Climate Projections for the Future

This chapter describes potential future changes in climate for a range of scenarios of future greenhouse gas emissions. It does not discuss the impacts of those changes (on ecosystems, coastal flooding, human health, and so on) – these are discussed in chapter 4. The projections in this chapter mainly assume no specific policies to reduce greenhouse gas emissions, because this is what most of the assessment of the Intergovernmental Panel on Climate Change (IPCC) has been based on. The extent to which reductions in greenhouse gas emissions could reduce future climate change is discussed in later chapters (particularly chapters 6 and 7).

Most of the key material in this chapter is based on the IPCC’s Fourth Assessment Report (AR4), in particular the Working Group I report (WGI chapters 10 and 11) and Synthesis Report (SYR Topics 3 and 5). Since the AR4, further research advances have been made. Perhaps the most significant area of research is how much and how fast sea level could rise due to the potential melting and disintegration of the polar ice sheets. The chapter refers to some of the more recent papers when we discuss what we know and do not know about future sea-level rise.

Chapter contents

3.1 Introduction ..................................................................................................................62
3.2 Emissions scenarios ....................................................................................................63
  3.2.1 Emissions scenarios in the absence of climate policies ..................................64
  3.2.2 Comparison of SRES scenarios and recent non-mitigation scenarios .............67
  3.2.3 Link of emissions ranges with development pathways ...................................67
3.3 Climate projections until the end of the 21st century .............................................68
  3.3.1 Global increases in temperature and their dependence on emissions scenarios ..................................................................................................................68
  3.3.2 Regional changes in temperature .......................................................................71
  3.3.3 Implications of temperature increases for snow and ice ..................................71
  3.3.4 Changes in regional precipitation patterns ......................................................73
  3.3.5 Changes in climatic extremes ..........................................................................75
    Model projections of changes in heat waves, heavy precipitation, and dry days ..........................................................................................................................77
    Changes in tropical cyclones (hurricanes and typhoons) ........................................78
  3.3.6 Projections of sea-level rise .............................................................................79
3.4 Twenty-first century projections – summary and historical perspective ..........82
3.5 Climate change beyond the 21st century ..................................................................84
  3.5.1 Model simulations of temperature increases to 2300 .....................................84

3.5.2 Warming in the very long term – concept of equilibrium climate sensitivity ................................................................. 85

3.5.3 Long-term sea-level rise – thermal expansion and loss of ice sheets ............... 87
  Thermal expansion towards equilibrium ................................................................. 87
  Long-term fate of polar ice sheets in a warmer world ................................................. 87

3.6 Feedbacks and potential for rapid changes in the climate system ....................... 89

3.6.1 Coupling between climate and the global carbon cycle .................................. 90

3.6.2 Changes in ocean circulation and potential for abrupt changes .................... 92

3.6.3 Release of methane from hydrates and wetlands ............................................. 94

Boxes in chapter
Box 3.1: Carbon dioxide equivalent emissions and concentrations .......................... 65
Box 3.2: Timescales in responses of the climate system ............................................. 70
Box 3.3: Regional climate patterns: potential changes in monsoons and El Niño .......... 74
Box 3.4: Potential contributions of ice sheets to sea-level rise by 2100 – recent studies..... 80
Box 3.5: The ‘known unknowns’ of Greenland’s future beyond 2100 .......................... 89

3.1 Introduction

Chapter 2 demonstrated that current climate models have considerable ability to reproduce past climate change and identify its main causes. Climate models, which embody basic physical principles and are tested against observations, are the best available tools to understand potential future changes in climate resulting from future greenhouse gas and aerosol emissions. This chapter sets out the potential changes in climate under different scenarios of future greenhouse gas emissions; we consider the potential impacts of these changes on humans and ecosystems in chapter 4.

Before we get into details, it might be helpful to consider the different factors that affect future climate change and the statements we can reasonably expect to make about the future. All climate models and our basic physical understanding of how the climate system works agree that increasing concentrations of greenhouse gases will lead to further warming of the atmosphere and related climate changes. The key questions are not whether temperatures will increase, but how much and how quickly, and how this will affect other components of the climate system such as rainfall and sea-level rise. Different models give slightly different answers to these questions, so statements about future climate change are generally given as a range, sometimes with a best estimate, not as a single figure.

Natural climate variability, solar radiation, and volcanic eruptions will of course continue to play a role in addition to human influences on the climate. We, therefore, expect to continue to see year-to-year and decadal variations in temperature, rainfall, and climatic extremes superimposed on the underlying long-term warming trend from increasing greenhouse gas concentrations. Such natural fluctuations, over periods of a few years, can enhance or reduce the global warming signal but cannot be predicted for specific years far into the future. We, therefore, cannot make projections of the expected future climate and weather in any given year, but only for extended periods over which natural variability is likely to even itself out (recall that
the terms ‘climate’ and ‘climate change’ are meaningful only over periods of decades or longer). Similarly, we can make statements about the typical frequency with which extreme events would occur in a changing climate, but we cannot forecast when and where an individual storm, drought, or heat wave will occur.

Last, but not least, future climate change will also depend on the amount of future greenhouse gas and aerosol emissions. This leaves a considerable uncertainty about the amount of future change, but this is not an uncertainty of climate models but rather one of human choices. We can picture a scenario in which humans continue to burn all available fossil fuels and open up new reservoirs as much as possible, and one in which human society moves rapidly towards a low-carbon economy thanks to already known or yet to be developed new technologies. The climate under these alternative futures could be very different, but we cannot predict in any objective scientific sense which of those futures is more likely. Thus, statements about future climate change many decades into the future are generally called ‘projections’ rather than ‘predictions’ to emphasise that they depend on emissions scenarios. The first step we need to take, therefore, is to look at what future greenhouse gas and aerosol emissions might occur over the 21st century; only then can we investigate how much the climate would change in response to any one of these scenarios.

### 3.2 Emissions scenarios

The scientific literature distinguishes two groups of emissions scenarios. The first group of scenarios, variously called ‘baseline’, ‘non-intervention’, ‘business-as-usual’, or ‘reference’ scenarios, looks at the likely emissions under a range of assumptions about future economic growth, technological development, and even environmental concerns, but these scenarios assume that human society takes no specific measures to reduce greenhouse gas emissions for the rest of the 21st century. These scenarios are clearly hypothetical, but they form valuable reference cases of how the future could turn out if no additional climate policies to limit greenhouse gas emissions are implemented.

The second group of scenarios, called ‘intervention’ or ‘mitigation’ scenarios, assumes societies take explicit steps to reduce greenhouse gas emissions below the baseline scenarios. Many mitigation scenarios are based on a long-term target to stabilise global greenhouse gas concentrations at a certain level, and then determine how to most cost-effectively reduce emissions over time so that the various target concentrations are indeed reached.

Most projections of future climate change in the scientific literature, especially over the 21st century, are based on baseline (non-intervention) scenarios, in particular the scenarios described in the IPCC’s *Special Report on Emissions Scenarios* (SRES; IPCC, 2000). For this reason, most of the projections in this chapter and their impacts are also based on such scenarios: they describe future climate change and the potential impacts, if no dedicated policies or agreements are implemented to reduce future greenhouse gas emissions.

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21 Nonetheless, you will find plenty of people who leave you in no doubt about their firm opinion on this matter, at either extremes of the spectrum.

22 Some cynics, of course, argue that there is nothing hypothetical about baseline scenarios because this is exactly how the world has been behaving over the past decades and may continue to behave in future. Touché!
3.2.1 Emissions scenarios in the absence of climate policies

The IPCC developed a set of baseline emissions scenarios in its SRES (IPCC, 2000), and the scenarios it contains are accordingly called SRES scenarios. These scenarios span a very wide range of alternative social, economic, and technological developments and associated greenhouse gas emissions for 1990–2100. They are all baseline scenarios, that is, they assume that the world does not take any dedicated action to reduce greenhouse gas emissions. The goal of these scenarios is to explore how future greenhouse gas emissions might evolve in the absence of additional climate policies but under different rates and regional distribution of economic and technological development, population growth, and depending on how future societies might balance the consumption of natural resources with general concerns about sustainability (IPCC 2000).

It is obvious that no single scenario can capture the large variety of possible future development choices. The future can be pictured only through a set of scenarios that each explores potential alternative development paths in a self-consistent way. The SRES did this by grouping a large number of scenarios into four broad ‘families’ (labelled A1, B1, A2, and B2). Each family follows consistent storylines about how the world could develop between now and 2100. No likelihood has been attached to any of these alternative scenarios; they are all assumed to be equally plausible alternative development paths that the world could take if climate change were not an issue (IPCC 2000).

- The A1 scenario family assumes a world of rapid economic growth, rapid development, the introduction of new and more efficient technologies, and a global population that peaks in the middle of the 21st century at about 8.7 billion and then slowly declines. This family is further divided into three subgroups that describe alternative directions that technological developments could take (labelled A1F1, A1T, and A1B). The A1F1 family assumes that energy needs are met from ever more efficient extraction and use of fossil fuels, while the A1T family assumes that the technology focus will lie on developing non-fossil energy sources. The A1B family follows the middle between those two extremes.
- The B1 scenario family describes a world with less economic growth than the A1 family and instead more rapid changes in economic structures away from commodities towards an economy based on services and the generation and use of information, with emphasis on global solutions to economic, social, and environmental sustainability. It assumes the same population trend as the A1 family.
- The B2 scenario family describes a world with intermediate economic growth and emphasises more local solutions to economic, social, and environmental challenges than the A1 and B1 families. It assumes a stronger population growth than A1 and B1, reaching just over 10 billion in 2100.
- The A2 scenario family describes a very heterogeneous world, with strong differences between world regions in terms of economic and technological development, which leads to slower overall technological change and slower growth of the global economy than in the A1 and B1 families. It also assumes continued strong growth of the global population driven by population explosions in some regions, reaching about 15 billion in 2100.

All these baseline scenarios assume a continued increase in global gross domestic product (GDP), but global average growth rates vary from about 2.2% per annum in
the B2 family to about 3% per annum in the A1 family (for 1990–2100). For each of these scenario families, a single ‘marker’ scenario was selected to represent key socioeconomic development trends and associated greenhouse gas emissions. Most model studies of future climate change to date use the greenhouse gas emissions of one or several of the six SRES marker scenarios as inputs for climate projections and model studies of climate change impacts. The greenhouse gas emissions under the six different marker scenarios are shown in Figure 3.1, expressed in carbon dioxide equivalents (CO₂-equivalents) (see Box 3.1 for an explanation). It should be noted that these scenarios exclude not only any dedicated efforts to reduce greenhouse gas emissions but also any potential impacts of climate change that could affect economic growth and social development and therefore, by implication, also emissions. (IPCC 2000, WGIII 3.2, SYR 3.1)

**Figure 3.1:** Scenarios of future carbon dioxide equivalent (CO₂-eq) global greenhouse gas (GHG) emissions, 2000–2100

Note: The scenarios (B1, A1T, B2, A1B, A2, A1F1) assume no specific and additional measures to reduce greenhouse gas emissions. The solid lines illustrate alternative scenarios the Intergovernmental Panel on Climate Change developed in Special Report on Emissions Scenarios (SRES; IPCC, 2000). The grey area and dashed lines show the 80 percentile and extreme ends of the range found in the literature since 2000 for scenarios that assume no additional climate policies.

Source: SYR Figure 3.1.

**Box 3.1:** Carbon dioxide equivalent emissions and concentrations

Different greenhouse gases have a different effectiveness in warming the Earth’s climate, because of different atmospheric lifetimes and different abilities to absorb infrared radiation. It is useful to compare the warming effect of different gases through some common metric. The most widely used metrics are carbon dioxide equivalent (CO₂-eq) emissions and concentrations, which express the warming effect of different greenhouse gases through the warming effect of an equivalent amount of CO₂ (similar to how a single currency can be used to express the value of goods produced in different countries).
The **CO₂-equivalent emission** of a greenhouse gas is the amount of CO₂ the emissions from which would cause the same warming effect, over a given time-frame, as the emissions of a given amount of this greenhouse gas. (SYR 2.1)

The CO₂-equivalent emission is calculated by multiplying the amount of this gas with its so-called ‘global warming potential’ (GWP). The longer a gas remains in the atmosphere, and the better it is at absorbing heat radiation, the higher is its GWP. For example, methane (CH₄) is much more efficient at absorbing heat radiation than CO₂ is, but its lifetime in the atmosphere is much shorter. When integrated over a period of 100 years, the emission of 1 kg of CH₄ has about the same warming effect as 25 kg of CO₂; hence, instead of saying that 1 kg of CH₄ was emitted we can say that 25 kg CO₂-eq was emitted. If we integrate over a period of 500 instead of 100 years, the emission of 1 kg of CH₄ would have a smaller warming effect equivalent to only 7.6 kg CO₂, because most of the CH₄ would have already disappeared from the atmosphere within the first 100 years from the time of emission. (WGI 2.10)

Current policy agreements under the United Nations and national greenhouse gas inventories use a standard 100-year time-frame for GWPs and CO₂-eq emissions, with specific values based on the IPCC assessment in 1995. To be consistent with the United Nations climate change agreements, the IPCC and this volume also use this 100-year time-frame and these numerical values to calculate CO₂-eq emissions. (SYR 2.1)

The **CO₂-equivalent concentration** of a greenhouse gas, or a mixture of gases, is the concentration of CO₂ in the atmosphere that would have the same warming effect as this gas or mixture, relative to pre-industrial concentrations. For example, in 2005 the concentration of CO₂ was 379 parts per million (ppm), but the total warming effect from all greenhouse gases together (CO₂, plus CH₄, nitrous oxide (N₂O), and others; see Figure 2.4) was higher, equal to that of 455 ppm CO₂. We can, therefore, say that the concentration of all greenhouse gases was 455 ppm CO₂-eq. (WGI 2.10, SYR 5.4)

The concept of CO₂-equivalence, in principle, can be applied not only to greenhouse gases but also to aerosols. Aerosols have a net cooling effect, but the uncertainties related to their warming and cooling effects are considerably greater than for greenhouse gases and also depend on where aerosols are emitted. Using best estimates that take the distribution of aerosols around the world into account (see Figure 2.4), the current CO₂-eq concentration of greenhouse gases and aerosols together is about 375 ppm. This lower CO₂-equivalent concentration, compared to the value of 455 ppm if we account for greenhouse gases only, arises from the net cooling influence of aerosols on the climate. (WGI 2.4, 2.10, SYR 5.4)

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23 More recent assessments by the IPCC have slightly revised the GWPs of some greenhouse gases; for example, the 100-year GWP for CH₄ in the 2007 assessment is given as 25, whereas in the 1995 assessment it was given as 21 (WGI 2.10). This does not change the picture fundamentally, but it could have a significant effect on the balance of contributions from different sectors to a country’s overall emissions budget, because it means that the 100-year warming effect of CH₄ is now rated 20% higher than under the methods adopted under the current United Nations climate change agreement.
3.2.2 Comparison of SRES scenarios and recent non-mitigation scenarios

Studies undertaken since the publication of the IPCC’s SRES in 2000 that use the same broad set of assumptions are comparable to SRES scenarios in their global emissions ranges (see Figure 3.1). Some recent studies have used lower values for some emissions drivers, notably population projections, but changes in other drivers, such as economic growth, have tended to counterbalance the effect of lower population projections. Economic growth projections to 2030 are lower in more recent scenarios for regions such as Africa, Latin America, and the Middle East, but this has only minor effects on global economic growth and emissions. (WGIII 3.2)

Many emissions scenarios contain projections not only for the main greenhouse gases, but also for aerosols and other gases that act as air pollutants. In recent scenarios, projections for these drivers have generally been lower than in the SRES scenarios, reflecting the increasing implementation of air quality measures in many parts of the world. (WGIII 3.2)

Together, the emissions of greenhouse gases, aerosols, and other gases, including those resulting from deforestation, have formed the input for most modelling studies of future climate change discussed in this chapter. The outputs from these modelling studies, together with socioeconomic parameters such as population and income levels, have formed the input for most studies on the potential impacts of climate change, which are discussed in chapter 4.

3.2.3 Link of emissions ranges with development pathways

Almost all baseline (non-intervention) scenarios agree that without additional climate policies, greenhouse gas emissions will continue to grow substantially over the next few decades. SRES scenarios indicate that greenhouse gas emissions could increase from 2000 to 2030 by 25–90% (an increase of 9.7–36.7 Gt CO$_2$-eq).$^{24}$ Even though such an increase in emissions may appear staggering, it is merely a continuation of recent trends: between 1970 and 2004, greenhouse gas emissions increased 70%. Chapter 6 examines further the reasons for the historical and projected future emissions increases and the contributions from different sectors and regions. (WGIII 1.3, 3.2)

Over the course of the 21st century, the emissions under the different SRES scenarios diverge increasingly, which reflects the different development patterns that the world could take. The scenarios with the lowest emissions (B1 and A1T) project that in 2100, CO$_2$-equivalent emissions could fall to about 60–75% of year 2000 emissions due to global technological change, more efficient use of resources, and a global population that peaks in 2050 and then declines. In contrast, the scenarios with the highest emissions (A1FI and A2) imply that CO$_2$-equivalent emissions in 2100 could be more than three times greater than in 2000 due to increased use of fossil fuels, consumption patterns and, for the A2 scenario, continued population growth throughout the 21st century (IPCC, 2000; WGIII 3.2).

As mentioned above, these scenarios assume that no additional policies are implemented specifically to reduce greenhouse gas emissions. We discuss in later chapters the technological and policy options and international agreements that could

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$^{24}$ Emissions of greenhouse gases are often expressed in so-called CO$_2$-equivalents, which is a common and useful metric to compare and combine the warming effect of different greenhouse gases. See Box 3.1 for details.
reduce greenhouse gas emissions and thus future climate changes below the levels in the SRES scenarios. But first we need to look at the climatic consequences if any of the SRES scenarios described in this section were to become reality, and what difference alternative pathways would make on the climate in the near and more distant future.

3.3 Climate projections until the end of the 21st century

Based on the various baseline emissions scenarios discussed above, we can now make projections of future climate changes. Apart from the effects of greenhouse gas and aerosol emissions, the climate models used to make those projections include estimates of solar radiation similar to what was observed over the past two to three decades because we have no good reason to assume substantial future changes in the forcing from the sun in either direction. (WGI 10.2)

3.3.1 Global increases in temperature and their dependence on emissions scenarios

Figure 3.2 shows the projected changes in global average temperature until the end of the 21st century resulting from different SRES emissions scenarios. Three of the scenarios (B1, A1B, and A2) have been the subject of extensive modelling efforts by the scientific community, and for those scenarios the evolution of temperature is shown throughout the 21st century, as well as the best estimate and uncertainty range for the decade 2090–2099. The best estimates and uncertainties for 2090–2099 are derived from a large set of atmosphere–ocean general circulation models (discussed in Box 2.2) and models of lower complexity; in addition, agreement between observations and simulations of the current climate were to place boundaries on plausible future changes. (WGI 10.3, 10.5)

For the other scenarios (B2, A1T, and A1FI), we have only best estimates and uncertainty ranges for 2090–2099 but not their evolution during the 21st century. However, given that the response of the climate system is roughly proportional to the radiative forcing, we can get a sense of how global average temperatures would change during the 21st century under those other emissions scenarios.25 (WGI 2.8)

The global temperature projections in Figure 3.2 reveal some important ways in which the climate system is likely to behave in response to further greenhouse gas emissions.

Until about 2030, temperatures for the three scenarios (B1, A1B, and A2) diverge only little, even though their emissions differ substantially due to their varying focus on sustainability or energy expansion and global or more regionalised growth patterns. The reason for this similarity is that about half of the warming over the next two decades is due to greenhouse gas emissions that have already occurred, but the atmosphere is still adjusting to the change in energy balance that has been caused by these past emissions. This adjustment takes decades and, for some processes, even centuries (see Box 3.2).

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25 Note that even though the global average temperature increase is roughly proportional to the radiative forcing, different emissions scenarios that have the same radiative forcing could still produce different climate changes at the regional scale, especially as a result of differences in aerosol emissions.
Figure 3.2: Projections of greenhouse gas emissions, concentrations, and temperature change, 2000–2100

Notes: Left panel: Scenarios of carbon dioxide equivalent (CO$_2$-equivalent) greenhouse gas (GHG) emissions for a range of scenarios from the Special Report on Emissions Scenarios (IPCC, 2000) from 2000 to 2100. Middle panel: Resulting CO$_2$-equivalent GHG concentrations in the atmosphere. Concentrations continue to increase even for scenarios whose emissions decline after the middle of the century. Right panel: Global average temperature change reproduced for the 20th century (black line) and projected for the 21st century under the different emissions scenarios (coloured lines). The uncertainty bars indicate a 66% likelihood that the true value will lie within this range. The CO$_2$-equivalent concentrations in the middle panel are based on the methodology described in IPCC (2001); the concentrations in the middle panel may, therefore, not correspond directly to the concentrations used in the model simulations in the right-hand panel and should be taken as illustrative only.

Source: Based on SYR Figure SPM.5 and data in IPCC (2000; 2001, Appendix II.3.11).
Box 3.2: Timescales in responses of the climate system

The climate system responds over different timescales to any changes in greenhouse gas emissions. Some processes take a long time, which means that the climate system continues to warm long after the emission of some greenhouse gases, particularly carbon dioxide (CO$_2$), has occurred.

Global greenhouse gas and aerosol concentrations increase almost instantaneously when their respective emissions increase (i.e., within a couple of years). If their emissions decline, it depends on the lifetime of the gas or aerosol how quickly concentrations respond. As discussed in Box 2.1, the long life times of CO$_2$ mean that it takes centuries to millennia for the concentration of CO$_2$ to decline even if its global emissions are reduced substantially. Moderate reductions in CO$_2$ emissions do not lead to a reduction in concentration, only to a slower rate of increase of its concentration. In contrast, the concentration of methane (CH$_4$) would decline within a decade after emissions are reduced. The concentration of aerosols would respond even more quickly (within weeks) to global reductions in emissions.

The lifetime of greenhouse gases and aerosols is not the only source of inertia and time lags in the climate system. When greenhouse gas concentrations increase, the Earth’s energy balance changes. The resulting warming of the atmosphere does not occur instantaneously because it is coupled to the temperature of the surface of the ocean. The ocean acts as a cold-water bath that limits the speed at which atmospheric temperatures can rise in response to the increased input of energy. As a result, it takes about a century for atmospheric temperatures and the ocean surface to respond fully to the change in energy balance.

Yet longer timescales and delays are introduced by the slow mixing of the ocean surface with deeper ocean layers. This mixing process takes hundreds to a thousand years, and means that warming of the ocean as a whole will continue over very long timescales as the deep ocean slowly adjusts to higher temperatures at the Earth’s and ocean surface. A further consequence of this warming of the deep ocean is that atmospheric surface temperatures will continue to creep up further over many centuries even if greenhouse gas and aerosols concentrations, and hence the energy balance itself, were held constant after an initial increase.

Beyond the next few decades, temperatures under the three emissions scenarios (B1, A1B, and A2) diverge more and more due to the additional emissions of greenhouse gases, until by the end of the 21st century there is a substantial spread in warming between the three scenarios. Models cannot predict precisely how much the climate will warm for a given emissions scenario; the bars at the right-hand side of Figure 3.2 indicate the possible range of outcomes for each scenario. The range for each individual emissions scenario is of a similar magnitude as the difference in outcomes resulting from the choice of alternative emission scenarios. (WGI 10.3, 10.5)

These projections all assume that no specific action is taken to reduce greenhouse gas emissions, but even if we do take action, we can no longer avoid further warming entirely. Model studies show that even if we could have (hypothetically) kept the atmospheric concentrations of all greenhouse gases and aerosols constant at the level they were in 2000, the climate system would still warm by another 0.6°C over the next 100 years because the atmosphere keeps responding to the warming effect of
greenhouse gases that have already been added to the atmosphere (see Box 3.2). (WGI Figure 10.4, 10.7)

Keep in mind that the assumption of ‘constant concentrations from 2000 onwards’ is purely hypothetical, because to keep concentrations of greenhouse gases constant, emissions would have to fall immediately on a global scale. None of the real-world mitigation scenarios suggest that an immediate and sustained drop in global emissions is feasible; even the most stringent mitigation scenarios assume that it would take at least another decade to stop the global growth in emissions, followed by a continuous decline until emissions eventually reach almost zero by 2100. These are the toughest mitigation scenarios that the IPCC assessed as credible and feasible, but under these scenarios the CO₂-equivalent concentrations of greenhouse gases would still continue to increase until at least the middle of the 21st century. Hence, a further rise in atmospheric temperatures of even more than 0.6°C and other related changes in climate and sea level over the 21st century appear already inevitable. (WGI 10.3, 10.6, 10.7, WGIII 3.3, 3.5)

It is a matter of perspective whether these alternative futures are a source of despair or a sign of hope: indeed, there appears relatively little we can do to stop temperatures from continuing to rise in our lifetime, but alternative choices about our emissions will make a substantial difference about the climate in which our grandchildren will live and the consequences of these changes they will have to deal with.

### 3.3.2 Regional changes in temperature

Global average temperature is a convenient metric to indicate the magnitude of future climate change, but it is not the most meaningful quantity for anybody’s daily life. Nobody lives at the global average – just as no woman bears exactly 2.55 children, even though this is the current global average fertility rate (UN, 2006). The amount of warming is expected to differ significantly across different parts of the world, as shown in Figure 3.3. The absolute amount of warming depends on the emissions scenario, but the pattern of warming is similar for all scenarios. All land regions are expected to warm more than the adjacent oceans and the global average, with the greatest warming expected in high northern latitudes. The regions where least warming is expected are the northern North Atlantic and the Southern Ocean. This pattern continues observed trends during the 20th century and is consistent with the basic physical principles of warming caused by greenhouse gases, along with projected changes in wind and ocean circulation patterns. (WGI 3.2, 3.9, 10.3)

### 3.3.3 Implications of temperature increases for snow and ice

The rising temperatures will have significant effects on snow and ice cover. Snow cover and glaciers are projected to shrink further in virtually all parts of the world. The pace of this reduction is likely to accelerate due to rising temperatures and because of local feedbacks that increase warming and glacier melting as the area covered by glaciers reduces. Many smaller glaciers are likely to disappear under the higher warming scenarios by the end of the 21st century. In parallel, permafrost in high-latitude regions is expected to thaw to greater depths throughout the 21st century. This would initially lead to wetter soils during summer as the permafrost thaws, followed by drying of those warmed up soils in the late 21st century. (WGI 8.6, 10.3, 10.6, WGII 3.4, 15.3)

Snow cover is projected to reduce over most parts of the northern hemisphere; the largest decreases are expected during spring and in late autumn/early winter, which means a shorter period that snow cover persists. Changes in individual
locations will depend though on the specific interplay between rising temperatures and changes in rain and snowfall; a few regions (eg, Siberia) could see an increase in snow amount due to increasing precipitation. (WGI 10.3, 10.6, WGII 15.3)

**Figure 3.3:** Global pattern of warming, 2090–2099

![Global pattern of warming, 2090–2099](image)

Note: The global pattern of warming in 2090–2099 is shown relative to average 1980–1999 temperatures, for the A1B emissions scenario from the *Special Report on Emissions Scenarios* (IPCC, 2000). The pattern of warming under other emissions scenarios is very similar, but the absolute magnitude depends on the amount of emissions.

Source: SYR Figure SPM.6.

Sea ice is also projected to shrink in both the Arctic and Antarctic. Some projections indicate that Arctic sea ice could disappear entirely in late summer before the end and even by the middle of the 21st century. Recent observations of dramatic further reductions in Arctic sea ice during the past two years (see section 1.2.2) suggest that this could happen even sooner than predicted by current models. This is in part because thinning of sea ice in one year makes it more vulnerable to break-up in the following year, which may not be fully incorporated in those current projections and hence lead to the Arctic becoming ice-free even earlier (Maslanik et al, 2007; Stroeve et al, 2007; Rosenzweig et al, 2008; Smethurst et al, 2008; Zhang et al, 2008a; Zhang et al, 2008b; Eisenman and Wettlaufer, 2009).

The ocean around Antarctica is expected to remain too cold for sea ice to disappear entirely during this century, but simulations of observed changes and projections of future changes in Antarctic sea ice are difficult due to the interaction of atmospheric circulation changes with temperature over the Antarctic continent. (WGI 10.3, 10.6)

The implications of the projected changes in the snow and ice-covered regions of the world are profound. They will affect not only water storage and availability for humans and ecosystems, but also the functioning in particular of Arctic ecosystems and specific species, such as polar bears, that rely on sea ice as resting places and as a platform for hunting (WGII 3.4, 4.4, 15.4; SYR 3.3). We discuss the implications of these changes in chapter 4.
3.3.4 Changes in regional precipitation patterns

Changes in precipitation could be amongst the most critical consequences of increasing greenhouse gas concentrations, because water underpins so many essential processes in ecosystems and in human society. Models have become much better over recent years in simulating rainfall due to higher resolution and better representation of the key atmospheric processes involved in rainfall, and the general understanding of the processes that determine changes in precipitation has also improved. The latest set of model simulations suggests precipitation increases in high latitudes, but decreases in most subtropical land regions and some dry mid-latitudes and dry tropics, which would continue patterns observed in recent trends. The precipitation changes are shown in Figure 3.4. (WGI 3.3, 3.9, 10.3; WGII 3.3)

Figure 3.4: Changes in seasonal average precipitation projected in 2090–2099 relative to 1980–1999

Note: Changes are for the A1B emissions scenario from the Special Report on Emissions Scenarios (IPCC, 2000). The left panel shows seasonal changes for December, January, and February. The right panel shows changes for June, July, and August. Areas where more than 90% of models agree on the direction of change are stippled. Areas where less than 66% of the models agree on the sign of change are white.

Source: SYR Figure 3.3.

The projected precipitation changes show important seasonal variations, which are particularly relevant for countries that rely on seasonal rainfall. For example, Figure 3.4 shows that south and south-east Asia are expected to receive more rain during the summer months (their monsoon period), but less rain during the winter months (their dry season). More rain in a generally dry region such as the Indian subcontinent would be positive in principle, but if the increased rain comes primarily during the already wet season while the dry season becomes even drier, the implications are quite different (WGI 11.4, WGII 10.2, 10.3, 10.4). We examine the impacts of changes in rainfall patterns further in chapter 4.

Confidence in precipitation projections is very high for some regions (particularly high northern latitudes and some mid-latitudes and subtropical regions), while in other regions models are less consistent; in some parts of the world (for example central China and eastern United States, and wide parts of Australia) models do not even agree whether precipitation is likely to increase or decrease. Precipitation projections are generally more reliable for larger geographical (subcontinental) regions, while projections for individual catchments are more difficult even where models agree on broad patterns of changes because local climate patterns and feedbacks play a larger role. (WGI 10.3, SYR 6.2)
Box 3.3: Regional climate patterns: potential changes in monsoons and El Niño

Regional climate patterns such as the monsoons and El Niño Southern Oscillation play important roles in human societies because they have a large influence on seasonal rainfall, so impact on agriculture, water supplies, and natural hazards related to flooding. A critical question is, therefore, whether and how these existing climate patterns might change with increasing greenhouse gas concentrations.

Monsoons

The monsoons are a seasonal climate pattern in many subtropical regions. Every year, the heating of continental land masses in those regions leads to a reversal in regional wind patterns during summer, which then brings much-needed and often heavy rains to a parched landscape. Monsoons occur in south and east Asia and Australia but similar seasonal rainfall patterns also exist in parts of North and South America and Africa. The monsoons of south-east Asia and the Indian subcontinent are an essential part of agriculture and water supply for well over 1 billion people. Although the monsoon brings much-needed rain, heavy falls have caused flooding and deaths in many cities particularly in the Indian subcontinent. (WGI 11.1–7; WGII 9.2, 10.2, 11.2, 13.2, 14.2)

Model simulations of monsoons in a changing climate indicate that the rainfall associated with Asian monsoons could increase by some 10%, but also that it might become less reliable with stronger monsoons in some years and weaker monsoons in others. Projections of changes in monsoons are further complicated because El Niño events (see below) are known to reduce the strength of the monsoon, as does Eurasian snow cover, because it influences the regional heating pattern that drives the monsoon winds. Perhaps the most critical additional factor that influences monsoons comes from regional emissions of aerosols associated with the industrialisation of countries in the Asian region. If aerosol concentrations continue to increase, their ability to filter sunlight could reduce the strength of the monsoon, and the decreases in average monsoon precipitation over the past few decades have been linked to increased aerosol concentrations. On the other hand, if aerosol emissions reduce as part of efforts to improve local air quality, monsoon strength and associated rainfall could increase further driven by a changing climate. (WGI 10.3, 11.4, WGII 10.3)

Monsoons in other regions are mostly expected to increase with rising temperatures, because these changes would fuel the seasonal heating processes that fuel the monsoon winds and allow the atmosphere to transport more moisture. Decreases in monsoon precipitation are expected in the northern Sahel region, Mexico, and Central America largely because the main area of rainfall would shift away from these land areas. All these projections would be influenced by changes in aerosol emissions, which can influence the formation of monsoon winds and their moisture content. (WGI 10.3, 11.2, 11.5, 11.6)

El Niño/La Niña

The El Niño/La Niña pattern is an irregular climate oscillation that arises from the interaction between atmospheric and ocean temperatures in the east Pacific, but that can affect temperatures and rainfall in many parts of the world.
Normally, trade winds blow across the Pacific from east to west, so create a steady flow of warm water and air masses towards Australasia, while the upwelling of cold water reduces ocean and air temperatures near the west coast of South America. The warm and moist air masses bring regular rain to the western Pacific, but the air that arrives in South American countries, such as Ecuador and Peru, is cold and dry so these countries receive only little rainfall.

Every two to seven years, this picture changes into what is called an El Niño pattern: the layer of warm water shifts from the west into the central and eastern Pacific and the trade winds weaken or even reverse; warmer and moister air can rise near the western coast of South America, where it can lead to unusual and torrential rainfalls, while the drier air arriving in the west Pacific region increases the risk of droughts in Indonesia and Australia. These changes in atmospheric and ocean circulation spill over into other parts of the world and affect rainfall in eastern South America and parts of North America, the strength of monsoons over Asia, and rainfall patterns in central and east Africa. Not least, the ocean circulation changes related to El Niño also affect the amount of sea ice in parts of Antarctica.

The La Niña pattern interchanges with El Niño. During a La Niña, the trade winds are even stronger than usual, so even drier conditions exist in the west coast of South America but there is more rain and higher temperatures in the western Pacific.

Many climate models can reproduce the broad features of the El Niño/La Niña pattern, and they are indeed used to forecast the development of El Niño conditions for half a year or a year into the future, which is then used to advise farmers to prepare for drought conditions or governments to prepare for civil emergencies related to flooding. However, models do not agree on how El Niño patterns might change in the long term under sustained global warming from greenhouse gases. All models suggest that the El Niño pattern would continue, and the majority of models suggest that, on average, the Pacific Ocean could shift more into an El Niño–like mean state in the Pacific Ocean, which would increase average rainfall along the west coast of tropical South America but reduce rainfall in the south-west Pacific. However, models are almost evenly split as to whether the intensity of El Niño and La Niña variations might increase or decrease. (WGI 3.6, 8.4, 10.3)

3.3.5 Changes in climatic extremes
As greenhouse gas concentrations increase and the Earth’s energy balance changes, we expect this to affect not only global average temperature and patterns of annual average rainfall and winds, but also the frequency and intensity of climatic extremes such as heat waves, heavy rainfall, droughts, and storms. For most climatic extremes their frequency and intensity is expected to increase with rising average temperatures. Understanding the likely changes in extremes is particularly important because many of the potential impacts of climate change (discussed in chapter 4) could arise from changes in extreme events rather than changes in average temperatures or rainfall.

Human society and ecosystems in most regions are reasonably well adapted to the ‘normal’ range of variations in rainfall, extreme heat, and storms. For example, many ecosystems can cope with dry periods; cities are protected against flooding by levees and dykes and against heat by building design that includes air conditioning;
water reservoirs can buffer against dry periods in urban and rural areas; and early
warning systems can alert people to the likely occurrence of extreme storms. However, significant damages can occur if extremes fall outside the expected range of intensity or frequency, including because there may be too little time to recover from the previous extreme. (WGII 6.4, 7.4; see also chapter 5)

In a warmer climate, it appears intuitively plausible that the number of extremely hot days and heat waves would also increase, and that in areas where average precipitation increases, extremely heavy falls would also increase. More importantly though, even relatively modest changes in mean temperature and precipitation can lead to large changes in the frequency of extreme events. This is because the probability with which an extreme event (such as heavy rainfall) occurs usually depends on its intensity: there are regular instances of heavy rainfall (and cities are well protected against flooding associated with such events by their stop banks), but very rare instances of extremely intense rainfall (leading to flooding that could overtop existing levees). Even if the average intensity of rainfall increases by a relatively small amount, the number of times that an extremely intense rainfall occurs in excess of some fixed threshold could increase much more. The same applies to an increase in average temperature and the occurrence of extremely hot days: a small increase in average temperatures can still lead to a significant increase in the number of extremely hot days. This non-linear relationship between changes in average climate conditions and extremes is illustrated in Figure 3.5. (WGI Box TS.5)

**Figure 3.5:** Changes in extremes as a result of changes in mean climate

Note: For any given mean climate, there is a small percentage of extremely hot days as well as extremely cold days. If the mean climate becomes warmer, the temperature of the most extreme hot days will also increase, but more importantly, the number of days that exceed a given threshold may increase significantly.

Source: Based on WGI Box TS.5 Figure 1.
Model projections of changes in heat waves, heavy precipitation, and dry days

The basic statistical reasoning for the non-linear relationship between changes in average climate conditions and extremes is borne out by more high-resolution model studies for many extremes. Figure 3.6 shows the projected changes in the global average occurrence of heavy precipitation events, dry days, and heat waves, relative to the variability of their occurrence under recent average climate conditions (average of 1961–1990). In particular, heavy precipitation and heat waves show a large global increase compared with their current variability, while the projected global change in dry days is less pronounced. These changes would essentially continue already observed trends in the frequency and intensity of these extremes. (WGI 10.3)

Figure 3.6 shows that, in general, heavy precipitation increases particularly in regions where average rainfall increases, while dry days are expected to increase particularly in those regions where annual average rainfall reduces. The global area affected by drought is expected to increase globally, particularly in mid-continental areas such as the Mediterranean and the south-west United States, due to the combination of an increasing number of dry days and greater evaporation of soil moisture under higher temperatures (see also chapter 4). (WGI 10.3)

It is worth noting though that increases in heavy precipitation are projected to occur even in many regions where total rainfall is projected to decrease. The reason for this is that a warmer atmosphere can hold more water, which increases the chance that intense bursts of heavy rainfall are interspersed with longer dry periods. In other words, even where there is less rain, when it does rain, it is likely to rain harder. (WGI 10.3)

The magnitude of the projected changes in extremes, particularly heat waves, can be appreciated by comparing what we currently regard as extreme with what might be normal in future. For example, model simulations suggest that the temperatures during the heat wave of 2003 in Europe, which cost several tens of thousands of lives, would become standard summer temperatures by about the middle of the 21st century under mid-range business-as-usual emissions scenarios. By the late 21st century, a summer as hot as that of 2003 would likely be regarded as unusually cool, while an extremely hot summer in the second half of the 21st century would be entirely outside the range of current experiences (Stott et al, 2004). This is not to say that by the late 21st century every summer would cause as many deaths as the heat wave of 2003, because we can assume that society will adapt to at least some of the changes. Nonetheless, it does show that the changes in extremes may have significant implications on how people live their lives in order to deal with such changes.

Many but not all climatic extremes are projected to increase in a warming climate. Models as well as basic physical principles suggest that concurrent with increasing global average temperatures, the number of frost days would reduce significantly in most regions that currently experience frost. Concurrent with this trend, the growing season is expected to increase in most temperate regions of the world. (WGI 10.3)
Figure 3.6: Projected changes in rainfall and snowfall intensity, dry days, and heat waves over the 21st century

Note: Projected changes in precipitation (rainfall and snowfall) intensity, dry days, and heat waves over the 21st century compared with modelled changes during the 20th century. Left-hand panels show global average changes during the 20th and 21st centuries for a large set of climate models. Right-hand maps show the geographic distribution of changes in 2090–2099 compared with 1980–1999 from the same set of models. Changes in extremes are expressed in units of standard deviation (std. dev.), which is a measure for the frequency with which extremes normally occur. An increase by 1 std. dev. means that extremes that currently have only about a 1-in-40 chance of occurring would have a 1-in-6 chance in future (see also Figure 3.5).
Source: Based on WGI Figure 10.18 and Figure 10.19.

Changes in tropical cyclones (hurricanes and typhoons)
Model simulations project that tropical cyclones (hurricanes and typhoons) will increase in intensity in terms of wind speeds and, notably, the precipitation associated with such storms. Similar to other changes in extremes, these projections continue the already observed trend of increased intensity of tropical cyclones in the North Atlantic. (WGI 3.8, 10.3)
It is uncertain how much more intense these storms could become and how quickly those changes would happen. Model simulations of the past three decades produce a much smaller increase in storm intensity than what was actually observed in the North Atlantic. This could indicate that models underestimate the amount of future changes that could occur in future, but it could also mean that the observed recent increase in storms is an example of natural variability and increases in the longer term will not necessarily continue at the same rate as in the past three decades. (WGI 3.8, 10.3)

Most models indicate a reduction in the overall number of tropical cyclones, but the confidence in these projections is lower. Overall, models suggest fewer weaker storms but an increase in the number of the most intense storms. (WGI 3.8, 10.3)

### 3.3.6 Projections of sea-level rise

The two main drivers of sea-level rise in a warming world are the expansion of the existing ocean water as it warms up and the addition of water that was previously stored on land. Both processes are expected to contribute to global average sea-level rise throughout the 21st century. Most of the rise in sea levels over the 21st century is expected to come from thermal expansion, but the biggest uncertainty in projecting future sea-level rise comes from the future behaviour of the large ice sheets of Greenland and Antarctica. Current models that simulate the behaviour of these ice sheets suggest that Greenland will lose ice mass and contribute to sea-level rise over the 21st century, while Antarctica should remain too cold for widespread melting at its surface and should gain mass due to increased snowfall (and hence reduce sea level). Based on these factors, and including the melting of glaciers and snow elsewhere and thermal expansion, models project that sea level could rise further by 2100 by 18–38 cm under the lowest (B1) emissions scenario, or up to 26–59 cm under the highest (A1FI) scenario. (WGI 10.6)

These projections of sea-level rise have important limitations. First, the current model studies of sea-level rise do not include climate–carbon cycle feedbacks (see section 3.6.1). More importantly, current ice sheet models incorporate only the deposition of snow, melting at the surface if temperatures are high enough, and the steady flow of ice into the sea from glaciers at the margins of ice sheets. However, as discussed in chapter 1, many glaciers whose bounding ice shelves disappeared over the last decade have accelerated their flows, partly in response to warming of the oceans or increased input of meltwater. These dynamic processes and underlying mechanisms are poorly understood. They are, therefore, not incorporated into current ice sheet models but could increase the future loss of ice from both Greenland and Antarctica. Unfortunately, there is a wide divergence of views in the scientific community just how much such processes could affect projections for the 21st century. For example, we could assume that the acceleration of glacier flow in Greenland increases linearly with future temperature increases, in which case we could see another 10–20 cm of sea-level rise by 2100 on top of the above projections, that is, up to 0.8 m (WGI 10.5, 10.6).

We do not know whether these are realistic assumptions – the glacier flows do not necessarily increase linearly with temperature. Many recent studies show large local changes in ice flow associated with particular ice streams or glaciers in Greenland and Antarctica. These changes are striking, but they are not large enough to make major contributions to sea level per se, because they are local and still small compared to all contributions to the vast amount of water in the ocean. There are also questions about how long the ice will flow – some studies suggest that the changes
could stabilise again within a few years. The question of how ice flows may accelerate in future, therefore, becomes one of extrapolating from striking but local behaviour to much larger scales and/or longer times. Such questions of extrapolation naturally are highly uncertain and there is no convergence yet that would allow a revised best estimate for sea-level rise. However, recent studies all indicate the potential for sea level to exceed the range assessed by the IPCC due to further acceleration in glacier flows (Das et al, 2008; Joughin et al, 2008; Pfeffer et al, 2008; van de Wal et al, 2008; Nick et al, 2009).

In summary, we know the current ice sheet models give us only part of the potential sea-level rise from ice sheets, but we do not yet know how large the missing bit might be. The recommendation from the IPCC is, therefore, that its current sea-level rise projections should not be treated as best estimates, and in particular the upper ends of the model-based ranges for sea-level rise should not be considered as upper bounds. (WGI 10.6, SYR 3.2, 5.2)

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**Box 3.4: Potential contributions of ice sheets to sea-level rise by 2100 – recent studies**

Studies since the completion of the Fourth Assessment Report have tried to shed further light on the question of how fast sea level could rise, and how large the missing component of additional contributions from ice sheets could be. One study estimates that sea level could rise realistically by 0.8 m but even as much as 2 m by 2100 (Pfeffer et al, 2008). The actual future rate of sea-level rise would depend on how quickly ice flow from glaciers could accelerate and whether the observed acceleration would be sustained or even increased further with rising air and ocean temperatures. These questions have been explored in several recent field studies in Greenland and Antarctica, but they do not yet allow a definitive conclusion about the extent to which accelerated glacier flows could add to sea level rise (Alley et al, 2008; Das et al, 2008; Joughin et al, 2008; van de Wal et al, 2008; Holland et al, 2008; Nick et al, 2009).

Other recent studies have used the historical correlation between observed 20th century temperature change and sea-level rise to estimate potential future rise during the 21st century under a range of warming scenarios (Rahmstorf 2007; Horton et al, 2008). These studies suggest possible sea-level rise of about 0.5–1.4 m by 2100, but they were also criticised for their approach of using historical correlations only (Holgate et al, 2007; Schmith et al, 2007).

Recent analyses of sea-level rise during the last interglacial period (about 125,000 years ago) suggest that melting of polar ice sheets led to sea-level rise of 1.6–3 m per century when average temperatures were about 2°C higher than at present (Rohling et al, 2008; Blanchon et al, 2009). However, the rate of sea-level rise is likely to depend on whether the Earth is coming out of an ice age or moving from a warm period into an even warmer one (when there is less ice available to melt), so these studies on their own cannot be used as a direct prediction of future sea-level rise. Nonetheless, they underscore the possible extent to which melting of polar ice can contribute to rapid sea-level rise on century timescales.
The diversity of findings in more recent studies still cannot provide conclusive answers to the question how quickly and how much sea level might rise during the 21st century (Alley et al, 2008). However, the consistently higher values for sea-level rise in recent studies and the observed rapid responses of glaciers to higher temperatures further strengthen the warning by the IPCC that the upper end of the model-based ranges in its assessment should not be considered as upper bounds. For that reason, considerably greater increases in sea level during the 21st century than indicated in Table 3.1 cannot be ruled out (WGI SPM and SYR 3.2).

On regional scales, changes in ocean circulation and ocean density (resulting from changes in salinity) are expected to influence sea level in addition to the global average rise. In some places, sea level is likely to rise more than the global average, while in others it is expected to rise less. Figure 3.7 shows the regional pattern of sea-level rise based on model calculations for the middle value of the A1B scenario in 2100. The pattern has considerable uncertainties though: in some regions models are in good agreement about the magnitude of the regional change, while in other regions models show larger differences. (WGI 10.6)

**Figure 3.7:** Global pattern of sea-level rise at the end of the 21st century

Note: Global and regional sea-level rise for 2090–2099 relative to 1980–1999 under the A1B emissions scenario from the *Special Report on Emissions Scenarios* (IPCC, 2000), based on the average of 16 different climate models. Regional variations shown are due to changes in ocean density and circulation effects. Note that if enhanced loss of polar ice occurred this could lead to additional regional variations that are not considered here. Stippled areas denote regions where the different models show the strongest agreement about regional variations in sea level rise.

Source: Based on WGI Figure 10.32 and a global average sea-level rise of 0.35 m, which is the average of the estimates provided for the A1B scenario in WGI chapter 10.6.
3.4 Twenty-first century projections – summary and historical perspective

Table 3.1 provides a summary of the projected global average temperature and sea-level increases by the end of the 21st century under the range of SRES emissions scenarios. The fundamental conclusion from all the climate change projections we have discussed so far is that further warming and many other changes in the global climate system during the 21st century would very likely be larger, and in many scenarios considerably larger, than the changes already observed during the 20th century. These conclusions apply not only to global average temperature and sea level, but also to changes in average precipitation, reduction of snow and ice cover, and increases in many extremes such as heat waves, drought, and heavy precipitation. (WGI 10.3, 10.6, SYR 3.2)

**Table 3.1:** Projected changes in temperature and sea level in 2090–2099 relative to 1980–1999 and 20th century observations

<table>
<thead>
<tr>
<th>Case</th>
<th>Temperature change (°C at 2090–2099 relative to 1980–1999)</th>
<th>Sea-level rise (m at 2090–2099 relative to 1980–1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best estimate</td>
<td>Likely range</td>
</tr>
<tr>
<td>20th century change</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>B1 scenario</td>
<td>1.8</td>
<td>1.1–2.9</td>
</tr>
<tr>
<td>A1T scenario</td>
<td>2.4</td>
<td>1.4–3.8</td>
</tr>
<tr>
<td>B2 scenario</td>
<td>2.4</td>
<td>1.4–3.8</td>
</tr>
<tr>
<td>A1B scenario</td>
<td>2.8</td>
<td>1.7–4.4</td>
</tr>
<tr>
<td>A2 scenario</td>
<td>3.4</td>
<td>2.0–5.4</td>
</tr>
<tr>
<td>A1Fl scenario</td>
<td>4.0</td>
<td>2.4–6.4</td>
</tr>
</tbody>
</table>

Notes: Temperature changes are expressed as the difference from the period 1980–1999. To express the change relative to the period 1850-1899 add 0.5°C. Values for 20th century changes are estimates of the total change between 1900 and 2000. The projections for sea-level rise do not include potential further acceleration of loss of ice from the Greenland ice sheet. The ranges given for sea level, therefore, are not best estimates, in particular the upper end of the range should not be considered an upper bound.

Source: Based on SYR Table 3.1 and WGI 3.2, 3.9, 5.5.

We can get a further sense of the scale of these future changes by comparing temperatures over the next 100 years with what proxy data can tell us about past climate changes in the northern hemisphere over the past 1,300 years, shown in Figure 3.8. This comparison suggests that the climate changes projected over the 21st century, without additional measures to address greenhouse gas emissions, would indeed represent a momentous upheaval, even at the lower end of emissions scenarios and uncertainty ranges. In fact, proxy data going back further in time indicate that the projected rate of climate change during the 21st century will be unlike anything human civilisation has experienced over the past 10,000 years. (WGI 6.4, 10.3; IPCC 2001)
**Figure 3.8:** Projected increases in global average temperature compared to historical temperature changes

Note: Projected increases in global average temperature over the 21st century shown in perspective, compared to changes in northern hemisphere average temperatures reconstructed from various proxy data (see chapter 1 for details and limitations of those proxy data). The uncertainty bars at the right indicate a 66% likelihood for each SRES scenario from the Special Report on Emissions Scenarios (SRES; IPCC, 2000) that the warming in 2090–2099 will lie within this range.

Source: Based on WGI Figure 6.10 and Figure SPM.5.
3.5 Climate change beyond the 21st century

We already saw that some of the climate change between 2000 and 2100 is due to emissions that occurred before 2000. It should, therefore, come as no surprise that climate change will not stop in 2100 – 2100 is simply the date when most emissions scenarios end and many of the detailed model simulations stop. Nonetheless, we need to look beyond 2100 if we want to fully appreciate the climatic consequences of greenhouse gas emissions during the 21st century.

This creates an obvious problem: if we used emissions scenarios to simulate climate change beyond 2100 until 2200, we would then discover that climate change does not stop in 2200 either due to the emissions that have occurred between 2100 and 2200, and so on. At the same time, it makes little sense to develop emissions scenarios beyond 2100 because societal structures and technologies could change so much over the next century that such scenarios would eventually become entirely arbitrary.

What we can do though is to look at hypothetical scenarios where greenhouse gas concentrations are simply held constant at various levels from 2100 onwards. After all, the ultimate goal of global climate negotiations is to stabilise the concentration of greenhouse gases in the atmosphere – the only question is what an appropriate level might be. In this chapter we assume a range of arbitrary stabilisation levels, and then use climate models and basic physical principles to see how high and how much longer temperatures would continue to rise for any of these levels, and how this would affect further melting of ice sheets and the rise of global average sea levels in future centuries. Such basic tests of the climate system can then be used to inform decisions about the level at which we want to stabilise greenhouse gas concentrations in order to avoid long-term consequences that might be regarded as unacceptable. We explore the steps we would need to take to stabilise greenhouse gas concentrations and the considerations that might help us to decide appropriate stabilisation targets in chapters 7 and 8.

3.5.1 Model simulations of temperature increases to 2300

Figure 3.9 explores the long-term consequences of stabilising greenhouse gas concentrations. The study assumed that emissions of greenhouse gases and aerosols follow the two SRES scenarios B1 and A1B throughout the 21st century. Then, from 2100, the concentrations of greenhouse gases and aerosols in the atmosphere were artificially kept constant at the level they had reached in 2100. The CO₂-equivalent concentrations of greenhouse gases and aerosols together at this time are about 600 ppm and 850 ppm for the B1 and A1B scenarios, respectively.²⁶ (WGI 10.7, SYR Table 3.1)

Several high-resolution atmosphere–ocean general circulation models were run for this experiment until 2300. Their results show that even if greenhouse gas concentrations were stabilised in 2100, global average temperature would inexorably creep upwards for at least the next two centuries, with an increase of about 0.5°C

²⁶ Keep in mind that this is a hypothetical test intended to understand the behaviour of the climate system; these are not realistic mitigation scenarios. Emissions would have to fall quite suddenly and drastically after 2100 to stop the concentrations of CO₂ from rising further if they had followed the A1B path until 2100. Also, aerosol concentrations would be unlikely to remain constant in the real world beyond 2100, because if we were able to drastically reduce CO₂ emissions from 2100, this would likely also eliminate many sources of aerosols. Removing all aerosols would remove their cooling effect and lead to additional warming after 2100.
Climate Projections for the Future

between 2100 and 2200 alone. This ongoing warming is due to the inertia of the climate system: the heat content of the atmosphere and ocean are expected to continue to gradually increase and snow, ice, and land-cover are expected to continue to change for many centuries in response to the Earth’s altered energy balance resulting from the increased greenhouse gas concentrations. (WGI 10.7)

**Figure 3.9:** Simulated long-term warming under two emissions scenarios

Note: In these two scenarios, emissions followed the B1 and A1B scenarios from the *Special Report on Emissions Scenarios* (IPCC, 2000) until 2100, and then the concentrations of all greenhouse gases and aerosols were artificially held constant from 2100. The lines show the average warming simulated by a range of models. The shaded bars on the right-hand side show the ultimate warming at equilibrium, based on the concept of climate sensitivity (see section 3.5.2). It would take more than 1,000 years for the climate system to reach its equilibrium even if all concentrations are held constant from 2100, which would require reducing CO$_2$ emissions to close to zero.

Source: Based on WGI Figure 10.4 and data and information in WGI 10.7 and SYR Table 3.1.

### 3.5.2 Warming in the very long term – concept of equilibrium climate sensitivity

Will climate change stop at least in 2300? Very few high-resolution models have been used to simulate such long timescales, simply because it becomes very expensive in terms of computer time and because it becomes increasingly harder to know whether we are looking at real climate change or an artefact of the model itself.

Fortunately, one property in climate models can help us to estimate the global average temperature change over very long timescales – the so-called ‘equilibrium climate sensitivity’. The equilibrium climate sensitivity is defined as the warming that would take place if we double the atmospheric concentration of CO$_2$ and then wait (however long it takes) for the climate system to reach a new equilibrium – that is, until temperatures settle at a new stable level that is consistent with the altered energy balance of the climate system. How long it takes to reach equilibrium varies between different models and depends on the level of greenhouse gas concentrations. Most of the further warming occurs within the first century after concentrations are stabilised, but temperatures can continue to increase for many centuries until equilibrium is finally reached. (WGI 8.6, 9.6, Box 10.2)

The recent generation of models suggests that the best estimate of equilibrium climate sensitivity is about 3°C. In other words, if we doubled CO$_2$-equivalent
greenhouse gas concentrations from their pre-industrial value of about 280 ppm to 560 ppm, we would expect the world to eventually warm by about 3°C relative to pre-industrial temperatures. The uncertainty range for the equilibrium climate sensitivity is 2–4.5°C, which means there is at least a 66% probability that the real value lies within this range, with 3°C being the best estimate. This range is also supported by observations of the basic energy balance of the climate system (how much energy it receives from the sun, how much we know additional greenhouse gas concentrations are responsible for absorbing heat that would otherwise be radiated into space, and how much the Earth has already warmed in response over the 20th century). (WGI 8.6, 9.6, Box 10.2)

Unfortunately, uncertainties around historical observations are too large to determine the ‘true’ climate sensitivity more precisely by simply comparing models with historical observations. We are very confident that the true value for climate sensitivity is not much lower than the 2–4.5°C range, but it is not possible to be equally confident about an upper bound. Models that have very high values for climate sensitivity above 4.5°C generally show poorer agreement with observations, but the level of disagreement is not large enough to rule those models out entirely. (WGI 8.6, 9.6, Box 10.2)

The concept of equilibrium climate sensitivity allows us to estimate long-term warming for any level of stable greenhouse gas concentrations, as long as they are expressed in CO₂-equivalents. Figure 3.9 shows, in addition to the detailed model simulations, the equilibrium warming ranges for 2100 concentrations for the B1 and A1B scenarios of about 600 ppm and 850 ppm CO₂-equivalent, respectively. The best estimates for these concentration levels are 3.3°C and 4.8°C above pre-industrial temperatures (or about 2.8°C and 3.5°C above 1980–1999 temperatures). This means that the eventual equilibrium warming would be about 40–50% greater still than the warming realised by 2100, which is when greenhouse gas concentrations are stabilised in these scenarios. (WGI 10.7)

It must be emphasised that the equilibrium climate sensitivity is not on a par with a full model simulation of the global climate over the entire period. Two caveats in particular need to be kept in mind. The first is that equilibrium climate sensitivity is primarily a diagnostic tool for climate models that tells us how the various components of the climate system would interact in response to increased greenhouse gas concentrations, but it is not a directly observable quantity in the real world. The second caveat is that equilibrium climate sensitivity may not capture all the relevant future changes and feedbacks in the climate system if the world warms very substantially (eg, if large tracts of tropical rainforest turn into savannah, which would release large additional amounts of carbon into the atmosphere and fuel even more warming). (WGI 8.6, 9.6, Box 10.2)

Nonetheless, equilibrium climate sensitivity is a helpful tool to peer into the distant future and the long-term consequences of increasing greenhouse gas concentrations without having to spend many months of computer time. Also, many mitigation scenarios use equilibrium climate sensitivity to characterise the climatic consequences of stabilising greenhouse gas concentrations at different levels, and hence the best estimate and uncertainty range for climate sensitivity are of intense

Pre-industrial temperatures were about 0.5°C cooler than the average temperature over 1980–1999, which we have used for the climate projections in this chapter so far. A warming of 2.5°C above 1980–1999 temperatures therefore means a warming of about 3°C above pre-industrial temperatures.
interest to the climate policy community. We return to the challenge of stabilising greenhouse gas concentrations and their climatic consequences in chapters 7 and 8.

### 3.5.3 Long-term sea-level rise – thermal expansion and loss of ice sheets

**Thermal expansion towards equilibrium**

Sea-level rise is expected to show even more inertia than atmospheric temperatures. Thermal expansion would continue to contribute to sea-level rise for many centuries after greenhouse gas concentrations have stabilised, as long as the ocean water gets warmer. While circulation patterns within the top few hundred metres of the ocean can regionally redistribute heat in the ocean over a period of weeks, ocean currents take much longer to transport water thousands of metres below the surface and all around the world (see Box 3.2). As a result, it would take many centuries to more than a millennium for the global ocean to fully warm up in response to higher atmospheric temperatures. Sea level, therefore will continue to rise well beyond 2100, even if greenhouse gas concentrations were to be stabilised at close to current levels. (WGI 10.7)

In the very long term, a range of ocean models estimate that thermal expansion alone would raise sea levels by 0.2–0.6 m for every degree Celsius that the atmosphere warms above pre-industrial temperatures. For the two scenarios in Figure 3.9, which assume that greenhouse gas concentrations stabilise in 2100 at the levels reached under the B1 and A1B scenarios, the eventual long-term sea-level rise from thermal expansion alone would be 0.7–2.0 m and 1.0–2.9 m, respectively. This component of sea-level rise is inevitable because it follows basic physical principles of water expansion, but it would take many centuries to be fully realised. The magnitude of such a sea-level rise is huge and would have major impacts on the world’s coastlines, societies, and coastal ecosystems. (WGI 10.7)

**Long-term fate of polar ice sheets in a warmer world**

Although the commitment to long-term sea-level rise from thermal expansion alone is large, the potential contribution from the melting of the massive ice sheets of Greenland and Antarctica could be larger still. The last time the world was a few degrees warmer than today, about 125,000 years ago, sea levels were 4–6 m higher, mainly due to a reduction in the Greenland ice sheet and other Arctic ice fields. (WGI 6.4)

The current generation of ice sheet models suggests that if global average warming is sustained for millennia in excess of 1.9–4.6°C above pre-industrial temperatures (about 1.4–4.1°C above 1980–1999 temperatures), almost the entire Greenland ice sheet would eventually disappear through the process of melting alone; the volume of water added to the ocean would raise sea levels by 7 m. While all models agree that the Greenland ice sheet would eventually disappear in such a warmer world, there is little agreement regarding how quickly the melting and disintegration of the Greenland ice sheet would occur (see also Boxes 3.4 and 3.5). Figure 3.10 shows an example of a model simulation based on surface melting alone. (WGI 10.7)
Figure 3.10: Modelled reduction of Greenland ice sheet under elevated temperatures

![Modelled reduction of Greenland ice sheet](image)

Note: Modelled reduction of Greenland ice sheet for greenhouse gas concentration of 1,120 ppm CO$_2$-equivalent. The simulation is assumed to start in 2100.
Source Based on WGI Figure 10.38.

The long-term fate of the Antarctic ice sheet is more difficult to evaluate than that of Greenland. Models that consider surface melting processes suggest only that the Antarctic ice sheet is likely to remain too cold for widespread surface melting, even in the long term. But much of the West Antarctic ice is grounded below sea level and so susceptible to changes in ocean as well as air temperatures. The recent loss of some ice shelves (ie, floating tongues of ice) has been observed to increase glacier flows especially around the West Antarctic ice sheet and Antarctic Peninsula and has led to a net loss of ice mass over the past decade. If further warming were to speed up the flow of more and more glaciers, this could lead to a sustained net loss of ice mass from Antarctica. If the entire West Antarctic ice sheet disappeared, this would add roughly another 5 m to global sea levels. However, the literature gives insufficient evidence of any temperature thresholds where sustained loss of ice due to dynamic processes could occur; all we know is that the risk increases with increasing air and ocean temperatures. (WGI 10.7)

A recent study of the behaviour of the West Antarctic ice sheet during the past 3 million to 5 million years shows that it grew and shrank regularly with falling and rising temperatures related to changes in the Earth’s orbit around the sun, resulting in sea-level rise of up to 7 m (including contributions from the rest of Antarctica). During periods of reduced ice cover, ocean temperatures were about 3 degrees warmer than at present even though CO$_2$ concentrations were only around 400 ppm or less (Naish et al, 2009). This study confirms that the West Antarctic ice sheet is vulnerable to melting under higher temperatures, but the key question remains how quickly this melting may occur. A recent modelling study suggests that melting could take about a millennium (Pollard and de Conto, 2009). Because much of the heat responsible for melting is thought to come from warmer ocean rather than air temperatures, and the ocean responds only slowly to changes in atmospheric temperatures, such a melting process could be initiated during the 21st century and be very difficult to halt or reverse even if atmospheric temperatures were to decline again in subsequent centuries.
Box 3.5: The ‘known unknowns’ of Greenland’s future beyond 2100

Given the daunting prospect of a melting Greenland ice sheet and its consequences for global sea levels, two key questions arise: how quickly would Greenland melt, and could this melting be reversed if temperatures dropped again sometime beyond 2100?

We already discussed the quandary with regard to the first question (Box 3.4). Current models that look primarily at changes in snowfall and melting suggest that this process would take millennia, but they do not account for potential changes in the flow speed of glaciers. If such dynamic ice flow processes increase with warming, the Greenland ice sheet could lose ice faster than projected by current models, but at this stage we do not know how much faster this might be. It is important though to keep a sense of scale: even with an accelerated loss, the complete loss of Greenland ice would still take many centuries – there are no scientifically credible suggestions that all of the Greenland ice sheet could be gone by 2100 (WGI 6.4, 10.7, WGII 19.3). This is little consolation of course for people who live in low-lying areas and for whom a rise in sea level of even 0.5–1 m over the next 100 years would have devastating consequences.

The second question, could the melting of Greenland be stopped or reversed if temperatures were to decrease again sometime after 2100, is even harder to answer. No model studies have been assessed that address this specific question. Some (but not all) models suggest that if Greenland were to melt entirely, bringing temperatures back down to current levels might not be sufficient to allow it to re-grow, and that temperatures might have to fall even further for the ice sheet to regain its current mass. This is because Greenland’s ice currently reflects most of the sunlight back into space; if the ice disappeared completely, dark bare ground would absorb sunlight and increase local temperatures. Also, the top of the ice sheet is currently several thousand metres above sea level, while the bedrock surface of Greenland itself is only a few hundred metres high, and temperatures are naturally lower at high altitudes. These feedbacks suggest that the task of reversing even partial melting would become harder the more the melting has already progressed, but the scientific literature gives insufficient evidence about any particular thresholds in this process. (WGI 10.7)

3.6 Feedbacks and potential for rapid changes in the climate system

The discussion of future climate changes in this chapter has assumed that the climate responds in a ‘well-behaved’ manner to rising greenhouse gas concentrations – that is, as concentrations increase, the climate changes slowly and accordingly. Unfortunately, the real world may not be quite as well behaved, because many feedbacks in the climate system could accelerate the climate response, or could

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28 It is obvious that Greenland can grow back if temperatures fall low enough: the proof is that we currently do have a Greenland ice sheet, but its ice volume was much smaller 125,000 years ago. However, the way we got the Greenland ice sheet back is by going through an ice age. This provides cold comfort and does not answer the question how much temperatures would have to drop to just stop its further disintegration. Also, based on what we know about the solar system and the Earth’s orbit around the sun, we do not expect another ice age for at least the next 30,000 years.
otherwise lead the climate system to respond in a more ‘jerky’ or ‘hypersensitive’ manner than the models suggest (WGI Box 10.1).

Some well-known feedbacks in the climate system were discussed in chapter 2, such as increasing water vapour with rising temperatures and the changing surface reflectivity as snow and ice give way to vegetation, bare ground, or open sea water. These feedbacks form part and parcel of climate simulations and are included in this chapter’s model projections of future changes. Two further feedback mechanisms were the subject of intensive scrutiny in the recent IPCC assessment and are discussed below: the coupling between the climate and the global carbon cycle, and the mechanisms that could lead to a change in the global ocean circulation. Finally, we also briefly discuss the potential for a catastrophic release of CH$_4$ that is stored in permafrost and on the ocean floor.

3.6.1 Coupling between climate and the global carbon cycle

Every molecule of CO$_2$ that is emitted into the atmosphere (be it from natural sources or human activities) eventually gets absorbed by the ocean or taken up by plants; some of this carbon may in turn be consumed by animals (including by shell-building organisms in the oceans). Before too long, this carbon is released back into the atmosphere as plants and animals die and their cells decay. A small fraction of the carbon in dead plants and animals may become buried at the bottom of the ocean or in wet soils where they form mudstones and harder rocks, or over millions of years slowly turn into coal, oil, or natural gas. This latter process is where fossil fuels come from, which we are now releasing back into the atmosphere in a matter of decades. In addition, slow weathering of silicate-containing rocks permanently removes carbon from the atmosphere and transforms it into limestone sediments. (WGI 7.1, 7.2, 7.3)

This global carbon cycle is intricately linked to the Earth’s climate because the rate at which CO$_2$ is absorbed and released by the ocean and plants depends on temperature. The higher temperatures climb the less carbon is absorbed by the ocean and land, and the more carbon is released back into the atmosphere. Over the past two decades, the oceans and land have on average absorbed every year almost half of the CO$_2$ that was emitted by the burning of fossil fuels. As the absorption rate of CO$_2$ decreases with rising temperatures, the fraction of CO$_2$ that remains in the atmosphere in future is projected to become greater; this means the concentration of CO$_2$ in the atmosphere will increase even faster and lead to even more warming. The result is a so-called positive feedback loop (although there is nothing positive about this feedback from a human and climate perspective). (WGI 7.3)

Climate–carbon cycle feedbacks occur in many parts of the global carbon cycle. For example, ocean water is less able to absorb CO$_2$ at higher temperatures, and soils and plants breathe out more CO$_2$ the warmer it gets. On the other hand, higher CO$_2$ concentrations can stimulate faster plant growth, which means plants could in turn absorb more CO$_2$ from the atmosphere through photosynthesis if CO$_2$ concentrations were higher, but the effectiveness of this ‘carbon-fertilisation’ also depends on the availability of other nutrients and water. Plant growth could be limited where soil moisture reduces because of higher temperatures or reduced rainfall, but could increase where currently dry regions receive substantially more rain. In addition, climate change could lead to a decay of large tracts of rainforest in the Amazon basin, which would in turn release large amounts of carbon currently stored in trees and soils back into the atmosphere. A schematic diagram of the global carbon cycle and its main links to the climate system is shown in Figure 3.11. (WGI 7.3, 10.4)
All models that include this climate–carbon cycle coupling conclude that rising temperatures and associated climate changes caused by continued greenhouse gas emissions would reduce the overall ability of the ocean and land to absorb carbon from the atmosphere in the future. For a given emissions scenario, all models indicate greater warming than when this climate–carbon cycle feedback is ignored. For example, for the A2 scenario, the additional warming purely from the feedbacks between climate and carbon cycle is more than 1°C by 2100. (WGI 10.3, 10.4)

The range of climate–carbon cycle feedbacks is already included in this chapter’s model projections and uncertainty estimates of temperature rise over the 21st century. Climate–carbon cycle feedbacks are part of the reason why the upper ranges of temperature projections in the recent assessment by the IPCC are higher than in previous assessments when less was known about these feedbacks. (WGI 10.3)

**Figure 3.11:** Global carbon cycle and its links to the climate system

Models differ remarkably regarding the strength of the climate–carbon cycle feedback. The model with the strongest feedback results suggests that the land could stop absorbing CO$_2$ and even turn into a source of CO$_2$ well before the end of the 21st century; other models suggest more moderate changes. The results depend not only on climate changes but also on other global trends; for example, if logging and
land clearance persist in the Amazon basin, the forest ecosystem in this region would be more likely to change its functioning dramatically and turn into a source of CO$_2$ than if strict forest protection measures are in place. (WGI 10.3; WGII 4.4)

### 3.6.2 Changes in ocean circulation and potential for abrupt changes

Ocean currents play an important role in the world’s climate because they can transport enormous amounts of heat energy between different parts of the world. Contrary to intuitive perception, the world’s oceans are not largely static water masses; immense quantities of water are constantly flowing through the world’s large ocean basins in a complex system that is also described as ‘the great conveyor belt’.

The northern North Atlantic is one of the regions that drives this conveyor belt. The ocean flows northward on the surface across the Atlantic equator, where it heats up and due to evaporation becomes more salty. As it reaches the higher latitudes of the North Atlantic, the surface water cools down and becomes more and more dense until it sinks from the surface to the bottom of the ocean. The resulting great plunge of water ensures a steady flow of warm ocean waters into the high-latitude region between Iceland, Greenland, and Scandinavia. This warm current maintains average temperatures in Scandinavia several degrees above what they would otherwise be. A schematic illustration of this process, also known as meridional overturning circulation, is shown in Figure 3.12. (WGI 10.3, Box 10.1)

For several decades, concerns have been raised that climate change could lead to a reduction, if not shutdown, of this circulation process and plunge northern Europe into a sudden ice age, with potential flow-on effects for other regions of the world. The reason for this concern is that projected increases in rainfall in northern high latitudes, along with higher temperatures that lead to increased ice and snow melt, would increase the amount of freshwater that reaches the northern North Atlantic. In addition, warm equatorial ocean waters would reach further north before cooling down and sea-ice formation would be reduced. In principle, the combination of these effects could mean that, eventually, sea water no longer becomes dense enough to sink down in the high northern Atlantic, so could shut down the essential mechanism behind the global ocean circulation system. (WGI 10.3, Box 10.1)

Palaeoclimatic evidence indicates that such events have occurred in the past. Ice core records show that at the end of the last ice age, Greenland temperatures dropped by as much as 10°C within a decade or so. Some studies suggest that this was due to the sudden outburst of a huge glacier lake that had formed as the massive ice sheet covering northern North America slowly melted. The injection of a very large amount of freshwater from this bursting lake into the northern Atlantic may have effectively shut down the Gulf Stream for a few centuries, until it recovered almost equally as suddenly several centuries later. We also have evidence that the ocean circulation in the northern North Atlantic shifted gears repeatedly during the last ice age, which led to equally significant and rapid regional temperature changes, but the detailed causes for these repeated changes are not well understood. (WGI 6.4, 6.5, Box 10.1)
Figure 3.12: Meridional overturning circulation (MOC) in the North Atlantic and possible influences of climate change
Climate models that simulate the future behaviour of the ocean circulation in the northern North Atlantic all agree that the circulation would indeed weaken by an average of about 25% by 2100, but with a large range ranging from no change up to 50%. These projections are for the range of SRES scenarios based on the combined effects of higher temperatures, ice melt, and increased precipitation with resulting increased river flow in the Arctic. (WGI 10.3)

A permanent significant weakening of the ocean circulation, even if it does not occur abruptly, could have significant flow-on effects on the productivity of marine ecosystems and fisheries, the uptake of CO$_2$ by the oceans, and oceanic oxygen concentrations. However, no model produces a rapid shutdown during the 21st century. Even where the ocean circulation is reduced, northern Europe is still projected to warm relative to present-day conditions, because the global effect of greenhouse gases is expected to outweigh the reduced warming from a weakened ocean circulation. Based on currently available data, which include only a few snapshots going back in time, there are no clear indications of any recent significant changes in the observed strength of the ocean circulation (WGI Box 5.1). The possible effect of warming beyond 2100 has been studied with fewer models and with lower resolution. Some of these models suggest that the ocean circulation could shut down in the longer term if the forcing from greenhouse gases is rapid and strong enough, but also that it could recover from such a shutdown over the course of several centuries. (WGI 10.3, Box 10.1; WGII 19.3)

It is still an open question whether models do not show abrupt changes over the 21st century because such changes are not likely or because models fail to capture some important mechanisms and regional feedbacks that could lie behind abrupt changes that we know have occurred in the past. One important constraint is that much of our information on past abrupt changes in ocean and atmospheric circulations are from cold periods (ie, during or at the end of ice ages). During such periods, there were more massive ice sheets that had a greater potential to influence high-latitude ocean temperatures and salinity. We have much less evidence of abrupt changes during warm periods, which limits the degree to which we can use palaeoclimatic information to infer the likelihood or risk of future abrupt changes.

### 3.6.3 Release of methane from hydrates and wetlands

A third concern about abrupt changes and positive feedbacks focuses on the potential for the additional release of CH$_4$ stored in soils, wetlands, and the ocean as the climate system warms. Large quantities of CH$_4$ are stored as methane hydrates (water ice crystals with CH$_4$ molecules trapped within them) in the sea floor and in permafrost. As the climate warms, these hydrates could disintegrate and release the CH$_4$ into the atmosphere, creating a strong positive warming feedback. Similarly, the water-logging of large areas in the Arctic as ice and snow melts could create additional wetlands in whose anaerobic conditions additional CH$_4$ could be produced and released into the atmosphere. The quantities of CH$_4$ that could enter the atmosphere through these pathways are staggering: estimates range from 500 GtC to 10,000 GtC for CH$_4$ stored in sea-floor hydrates, and from 7.5 GtC to 400 GtC for CH$_4$ stored in permafrost. This may be compared with the total amount of CH$_4$ currently in the atmosphere of only about 4 GtC. Releasing even only small amounts of the CH$_4$ from hydrates to the atmosphere could clearly have major consequences for the Earth’s climate.
The IPCC assessment did not quantify the probability of large releases of CH$_4$ hydrates in the near future but noted that they could constitute an important feedback over timescales of thousands of years (WGI 7.4). A more recent assessment examined the issue in more detail (CCSP, 2008). This assessment concluded that even though various suggestions have been made about the possibility of catastrophic releases of CH$_4$ induced by a warming climate (both in scientific studies and in the popular press), modelling and detailed studies so far indicate that no such rapid releases occurred in the past 650,000 years, and that catastrophic releases during the 21st century are very unlikely. However, the CCSP assessment also concluded that it is very likely that climate change will increase the rate of gradual emissions of CH$_4$ from both hydrates and wetlands. The magnitude of these additional emissions is very difficult to estimate based on existing data, but it is expected that this positive feedback between climate change and the release of CH$_4$ from hydrates will have a significant influence on global warming in the very long term, that is, over the next 1,000 to 100,000 years (CCSP, 2008).