generating a heat – the hot breath of our civilisation.
>
> How can we ever begin to restrain ourselves? We resemble a successful lichen, a ravaging bloom of algae, a mould enveloping a fruit.
>
> We are fouling our nest, and we know we must act decisively, against our immediate inclinations. But can we agree among ourselves?
>
> We are a clever but quarrelsome species – in our public discourses we can sound like a rookery in full throat. We are superstitious, hierarchical and self-interested, just when the moment requires us to be rational, even-handed and altruistic.
>
> We are shaped by our history and biology to frame our plans within the short term, within the scale of a single lifetime. Now we are asked to address the wellbeing of unborn individuals we will never meet and who, contrary to the usual terms of human interaction, will not be returning the favour.
>
> On our side we have our rationality, which finds its highest expression and formalisation in good science. And we have a talent for working together – when it suits us.
>
> Are we at the beginning of an unprecedented era of international cooperation, or are we living in an Edwardian summer of reckless denial? Is this the beginning, or the beginning of the end?

"Let's Talk about Climate Change," openDemocracy.net, April 21, 2005 http://www.opendemocracy.net/globalization-climate_change_debate/article_2439.jsp

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Recommended web links

www.ipcc.ch   The full IPCC reports are accessible here

www.reaclimate.org   A discussion weblog about climate science at a level similar to this book, founded by the authors of this book together with six other colleagues

http://news.bbc.co.uk/1/hi/in_depth/629/629/7074601.stm The top ten "climate skeptics" arguments, answered by the BBC online news team

http://environment.newscientist.com/channel/earth/dn11462 "Climate change: a guide for the perplexed", by *New Scientist* magazine

http://cdiac.ornl.gov/ The Carbon Dioxide Information Analysis Center, U.S. Department of Energy, with latest atmospheric concentration data for greenhouse gases

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