THE EUROPEAN ENVIRONMENT

STATE AND OUTLOOK 2010

UNDERSTANDING CLIMATE CHANGE

European Environment Agency

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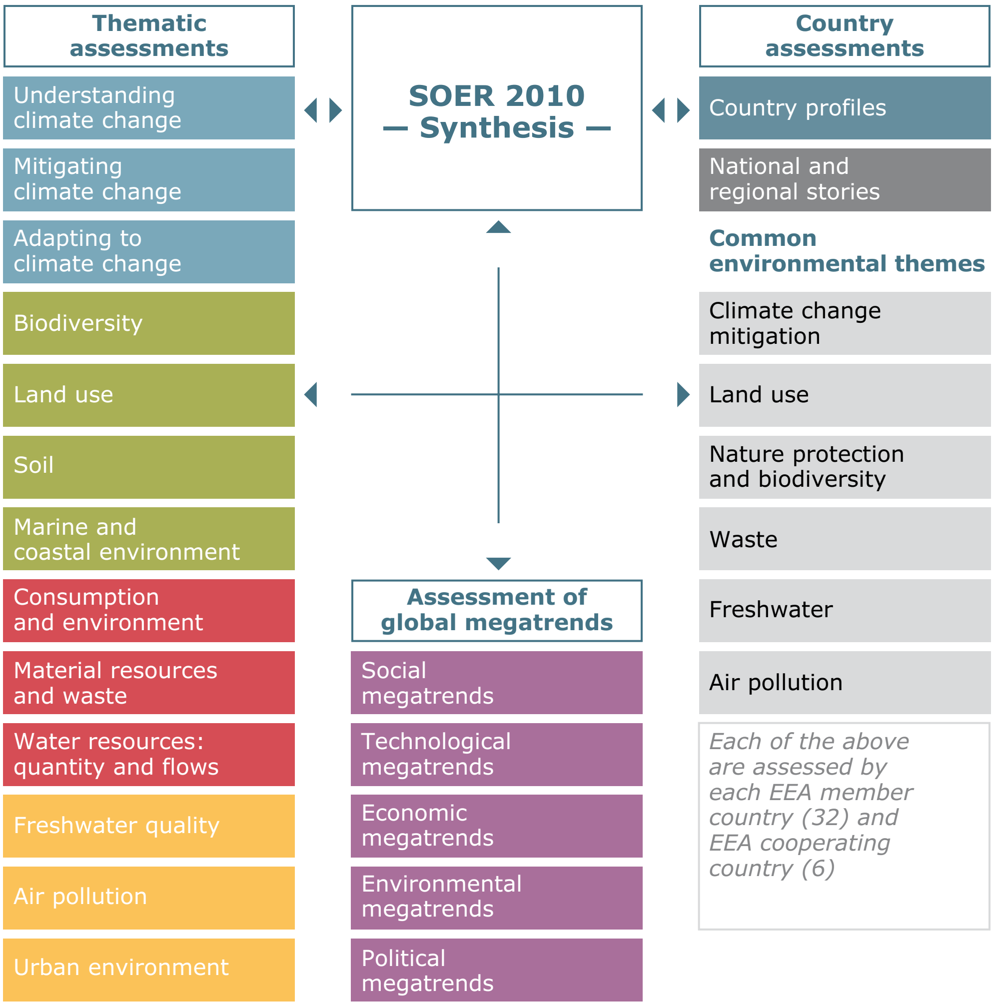

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Understanding climate change

Summary

Average global air and ocean temperatures are rising, leading to the melting of snow and ice and rising global mean sea level. Ocean acidification results from higher CO_2 concentrations. With unabated greenhouse gas emissions, climate change could lead to an increasing risk of irreversible shifts in the climate system with potentially serious consequences. Temperature rises of more than 1.5–2 °C above pre-industrial levels are likely to cause major societal and environmental disruptions in many regions. The atmospheric CO_2 concentration needs to be stabilised at 350–400 parts per million (ppm) in order to have a 50 % chance of limiting global mean temperature increase to 2 °C above pre-industrial levels (according to the IPCC in 2007, and confirmed by later scientific insights).

What are the current and projected future greenhouse gas concentrations?

In the year 2009, the atmospheric CO_2 concentration was about 387 ppm, which is 38 % above the pre-industrial level of 278 ppm. The concentration of the six greenhouse gases ([1]) covered by the Kyoto Protocol reached 438 ppm CO_2-equivalent in 2008, an increase of 160 ppm from the pre-industrial level. Under the emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC), the overall concentration of the six 'Kyoto gases' is projected to increase to 638–1 360 ppm CO_2-equivalent by 2100.

What are the main changes in the climate system?

The global mean temperature in 2009 was between 0.7 and 0.8 °C higher than in pre-industrial times and the decade 2000–2009 was the warmest on record. Europe has warmed more than the global average. The annual average temperature for the European land area was 1.3 °C above the 1850–1899 average. Without global emission reductions, the IPCC expects global temperatures to increase further by 1.8–4.0 °C above 1980–1999 levels by 2100. Global temperature increase would exceed 2 °C above industrial times – the limit agreed by the EU — between 2040 and 2060 in all IPCC scenarios. The rise in temperatures has had, and will continue to have, serious impacts on various parts of the climate system. Some examples are:

- The extent of Arctic summer sea ice has declined by about 10 % per decade since 1979. The extent of the minimum ice cover in September 2007 was half the size of the normal minimum extent in the 1950s; the third lowest minimum occurred in September 2010. Summer ice is also getting thinner and younger.
- Observed global mean sea-level rise has accelerated over the past 15 years. From 2002 to 2009, the contributions of the Greenland and West Antarctic ice sheets to sea-level rise increased. In 2007, the IPCC projected a sea level rise of 0.18 to 0.59 m above the 1990 level by 2100. Recent projections show a maximum increase of about 1.0 m by 2100, while higher values up to 2.0 m cannot be excluded.
- Glaciers in the Alps lost about two-thirds of their volume between 1850 and 2009. The glacierised area in the Alps is projected to decrease to about one-third of the present area with a further rise in Alpine summer temperature of 2 °C.
- Acidification is occurring in all ocean surface waters as a result of increased atmospheric CO_2 concentrations. Coral reefs worldwide, which are centres of biodiversity and important as fish breeding grounds, are threatened by both ocean acidification and increasing temperatures. By 2100 the pH value could drop to 7.8, an increase in ocean acidity by 150 % compared to the pre-industrial pH of 8.2. The acidity of the ocean would be higher than at any time in the past 20 million years.

([1]) Carbon dioxide (CO_2), methane (CH_4), nitrous oxide which is also known as laughing gas (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC) and sulphur hexafluoride (SF_6). Greenhouse gases are often measured in CO_2-equivalent in order to allow for comparisons of their potential to contribute to global warming.

What are the global risks of climate change?

Land and ocean sinks have taken up more than half of global CO_2 emissions since 1800. But these natural sinks are vulnerable. They are highly likely to take up less CO_2 in the future. Moreover, poor nations and communities, ecosystem services and biodiversity are particularly at risk. A temperature rise of more than 1.5–2 °C above pre-industrial levels could cause disruptions in many regions. Unabated greenhouse gas emissions increase the risk of large-scale irreversible shifts in the climate system with potentially serious consequences for society and ecosystems. Recent research suggests that several key components of the climate system could undergo irreversible change at significantly lower levels of global temperature increase than previously assessed. The most important 'tipping elements' for Europe are the Greenland ice sheet, Alpine glaciers and Arctic sea ice.

What are the targets to limit global climate change?

To limit impacts and guide policy development, the Copenhagen Accord of December 2009 recognised a long-term climate limit of 2 °C global mean temperature increase, without specifying the base year. The Accord also mentions the need for a review in 2015 to consider a possible goal of limiting temperature rise to 1.5 °C on the basis of new scientific insights. According to the IPCC (2007), confirmed by later scientific insights, to have a 50 % chance of limiting the global mean temperature increase to 2 °C above pre-industrial levels, the atmospheric greenhouse gas concentration needs to be stabilised at about 445 to 490 ppm CO_2-equivalent (or about 350 to 400 ppm CO_2). To achieve this, global emissions should peak at the latest in 2015–2020 and decline to 50–80 % below 2000 levels by 2050.

1 Introduction

While the global climate has been remarkably stable for the past 10 000 years, providing a backdrop for the development of human civilization, there are now clear signs that the climate is changing (University of Copenhagen, 2009).

Anthropogenic climate change is one of our greatest environmental, social and economic threats and represents one of the greatest and widest-ranging market failures ever seen (Stern, 2006). Climate change is also being discussed as a possible security issue, in part because of possible large-scale intra- and inter-regional migration of people from the most affected regions. The United Nations (UN) is discussing the need to find integrated solutions for today's main global crises — financial, energy, food and climate (UNEP, 2009).

Observations show increases in average global air and ocean temperatures and extreme climatic events, widespread melting of snow and ice, rising global mean sea level and ocean acidification. It is very likely that most of the warming can be attributed to the emissions of greenhouse gases (GHG) by human activities. On the basis of the results of the IPCC Fourth Assessment Report (IPCC, 2007d) and recent studies, it is expected that, without strong and immediate global action to limit emissions, global temperature increase will significantly exceed 2 °C above the pre-industrial

Box 1.1 Findings from the Intergovernmental Panel on Climate Change (IPCC)

The 2007 Fourth Assessment Report from the United Nations Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007a; 2007b; 2007c; 2007d) concluded that *warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level*. The IPCC concluded further that *most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas (GHG) concentrations* and *continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century*.

By end of 2009/early 2010, several alleged errors in the IPCC 2007 report were reported in the media.

The IPCC stated in March 2010: *The IPCC stands firmly behind the rigor and reliability of its Fourth Assessment Report from 2007, but we recognize that we can improve. We have listened and learned from our critics, and we intend to take every action we can to ensure that our reports are as robust as possible* (IPCC, 2010a).

In March 2010, the UN and the IPCC decided that the Inter Academy Council (IAC), the umbrella organisation for various national academies of science from countries around the world, should perform an independent review of the IPCC processes and procedures to further strengthen the quality of the Panel's reports on climate change (IAC, 2010). The review was finalised by 30 August 2010, and recommended a fundamental reform of the IPCC management structure and a need to strengthen its procedures. On 30 August, the IPCC stated: *The IPCC will be strengthened by the IAC review and by others of its kind this year. We already have the highest confidence in the science behind our assessments. We're now pleased to receive recommendations on how to further strengthen our own policies and procedures* (IPCC, 2010b).

The review recommendations are expected to improve the preparation by the IPCC of its fifth major assessment of global climate change, due to be published in 2013–2014. The recommendations were discussed at the IPCC plenary meeting (11–14 October 2010, South Korea). The meeting accepted many of the recommendations of the IAC and started to implement several immediately. These include guidance on uncertainty, non-peer-reviewed literature and addressing potential errors. In addition, the panel agreed to set up a task group which will address the establishment of an executive committee, review the key responsibilities of the secretariat, as well as the terms of reference of chairs and co-chairs of the working groups. The IPCC also decided to implement a rigorous conflict of interest policy and established a task group to propose options. The panel in addition accepted the recommendation to develop a communication strategy (IPCC, 2010c).

The EU Environment Council of 14 October 2010 (EU, 2010) stated: The Council of the European Union emphasises the IPCC's crucial role in deepening our understanding of climate change through its robust and solid scientific assessments; welcomes the report made by a committee of the Inter Academy Council related to the review of the processes and procedures of the IPCC; recognises ongoing efforts within the IPCC to the same ends; underlines the importance of the timely delivery of the Fifth Assessment Report; remains convinced that the IPCC offers the most authoritative and comprehensive assessment process on the existing science of climate change.

level. The EU objective is to limit the increase to less than 2 °C (EU, 2010). Beyond this level irreversible and possibly catastrophic changes — 'dangerous climate change' — become far more likely (University of Copenhagen, 2009).

Many scientific conferences and reports since publication of the IPCC Fourth Assessment Report have confirmed the key messages of the report or shown that climate change trends, projections and risks may be more pronounced than reported by IPCC (PBL, 2009; UNEP, 2009; Allison et al., 2009; University of Copenhagen, 2009; AMAP, 2009; Sommerkorn and Hassol, 2009; Rummukainen et al., 2010). For example, the scientific climate change congress held in Copenhagen in March 2009 (University of Copenhagen, 2009) stated that *recent observations show that greenhouse gas emissions and many aspects of the climate are changing near the upper boundary of the IPCC range of projections. Many key climate indicators are already moving beyond the patterns of natural variability within which contemporary society and economy have developed and thrived* and r*ecent observations show that societies and ecosystems are highly vulnerable to even modest levels of climate change, with poor nations and communities, ecosystem services and biodiversity particularly at risk. Temperature rises above 2 °C will be very difficult for contemporary societies to cope with, and will increase the level of climate disruption through the rest of the century*. In this respect it should be noted that the growth in global GHG emissions increased steeply from 2000 to 2004 compared to the 1990s, but slowed down after 2004. The recent slow-down in emissions growth is partly due to mitigation measures. The economic downturn is estimated to have caused a decrease in global CO_2 emissions of 3 % in 2009, compared to 2008 (PBL, 2009).

To keep global temperature increase to less than 2 °C above the pre-industrial level, GHG emissions must stop increasing in the coming decade and then be reduced significantly and continue to decline afterwards (IPCC, 2007c). This requires a rapid, sustained, and effective transition to a low-carbon economy and a halt to global deforestation, which will need substantial financial flows especially towards developing countries. However, mitigation costs will be low compared with costs of inaction in the long term (Stern, 2006). There will be a wide range of potential benefits including increases in the number of jobs in sustainable energy, lower costs of controlling air pollutant emissions from transport and energy, reduced damage to public health and the restoration and revitalisation of ecosystems.

The Copenhagen climate conference in December 2009 (COP15 under the UN Framework Convention on Climate Change (UNFCCC)) took note of the Copenhagen Accord but did not agree on binding emission reduction targets after 2012 (UNFCCC, 2009). The challenge is to turn the Copenhagen Accord into an effective and legally-binding agreement by one of the next conferences of parties — COP16, in Mexico, November–December 2010, or COP17, December 2011.

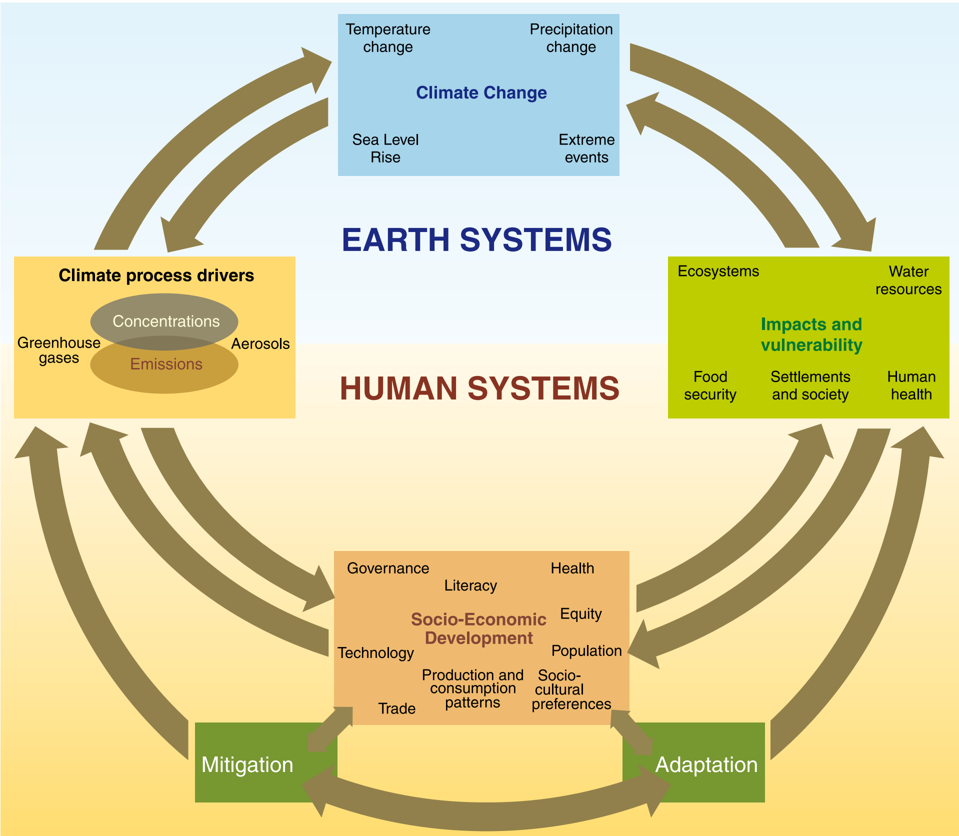
The Copenhagen Accord:

- recognised the objective of keeping the maximum global average temperature rise below 2 °C, although without specifying the base year or period, and the need for a review in 2015 to consider a possible goal of limiting temperature rise to 1.5 °C using new scientific insights;
- called for listing economy-wide emission reduction targets for developed countries and mitigation action by developing countries by 31 January 2010;
- recognised the need for enhanced action on adaptation to reduce vulnerability and build resilience in developing countries, especially least developed countries (LDC), small island developing states (SIDS) and Africa;
- outlined the main elements of developed countries' commitments for new and additional funding for both adaptation and mitigation in developing countries, including a Fast Start programme, with USD 30 billion of funding for 2010–2012 and long-term finance of USD 100 billion annually by 2020. This funding will come from a wide variety of sources, public and private, bilateral and multilateral;
- stressed the importance of establishing robust monitoring, reporting and verification;
- highlighted the need for immediately setting up mechanisms for reducing emissions from deforestation and forest degradation and other land-use changes;
- recognised the need to step up action on the development and transfer of technology.

By September 2010, a total of 138 countries have expressed their intention to be listed as agreeing to the Copenhagen Accord (UNFCCC, 2010).

Mitigation of climate change as well as climate change impacts, vulnerability, adaptation are covered in separate chapters.

Figure 1.1 **Schematic framework representing anthropogenic drivers, impacts of and responses to climate change, and their linkages**



Source: IPCC, 2007d.

2 Climate change and its impacts

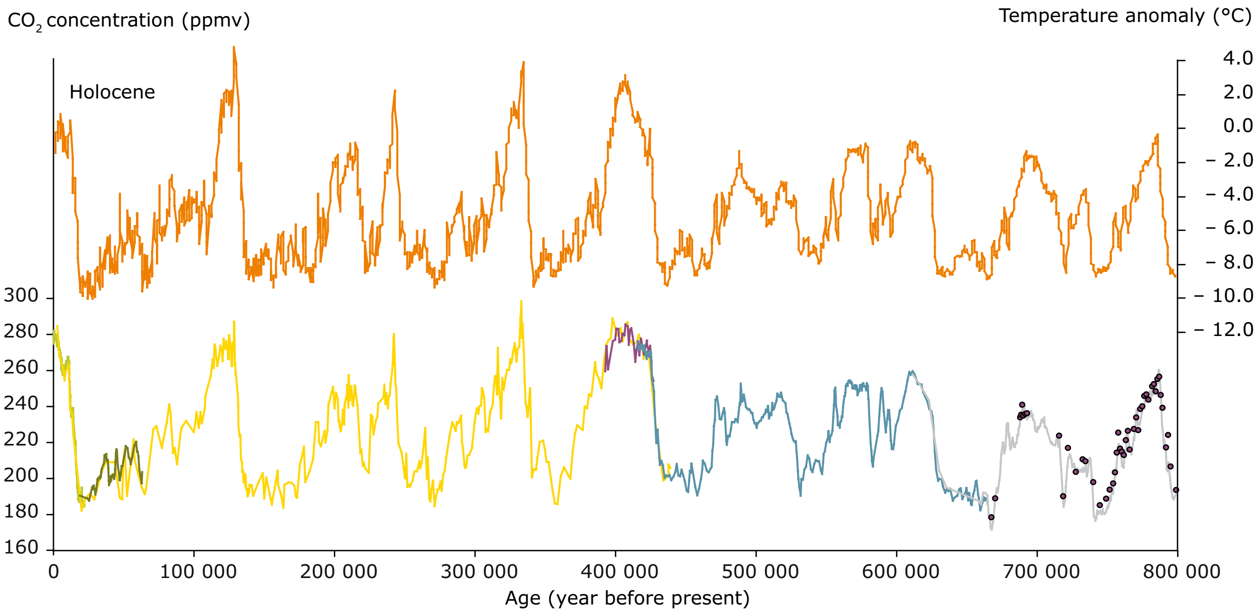
2.1 Atmospheric greenhouse gas concentrations and global temperature

The Earth's climate has oscillated about every 100 000 years between glacial periods, during which the global mean temperature was about 5 °C lower than today, and inter-glacial periods, during which it was about equal to that of today, measured from ice core records (Figure 2.1). These transitions were triggered by changes in the position of the Earth's axis with respect to the sun, followed by mechanisms within the Earth's system that can amplify the initial changes. The changes in global mean temperature between ice ages and inter-glacial periods correspond with changes in atmospheric CO_2 concentration. CO_2 levels, 387 ppm in 2009, are at least 40 % higher now than at any time over the past 800 000 years.

The Earth is currently in an inter-glacial period that started about 10 000 years ago. A range of observations, including of ice cores and tree rings, have shown that the concentrations of GHG and aerosols in the atmosphere have been relatively stable during this period (left end of Figure 2.1). The rate of CO_2 emissions to the atmosphere from natural processes such as respiration by terrestrial vegetation, soils and marine vegetation, fires, and volcanism has been roughly equal to the rate of CO_2 removal, through photosynthesis, by terrestrial vegetation and uptake by the oceans. The concentration of atmospheric CO_2 has therefore been roughly constant. It is likely that the resulting stable climate was a key factor for the development of agriculture and consequently the building of permanent settlements and civilisation (University of Copenhagen, 2009).

Over the past 1 300 years the mean temperature in the northern hemisphere has stayed within a range of 0.5 °C. Variability within that range is explained by changes in the activity of the sun, volcanic eruptions emitting large amounts of dust particles into the atmosphere and natural

Figure 2.1 Antarctic temperature change and atmospheric carbon dioxide concentration (CO_2) over the past 800 000 years



Note: The record is derived from several ice cores from the Antarctic ice sheet, some more than 3 km long. The last 10 000 years, the present interglacial period (left end of the graph) is very stable. The orange line represents temperature; the other lines represent CO_2 concentration from different measurements.

Source: Lüthi et al., 2008.

Box 2.1 Climate sensitivity

The climate sensitivity of the global climate system is defined as the equilibrium global temperature response to a doubling of atmospheric CO_2 concentration. Climate sensitivity is one important element in global climate models that are used to estimate future climate change (Allison et al., 2009). Analyses based on ice cores and other sources suggest that climate sensitivity is likely in the range of 2–4.5 °C with a best estimate of about 3 °C, and is very unlikely to be less than 1.5 °C (IPCC, 2007d). Climate sensitivity is intimately linked to climate feedbacks that can either amplify — positive feedback — or dampen — negative feedback — the increase in atmospheric GHG concentrations and temperature. Greenhouse gases include CO_2; methane (CH_4); nitrous oxide (N_2O) and halocarbons, a group of gases containing fluorine, chlorine or bromine. An example of a positive feedback is the warming of the ocean enhancing the transfer of CO_2 to the atmosphere and increasing evaporation of water, which is also a GHG. An example of a negative feedback is the enhanced growth of vegetation due to increased CO_2 concentrations leading to a larger uptake by that vegetation. Many of the known feedback processes tend to amplify climate change. Recent studies generally confirm the likely range of the climate sensitivity from IPCC (2007d). While climate sensitivity below 1.5 °C is physically extremely unlikely, high values exceeding 6 °C cannot be excluded by the comparison of models with observations. Due to an essentially skewed distribution, it is more likely that climate sensitivity is underestimated — it is actually higher than the best estimate of 3 °C — rather than overestimated. There remain various uncertainties in climate sensitivity and feedback mechanisms, such as the role of clouds and aerosols, which are addressed by current research activities (PBL, 2010; Rummukainen et al., 2010).

variations in the exchange of CO_2 between the atmosphere, oceans and the terrestrial biosphere (Allison et al., 2009).

Changes in the atmospheric concentrations of GHGs and aerosols, land cover and solar radiation alter the energy balance of the climate system and are drivers of climate change. They affect the absorption, scattering and emission of radiation within the atmosphere and at the Earth's surface. The resulting positive or negative changes in energy balance due to these factors are expressed as radiative forcing, which is used to compare the warming or cooling influence of different GHGs and aerosols on global climate.

During the past 150 years, human activities have significantly changed the composition of the atmosphere. The burning of fossil fuels and deforestation, and to a lesser extent the large-scale raising of cattle, the use of synthetic fertilisers and emissions from specific industrial activities, have increased emissions and the atmospheric

Box 2.2 Solar and cosmic ray effects

IPCC concluded that although there has been some net warming effect from solar variability over the past 100 years, it is an order of magnitude smaller than the concurrent anthropogenic influences (IPCC, 2007a). Recent studies either confirm or do not convincingly reject this conclusion. The 11-year Sun's cycle varies due to solar processes, and shows periods of lowered and heightened activity. There was a well-known pronounced minimum, the Maunder minimum, in the 17th century. Over much of the 20th century, solar activity was high from an historical perspective, known as a 'grand maximum'. The observed variability in total solar irradiance (TSI) is small — the amplitude over the Sun's 11-year cycle is less than 0.1 W/m^2, compared to more than 4 W/m^2 for a doubling of GHG concentrations. We are currently experiencing a deep solar minimum. However, the current decrease in TSI is four times smaller than the change between solar maximum and solar minimum conditions. Between a solar cycle minimum and maximum, global temperature changes about 0.1–0.2 °C. There are studies that suggest that the level of solar activity may again decline which could lead to a new 'grand minimum', perhaps similar to the Maunder minimum, that could last for several decades. This might mean a solar induced cooling of the order of 0.2 ºC, within two to three decades. However, after the recovery of solar activity, temperature increase will be accelerated, as anthropogenic and solar forcing will both point in the direction of global warming. Thus the long-term projections of global warming in IPCC 2007 remain unchanged.

Regarding cosmic rays, IPCC (2007a) concluded that empirical associations have been reported between solar-modulated cosmic ray ionisation of the atmosphere and global average low-level cloud cover, but evidence for a systematic indirect solar effect remains ambiguous. Together with the lack of a proven physical mechanism and the plausibility of other causal factors affecting changes in cloud cover, this makes the association between galactic cosmic ray-induced changes in aerosol and cloud formation controversial. Based on more recent scientific literature there are many ambiguities still to be resolved regarding potential mechanisms of cosmic rays — cloud cover variations due to solar (magnetic) activity. Thus the galactic cosmic ray/clouds/climate hypothesis remains unproven (PBL, 2010; Rummukainen et al., 2010).

concentration of GHGs and aerosol particles. While some aerosols have a cooling effect, the combined effect of GHG and aerosol emissions is a very clear warming.

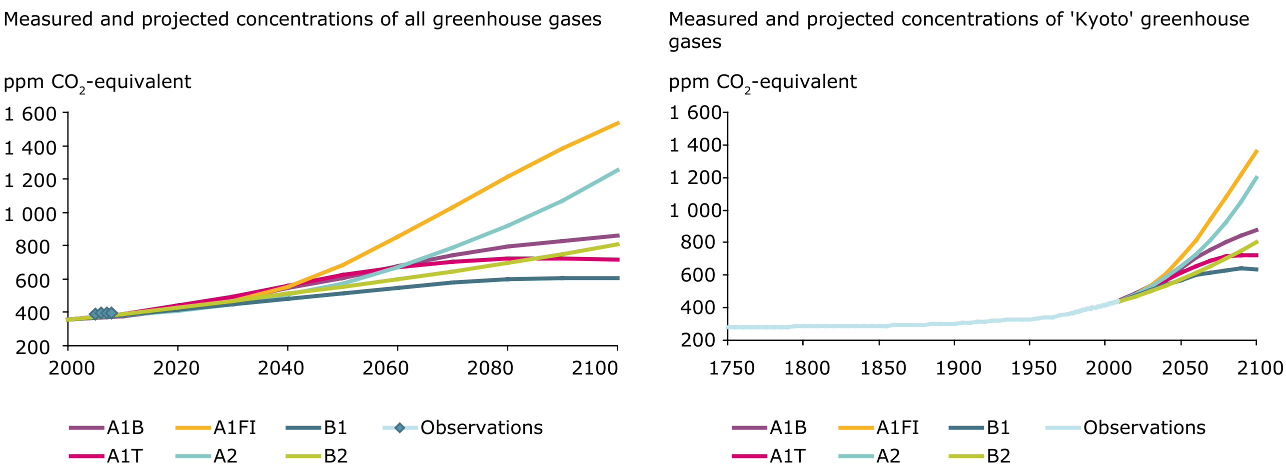
The IPCC's Fourth Assessment Report (IPCC, 2007a) concluded that: *[there is] a very high confidence (i.e. at least 90 % certainty) that the globally net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W/m²*. The report showed that the temperature increase of the last 50–100 years was mainly triggered by CO_2 and other GHG emissions from human activities. Based on a number of subsequent assessments of climate change science this statement is very robust (University of Copenhagen, 2009; UNEP, 2009; PBL, 2009; Allison et al., 2009; Rummukainen et al., 2010).

The atmospheric concentration of CO_2 — the most important GHG — reached 387 ppm in 2009 (NOAA/ESRL, 2010), which is 38 % above the pre-industrial level of 278 ppm. This increase was nearly entirely caused by human activities — about two third by fossil fuel use and one third by land-use change/deforestation. The CO_2-equivalent concentration of the six GHG — CO_2, CH_4, N_2O, hydrofluorocarbons (HFC), perfluorocarbons (PFC) and sulfur hexafluoride (SF_6 — included in the Kyoto Protocol reached 438 ppm CO_2-equivalent in 2008, an increase of 160 ppm from the pre-industrial level. According to the National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Gas Index (AGGI), the total radiative forcing by all long-lived GHG — CO_2, CH_4, N_2O, chlorofluorocarbons 12 and 11 (CFC-12,

Box 2.3 Climate change scenarios

Global and European assessments of climate change impacts and vulnerability are often based on scenarios from the Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000) and their underlying assumptions with respect to socio-economic, demographic and technological change. The SRES scenarios are grouped into four scenario families (A1, A2, B1 and B2) that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. The SRES scenarios do not include additional climate policies above current ones. The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. The projected changes in temperature and other climate change indicators differ among the SRES scenarios, with larger changes in the scenarios with the highest emissions. Of all the SRES scenarios, A2 has the highest emissions, A1B and B2 have emissions between the low and high end range and B1 has the lowest emissions (IPCC, 2007d).

Figure 2.2 Measured and projected concentration of all greenhouse gases (left) and Kyoto greenhouse gases (right)



Note: All main IPCC SRES scenarios are shown. There is no historical trend in the left figure due to the unavailability of long-term data for aerosols and ozone.

Source: IPCC, 2007a; WMO, 2009; NOAA, 2009. Adapted by EEA.

CFC-11), and various lesser gases — has increased by 26 % since 1990. CO_2 contributed about 64 % to the overall global radiative forcing from the pre-industrial period, and 85 % to the increase in radiative forcing over the past decade (NOAA, 2009).

Under the six SRES scenarios assessed by IPCC (2007c), the overall concentration of the six Kyoto gases is projected to increase to 638–1 360 ppm CO_2-equivalent by 2100, whereas the concentration of all GHGs may increase to 608–1 535 ppm CO_2-equivalent (Figure 2.2). A global atmospheric GHG concentration of 450 ppm CO_2-equivalent may be exceeded between 2015 and 2030.

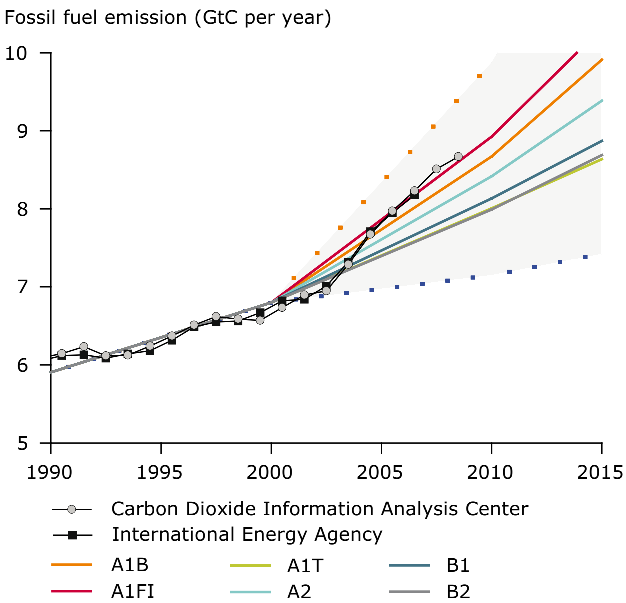
Total CO_2 emissions from fossil fuel burning, cement production and land-use change — mainly deforestation — have grown exponentially since 1800 (Global Carbon Project, 2009; Allison et al., 2009). The growth in fossil fuel CO_2 emissions has accelerated to about 3.4 % per year between 2000 and 2008. This rate is at the upper edge of the range of growth rates in the IPCC scenarios (Figure 2.3).

Without CO_2 sinks, which remove and store CO_2 from the atmosphere, human emissions since 1800 would have caused atmospheric CO_2 to increase from its pre-industrial value of 280 ppm to nearly 500 ppm. Land and ocean sinks have consistently taken up more than half of total CO_2 emissions since 1800. Without them, the actual CO_2 concentration in the atmosphere would be far higher than the current level.

However, the percentage of emissions absorbed by the reservoirs has likely decreased from 60–55 % in the past 50 years. These natural CO_2 sinks are vulnerable to climate and land-use change: they are highly likely to weaken further in the future because of several effects, including increasing ocean acidification, ocean circulation changes, and water, temperature, and nutrient constraints on the CO_2 uptake by land. Also, previously inert carbon pools may be mobilised and released into the atmosphere either as CO_2 or CH_4, which is a much more potent GHG than CO_2. Carbon pools of particular concern include tropical peatland, which is vulnerable to land-clearance and drainage, and the large stores of organic carbon in Arctic permafrost, which are vulnerable to warming. There is increasing confidence that the combined effect of these various processes will be an increase in the atmospheric CO_2 and CH_4 by 2100 and thereby amplifying climate change (Global Carbon Project, 2009).

The global temperature increase up to 2009 was about 0.7 °C (Met Office Hadley Centre, 2010; University of East Anglia, 2010) to 0.8 °C (NASA/GISS, 2010) compared with pre-industrial times. This historical increase corresponds to more than one third of the maximum

Figure 2.3 Observed global fossil fuel CO_2 emissions compared with six scenarios from the IPCC



Note: IPCC scenarios shown are from the IPCC Special Report on Emissions Scenarios (IPCC, 2000). Past emission data are from the Carbon Dioxide Information and Analysis Center (CDIAC) and the International Energy Agency (IEA).

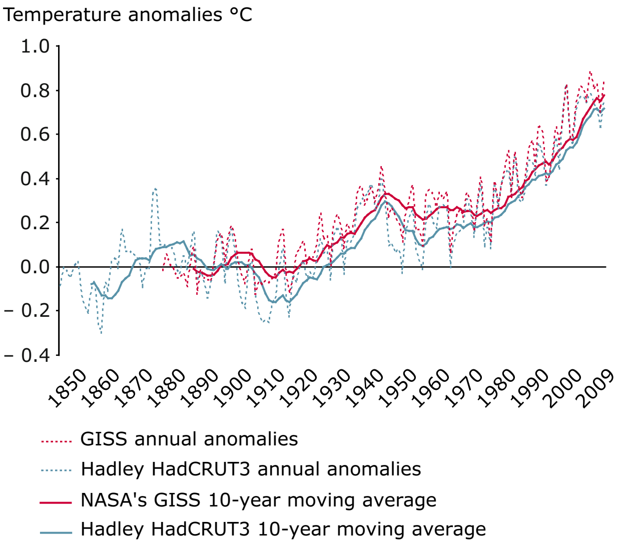
Source: Global Carbon Project, 2009.

increase in global mean temperature of 2 °C — the EU global climate stabilisation target (Figure 2.4). The two analyses differ slightly because of differences in the treatment of regions with few monitoring stations, including the oceans and the Arctic. The Hadley Centre/University of East Anglia leave out grid boxes without climate data while NASA/GISS data use interpolation to estimate missing data. As a result, the NASA representation suggests a somewhat higher increase in temperature in the last decade.

The 2000s (2000–2009) were warmer than the 1990s (1990–1999) which in turn were warmer than the 1980s (1980–1989) and all earlier decades since measurements started (WMO, 2010). The warmest year of the entire series was 1998, with a temperature of 0.55 °C above the 1961–1990 mean. Fourteen of the 15 warmest years in the series occurred between 1995 and 2009 (Met Office Hadley Centre, 2010; University of East Anglia, 2010).

The rate of increase in global average temperature is accelerating, from about 0.08 °C per decade over the past 100 years, to 0.13 °C per decade over the past 50 years and to 0.17 °C per decade over the past 10 years (Met Office Hadley Centre, 2010; Climatic Research Unit University of East Anglia, 2010; NASA/GISS, 2010).

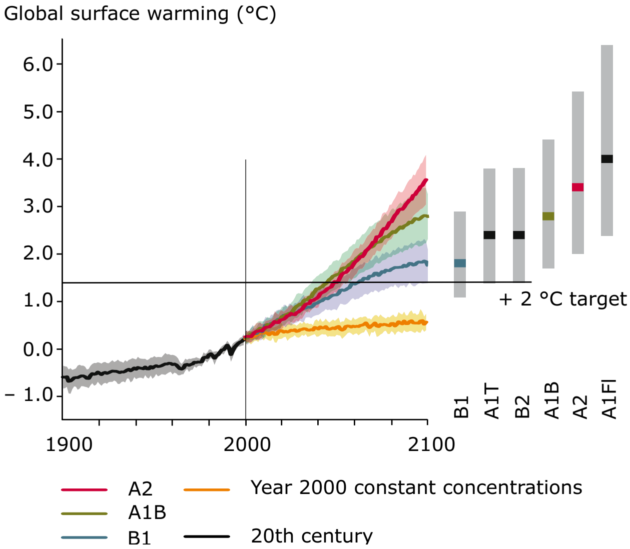
Figure 2.4 **Observed global annual average temperature deviations, 1850–2009, relative to the 1850–1899 average (CRU) and relative to 1880–1899 (NASA)**



Note: In blue, the source of the original anomalies is the MET Office Hadley Centre. The global mean annual temperature deviations are in relation to the base period 1961–1990. In red, the source of the original anomalies is NASA's Goddard Institute for Space Studies (GISS). The anomalies are in the source in relation to the base period 1951–1980. In both cases, the global mean annual temperature deviations have been adjusted by EEA to be relative to the period 1850–1899 (for Hadley Centre/CRU) and 1880–1899 (for NASA/GISS). The trend lines show the 10-year moving average of original anomalies. The dotted lines show the annual anomalies of HadCRUT3 (blue) data set and GISSTEMP data set (red) respectively.

Source: Met Office Hadley Centre and Climatic Research Unit University of East Anglia, 2010; NASA/GISS, 2010.

Figure 2.5 **Observed and projected global mean surface temperatures from 1900, for three IPCC scenarios and the 'Year 2000 constant concentration' pathway**



Note: Past and projected global surface temperature change relative to 1980–1999 is shown, based on multi-model averages for three selected IPCC scenarios. The bars in the middle of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for all six IPCC marker scenarios at 2090–2099 (relative to 1980–1999). Likely ranges in average 2090–2099 warming for all six IPCC scenarios are shown on the right. The black horizontal line has been added by EEA to indicate the EU Council conclusions and UNFCCC Copenhagen Accord objective of 2 °C maximum temperature increase above the pre-industrial (– 1.4 °C above 1990 because of about 0.6 °C temperature increase from the pre-industrial period to 1990).

Source: IPCC, 2007c (adapted by EEA).

However, the rate of global average temperature increase has slowed somewhat over the past few years. Recent publications show that this is due to natural variations that are well understood (Allison et al., 2009; PBL, 2009). The past decade started with a strong *El Niño* event in 1998, increasing global temperature by about 0.25 °C, and ended with a significant *La Niña* event in 2008, lowering temperature by about 0.15 °C. Moreover, the land temperature trend continued unabatedly upwards, while the reconstructed ocean surface temperatures showed a slowdown — for example, in the Southern Ocean, a region with downward trends over the past 11 years.

Arctic air temperatures, based on monitored data and interpolations, have risen at almost twice the rate of the global average rise over the past few decades. This arctic amplification of global warming is largely a result of reduced surface reflectivity associated with the loss of snow and ice, especially sea ice (IPCC, 2007a).

Without global action to limit emissions, the IPCC expects global temperatures to increase further by 1.8–4.0 °C above 1980–1999 levels by 2100. Taking into account the full uncertainty range the projected temperature increase is 1.1–6.4 °C (Figure 2.5). Temperature increase since pre-industrial times would exceed 2 °C between 2040 and 2060 in all IPCC scenarios.

2.2 European temperature, precipitation and storms

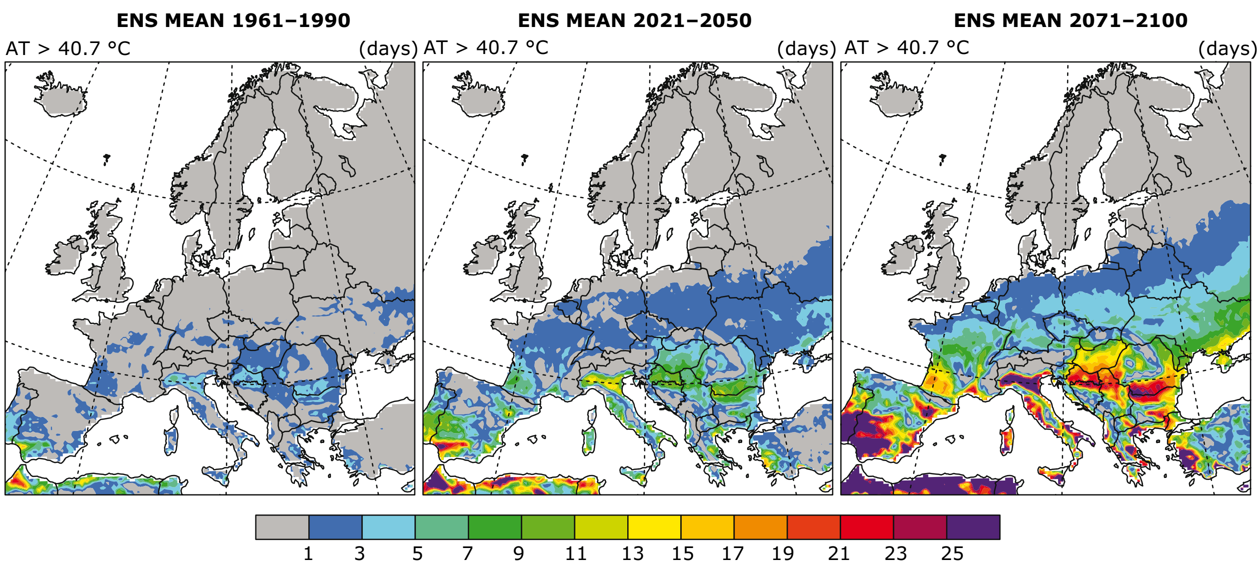
Europe has warmed more than the global average. The annual average temperature for the European land area by 2009 was 1.3 °C above the 1850–1899 average, and for the combined land and ocean area 1 °C above. Considering the land area, nine of the 12 warmest years since 1850 have occurred in the past twelve years (1998 to 2009) (EEA, 2010a). High-temperature extremes — hot days, tropical nights, and heat waves — have become more frequent, while low-temperature extremes — cold spells, frost days — have become less frequent in Europe (IPCC, 2007a; Haylock et al., 2008). The average length of summer heat waves over western Europe doubled over the period 1850–2009 and the frequency of hot days almost tripled. The 2009 winter was relatively cold in most of Europe with extensive snowfall in many places. The spring and summer of 2009 were warmer than the long-term average, particularly over southern Europe. Spain had the third warmest summer after the very hot summers of 2003 and 2005. Autumn, in contrast, was cold again (WMO, 2010).

The annual average temperature in Europe is projected to rise during this century with the largest warming over eastern and northern Europe in winter, and over southern Europe in summer. Summer temperature is projected to increase by up to 7 °C in southern Europe and 5 °C in northern Europe by 2080–2100 compared with 1961–1990. Across Europe, high temperature extremes such as heat waves are projected to become more frequent, intense and longer during this century, whereas winter temperature variability and the number of cold and frost extremes are projected to decrease further. According to the projections, the most affected regions in Europe will be the Iberian and the Apennine Peninsulas and south-eastern Europe. The maximum temperature during summer is projected to increase far more in southern and central Europe than in northern Europe, whereas the largest reduction in the occurrence of cold extremes is projected for northern Europe. The number of days with apparent temperature (heat index) exceeding 40.7 °C will double in most parts of southern Europe (van der Linden and Mitchell, 2009; Ficher and Shaer, 2010) (Map 2.1).

Annual precipitation increased in northern Europe by 10–40 % but decreased in some parts of southern Europe by up to 20 % in the 20th century. Mean winter precipitation has increased in most of western and northern Europe by 20 to 40 %, whereas southern Europe and parts of central Europe were characterised by drier winters (EEA/JRC/WHO, 2008).

Annual mean precipitation is projected to increase by 2071–2100 compared to 1961–1990 by about 10 to 20 % in northern Europe and to decrease by 5–20 % in southern Europe and the Mediterranean (Map 2.2). Seasonally, models project a large-scale increase in winter precipitation in mid and northern Europe and a decrease in many parts of Europe in summer by up to 40 % (Map 2.2).

Map 2.1 Projected average number of summer days in Europe exceeding the apparent temperature (heat index) threshold of 40.7 °C



Note: The maps show the number of summer days in Europe exceeding the apparent temperature (heat index) threshold of 40.7 °C as simulated by five ENSEMBLES Regional Climate Models for the IPCC SRES A1B emission scenario. The apparent temperature (often referred to as the heat index) represents heat stress on the human body by accounting for temperature and in addition the effects of environment factors, such as humidity, and by representing the nonlinear nature of heat stress.

Source: van der Linden and Mitchell, 2009; Ficher and Shaer, 2010.

While there are uncertainties in the magnitude and geographical details of the changes, Europe can clearly be divided into two regimes, with projected increases in precipitation in the north and decreases in the south.

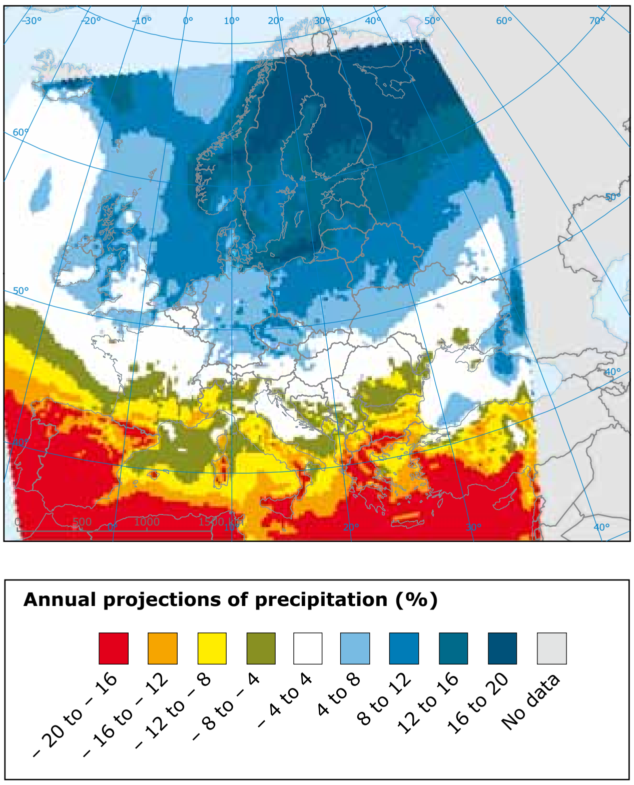
Storms in Europe are associated with the passage of intense extra-tropical cyclones. Storminess in Europe has varied over the past century with no clear long-term trend. Storm frequency was relatively high during the late 19th and early 20th century and then decreased in central and northern Europe. The recent high level is similar to the late 19th century level of storminess. Extra-tropical storm tracks are projected to move pole-wards, with consequent changes in wind, precipitation and temperature patterns, continuing the broad pattern of observed trends over the past half-century. Climate models do not indicate significant changes in the number of northern hemisphere extra-tropical storms in the future (EEA/JRC/WHO, 2008; IPCC, 2007, van der Linden and Mitchell, 2009).

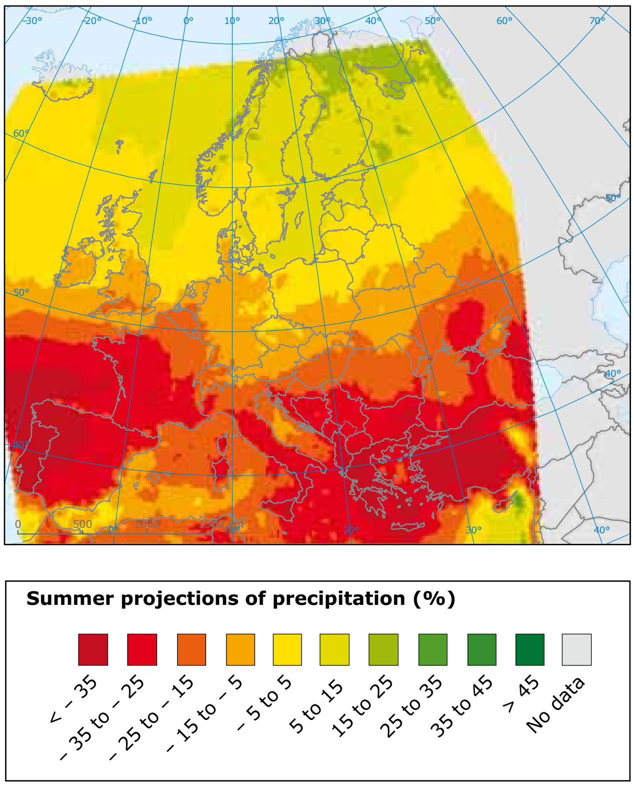
2.3 Arctic sea ice

The extent of sea ice in the Arctic has been declining rapidly, especially in summer (see also SOER 2010 marine and coastal environment assessment). Since satellite observations started in 1979, summer ice extent has shrunk by 10.2 % per decade (Figure 2.6). The reduction in maximum winter extent is smaller (Stroeve et al., 2007). The extent of the minimum ice cover at the end of the melt season in September 2007 broke all previously observed records — it was roughly half the size of the normal minimum extent in the 1950s. The strong negative trend was further reinforced when the second-lowest and third-lowest minimum extents were recorded in 2008 and 2010, respectively (Koç et al., 2009; NSIDC, 2010).

Despite a scarcity of observations of Arctic sea ice thickness, it can be concluded that Arctic sea ice is getting thinner and younger since less ice survives the summer to grow into thicker multi-year floes (Map 2.3). Submarine sonar measurements, covering only the central part of the Arctic Ocean, showed an overall average winter ice thickness of 1.9 metres in 2008, compared with 3.6 metres in 1980 (Kwok et al., 2009). Between 2004 and 2008, the total area covered by the thicker, older, multi-year ice shrank by more than 40 % to 1.54 million km². First-year ice made up more than 70 % of the total cover in the 2008/2009 winter, compared to 40–50 % in the 1980s. Currently less than 10 % of the

Map 2.2 Projected changes in annual (left) and summer (right) precipitation between 1961–1990 and 2071–2100





Note: Left: annual; right: summer (June, July, August) percentage change as simulated by ENSEMBLES Regional Climate Models for the IPCC SRES A1B emission scenario.

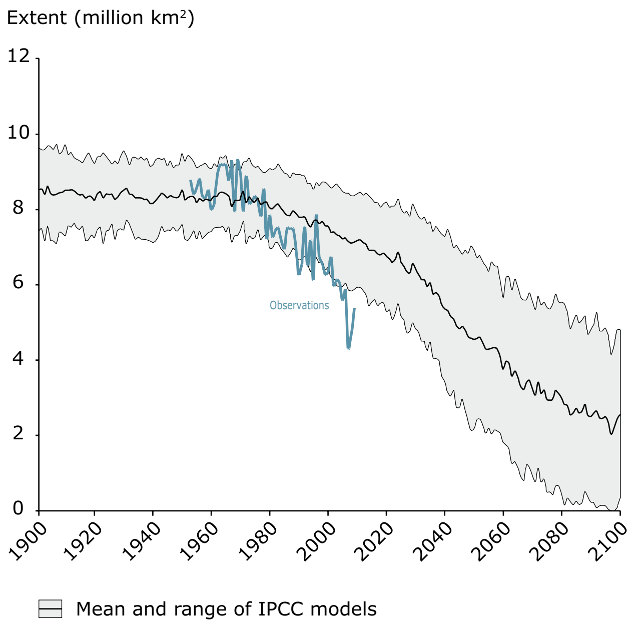
Source: van der Linden and Mitchell, 2009.

Arctic sea ice is older than two years and this implies that the volume of Arctic sea ice has greatly diminished (Koç et al., 2009).

Arctic summer sea ice will very likely continue to shrink in extent and thickness, leaving larger areas of open water for an extended period. It is also very likely that winter sea ice will still cover large areas. The speed of change, however, is uncertain. Several recent international assessments concluded that mostly ice-free late-summers might occur by the end of the century (IPCC, 2007a). However, the data from 2007, 2008, and 2009 show that Arctic sea ice cover is shrinking significantly faster than projected by climate models (Figure 2.6) (Koç et al., 2009). This is likely due to a combination of several model deficiencies, including incomplete representation of ice albedo effects (dark open water reflects much less sunlight than white snow-covered surfaces) and of vertical and horizontal water mixing in the ocean. Due to the existence of natural variability within the climate system, it is not possible to predict the precise year in which the Arctic Ocean will become seasonally ice free (Allison et al., 2009).

Amplification of global warming in the Arctic will have fundamental impacts on northern hemisphere weather and climate (UNEP, 2009; Sommerkorn and Hassol, 2009) (see also the section on tipping elements):

Figure 2.6 Observed and projected Arctic September sea-ice extent, 1900–2100



Source: National Snow and Ice Data Centre (NSIDC), 2009.

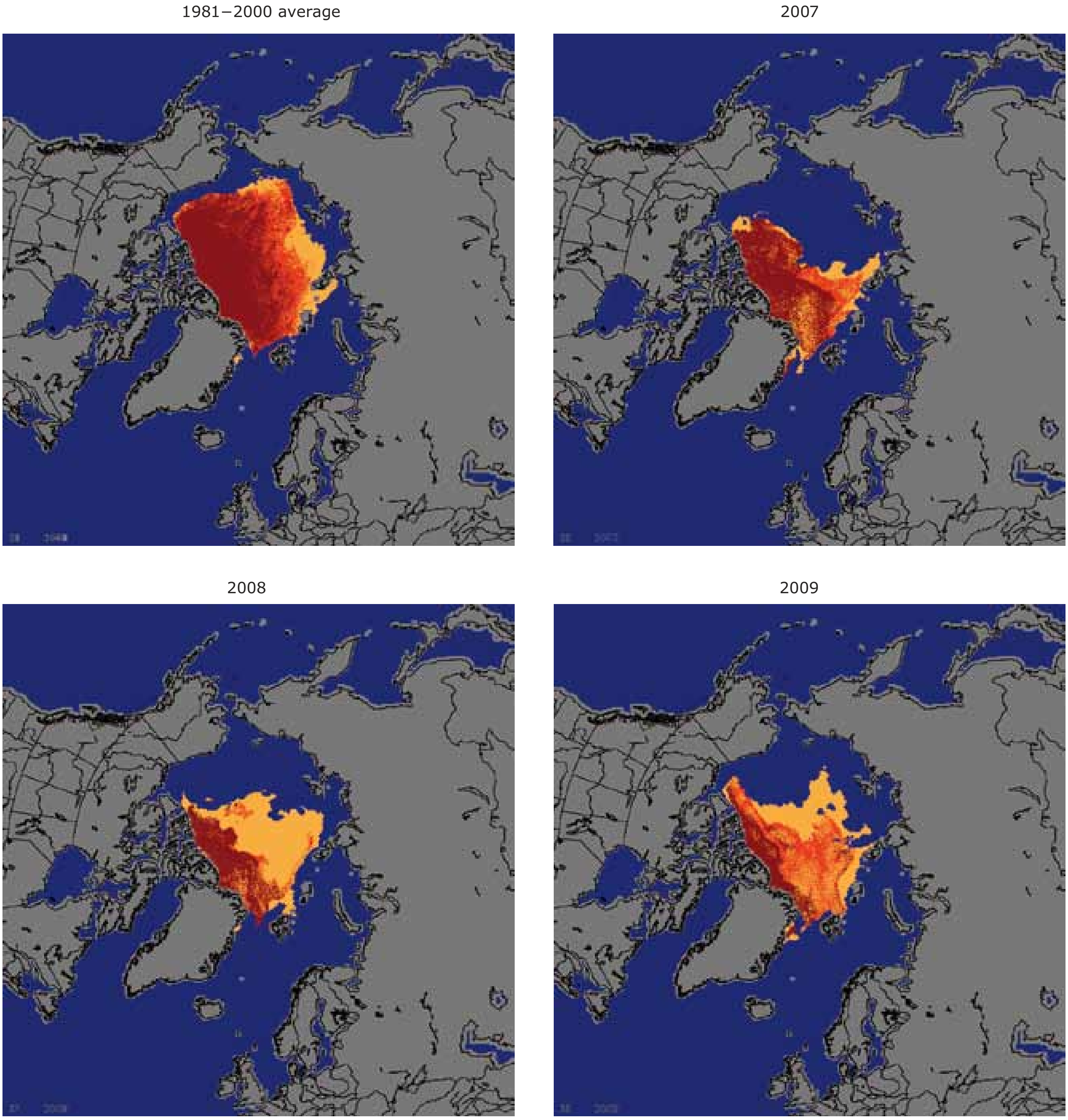
- Reduced sea ice amplifies warming, since open water reflects much less sunlight. Reduced sea-ice cover is already amplifying warming in the Arctic earlier than projected. This amplification will become more pronounced as more ice cover is lost over the coming decades.
- Amplified warming spreads over land. Amplified atmospheric warming in the Arctic will probably spread over high-latitude land areas, hastening degradation of permafrost, leading to increased release of GHGs presently locked in frozen soils, leading to further Arctic and global warming.
- Weather patterns are altered. The additional warming in the Arctic will affect weather patterns there and beyond by altering the temperature gradients and circulation patterns in the atmosphere. It may also affect temperature and precipitation patterns in Europe and North America.

The sea ice is an ecosystem filled with life uniquely adapted to these conditions, from micro-organisms in channels and pores within the ice and rich algal communities underneath it, to fish, seals, whales and polar bears. Because the diversity of life on the ice usually increases with the age of the ice floes, as the ice gets younger and smaller, the abundance of ice-associated species will be reduced, with a risk of extinction for some of them.

Furthermore, diminishing Arctic sea ice is already impacting indigenous people and cultures. Sea ice is an important part of the hunting grounds and travel routes of many Arctic peoples and, as ice retreats, they are forced to change subsistence strategies and address safety concerns. Indigenous Arctic peoples will thus face serious economic, social and cultural changes.

Less summer ice will ease access to the Arctic Ocean's resources including oil and gas, though the remaining ice will still pose a major challenge for operations during most of the year. As marine species move northwards to a warmer sea with less ice, so too will the fishing fleet. It is however unclear whether the fisheries will become richer or not. Fish species react differently to changes in marine climate, and it is hard to predict whether the timing of the annual plankton blooms will continue to match the growth of larvae and young fish. Shipping and tourism have already increased and will continue to do so. However, drift ice, short sailing seasons and lack of infrastructure will impede a rapid development of the transcontinental shipping of goods. Traffic linked to extraction of Arctic resources on the fringes of the Arctic sea routes will grow first. These activities represent new pressures and risks to an ocean that has so far been closed to most economic activities.

Map 2.3 Arctic summer sea-ice age 1981–2000 compared with 2007, 2008, and 2009



First-year ice (< 1 year old) | Second-year ice (1–2 years old) | Older ice (> 2 years old) | Open water | Land

Note: These images compare ice age, a proxy for arctic summer sea ice thickness, in 2007, 2008, 2009, and the 1981–2000 average. 2009 saw an increase in second-year ice over 2008. At the end of summer 2009, 32 % of the ice cover was second-year ice and three-year and older ice was 19 % of the total ice cover, the lowest in the satellite record.

Source: National Snow and Ice Data Center (NSIDC), 2009; Koç et al., 2009.

2.4 Greenland ice sheet

The Greenland ice sheet has experienced an increase in surface melt extent, mass loss, freshwater runoff and thinning along its periphery over the last few decades. Areas with melting can be measured from satellites, and from 1979 to 2008 the cumulative melt area increased by approximately 30 % (Figure 2.7). The other mechanism behind the ice loss since the 1990s is the accelerated flow of outlet glaciers towards the sea which accounts for more of the ice loss than surface melting.

Overall mass balance estimates, taking into account accumulation, melting and ice discharge, indicate that the Greenland ice sheet is losing volume at an increasing rate. Whereas the annual net loss from 1995 to 2000 was 50 Gt, from 2003 to 2006 about 160 Gt were lost per year, with an uncertainty in the order of 50 Gt (Koç et al., 2009; AMAP, 2009; Wouters et al., 2008). However, there are still considerable discrepancies between different estimates of ice loss rates.

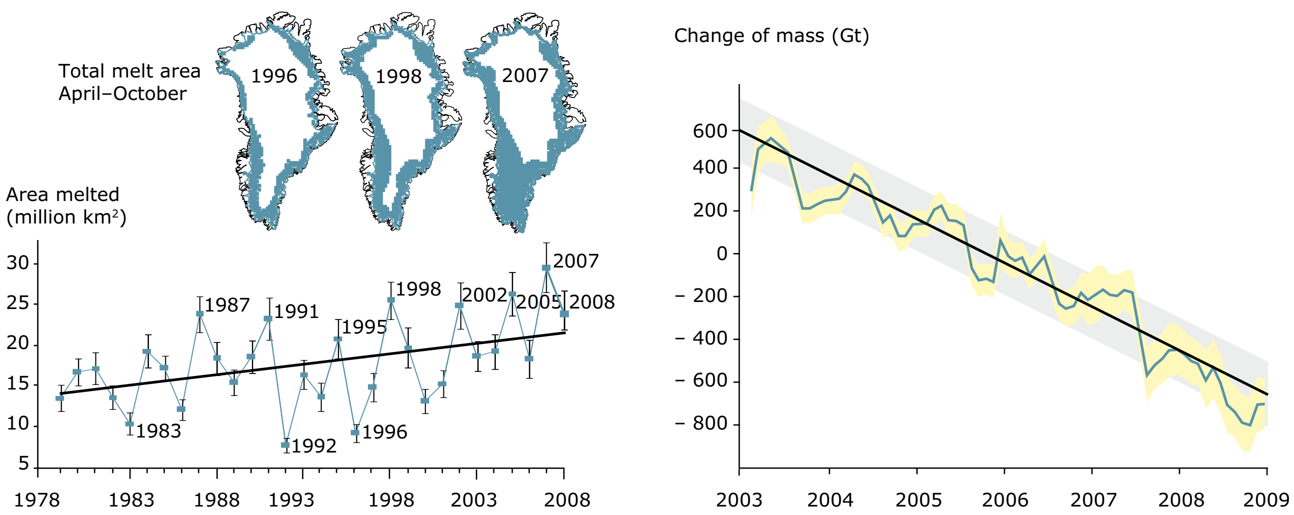
The Greenland ice sheet loss strongly influences sea level. Further changes in the Greenland ice sheet due to global climate change are thus of great significance. Projections of the response of the Greenland ice sheet to climate change show that the surface melt area and the loss of mass will both increase. However, making reliable predictions of the future of the Greenland ice sheet is difficult because the processes causing the faster movement of the glaciers still need to be better understood and more observations are needed. The accelerated ice flow has only been observed for a rather short period and scientists are now trying to better understand the processes driving this phenomenon, which in turn should allow better models to be developed.

2.5 Sea-level rise

Population densities in coastal regions and on islands are about three times the global average. Even a small sea-level rise could have significant societal, environmental and economic impacts through coastal erosion, increased susceptibility to storm surges and resulting flooding, ground-water contamination by salt intrusion, loss of coastal wetlands, and other effects (Allison et al., 2009).

During the 20th century, tide gauge data show that the global sea level rose by an average of 1.7 mm/year (IPCC, 2007a). This was due to an increase in the volume of ocean water as a consequence of temperature rise, although inflow of water from melting glaciers and ice-sheets is playing an increasing role. For the period 1961–2003, thermal expansion contributed about 40 % of the observed sea-level rise, while shrinking mountain glaciers and ice sheets contributed about 60 % (Allison et al. 2009; IPCC, 2007a). Sea-level rise has been accelerating over the past 15 years, 1993–2008, to 3.1 (± 0.6) mm/year, based on

Figure 2.7 Melting area 1979–2008 (left) and mass change 2003–2009 (right) of the Greenland ice sheet



Note: The left figure shows the area of the Greenland ice sheet melting during 1979–2008, derived from satellite remote sensing. Between 33–55 % of the total mass loss from the Greenland ice sheet is caused by surface melt and runoff. The ice-sheet melt area increased by 30 % between 1979 and 2008, with the most extreme melt in 2007. The right figure shows the loss of ice mass from the Greenland ice sheet from 2003 to 2009 based on satellite observations (compared to average values between 2003 and 2009).

Source: Allison et al., 2009; AMAP, 2009; Koç et al., 2009; Wouters et al., 2008 (updated).

data from satellites and tide gauges, with a significantly increasing contribution of ice-sheets from Greenland and Antarctica (Figure 2.8) (Alblain et al., 2009).

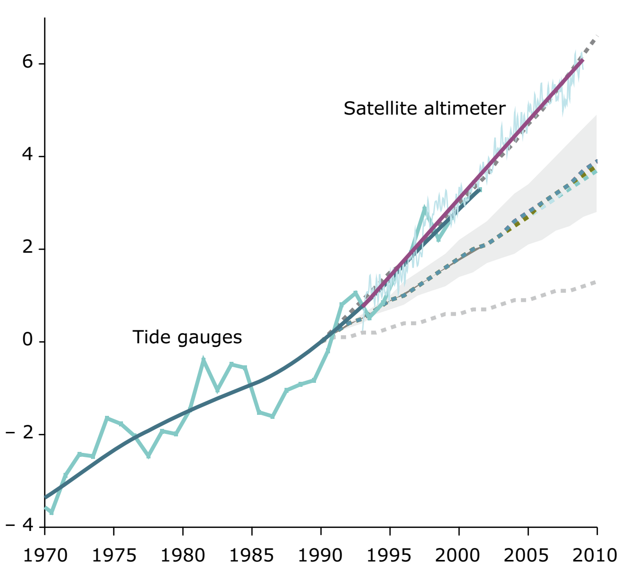
New results from the Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission show that the rate of mass loss for the Greenland and Antarctic ice sheets is increasing (see Section 1.4). In IPCC (2007a), the sum of estimates of the contributions to sea-level rise from thermal expansion and the melting of glaciers, ice caps and ice sheets fell short of the observed rise. Studies since then have greatly reduced this gap. The sum of the contributing effects now matches the observed total rise much better, signalling improved understanding of the mechanisms behind sea-level rise (Rummukainen et al., 2010).

The estimated current contribution from Greenland is 0.7 mm/year and the estimate for Antarctica is almost the same, according to observations from 2002 to 2009 (Allison et al., 2009; Scientific Committee on Antarctic Research, 2009).

Satellite observations indicate a large spatial variability of sea-level rise across the European seas (Map 2.4), with increases of for example 3.6 mm/year for the North Atlantic (50 °N to 70 °N) and 1.8 mm/year on average for the Mediterranean Sea. In part of the eastern Mediterranean sea-level rise has been higher than this average, while in the west it was lower. These local variations can be explained by variability of the North Atlantic Oscillation (NAO), inter-annual wind variability, changes in global ocean circulation patterns, or specific local structures of the circulation such as gyres, or isostatic uplift.

Sea level is projected to rise considerably during this century and beyond. In 2007 the IPCC projected a rise of 0.18–0.59 m above the 1990 level by the end of the 21st century (IPCC, 2007a). However, the models used in developing these projections did not include representations of dynamic ice sheets. Since then there have been a number of new studies on observed and modelled ice-sheet mass budgets that have considerably enhanced our understanding of ice-sheet vulnerabilities (Allison et al., 2009). Since 2007, reports comparing the IPCC projections with observations show that sea level is currently rising at a faster rate than indicated by IPCC projections (Figure 2.8).

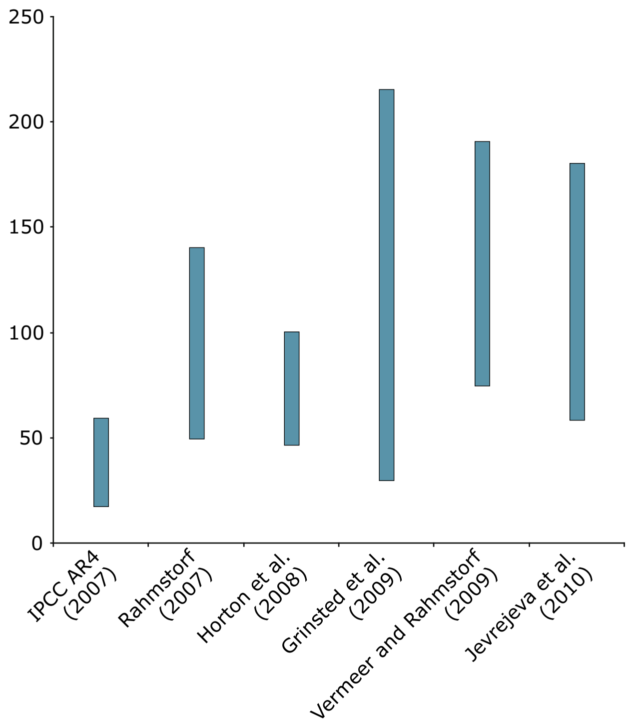
Figure 2.8 **Observed and projected change in sea level 1970–2008, relative to the sea level in 1990**



Note: The solid lines are based on observations smoothed to remove the effects of inter-annual variability (light lines connect data points). Data in most recent years are obtained from satellite-based sensors. The envelope of IPCC (2001) projections is shown for comparison; this includes the broken lines as individual projections and the shading as the uncertainty around the projections.

Source: University of Copenhagen, 2009; Rahmstorf et al., 2007.

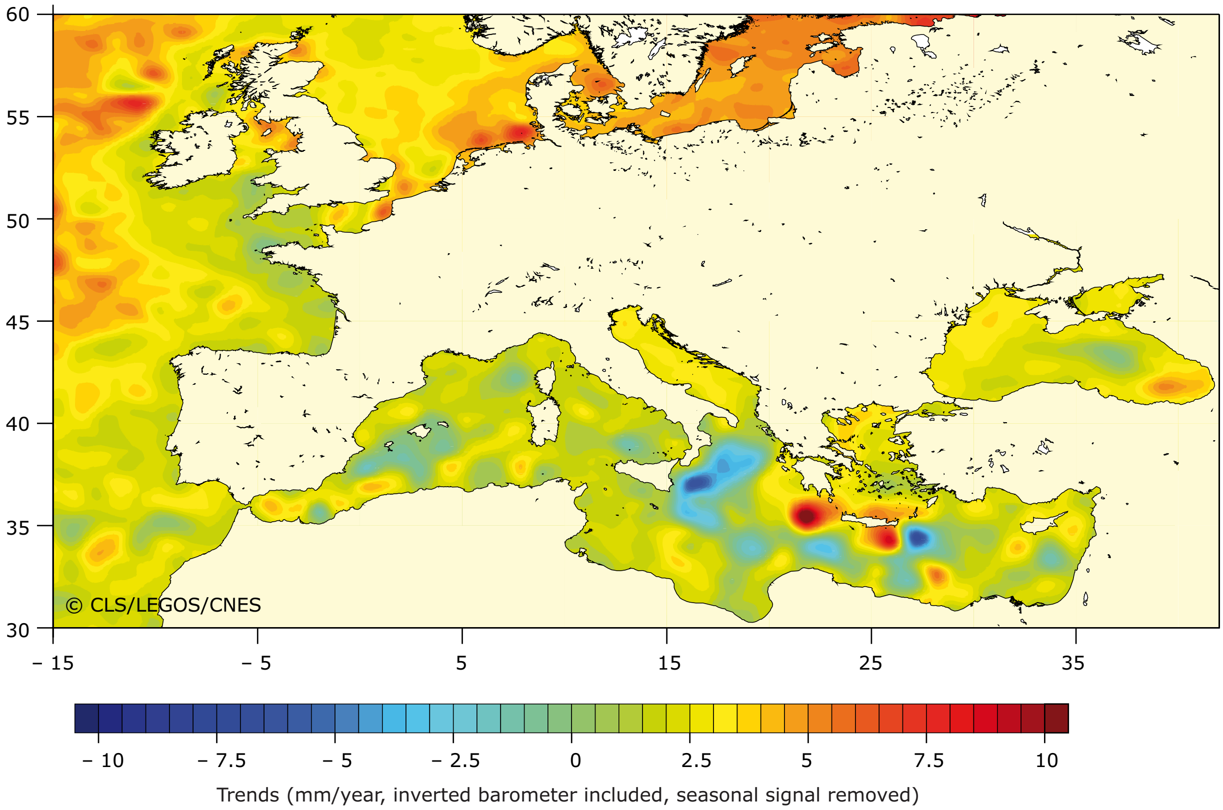
Figure 2.9 **Projected global average sea-level rise, 1990–2100**



Note: Estimates for 21st century sea-level rise from semi-empirical models as compared to the IPCC Fourth Assessment Report (AR4). For exact definitions of the time periods and emissions scenarios considered (IPCC, 2007a; Rahmstorf, 2007; Horton et al., 2008; Grinsted et al., 2009; Vermeer and Rahmstorf, 2009; Jevrejeva et al., 2010)

Source: Rahmstorf, 2010.

Map 2.4 Change in sea level in Europe, October 1992–June 2009



Note: Based on satellite data; trends in mm/year, inverted barometer included, seasonal signal removed. This map is produced at the CLS/CNES/LEGOS group and is also available through MyOcean.

Source: Ablain, M. et al., 2009; Cazenave, A. et al, 2009.

Sea-level rise projections are still subject to high uncertainties, because models of the behaviour of the polar ice sheets are still in their infancy. The major dynamic ice sheet uncertainties are largely one-sided: they can lead to a faster rate of sea-level rise but are unlikely to significantly slow the rate of rise (Allison et al., 2009). Other uncertainties are the effects on sea level of a slowing the Atlantic thermohaline circulation (THC) (Levermann et al., 2005), and of gravity changes induced by the melting of land-based ice-masses (see also below). Gravity changes are especially important since these have an effect on regional differences in sea-level rise and thus the melting of the West Antarctic ice sheet may in the long term be more important for sea-level rise in Europe than the Greenland ice sheet melting.

Recent estimates based on various different approaches, assuming unabated GHG emissions, suggest a projected global average sea-level rise of about 1.0 m or possibly — although very unlikely — up to 2.0 m by 2100 (Rahmstorf, 2007 and 2010; Lowe, 2010; Allison et al., 2009; UNEP, 2009). It is important to continue to monitor sea level and to improve projections. The uncertainties imply a need to keep a range of adaptation options open and to adjust adaptation strategies in response to new findings (Lowe, 2010).

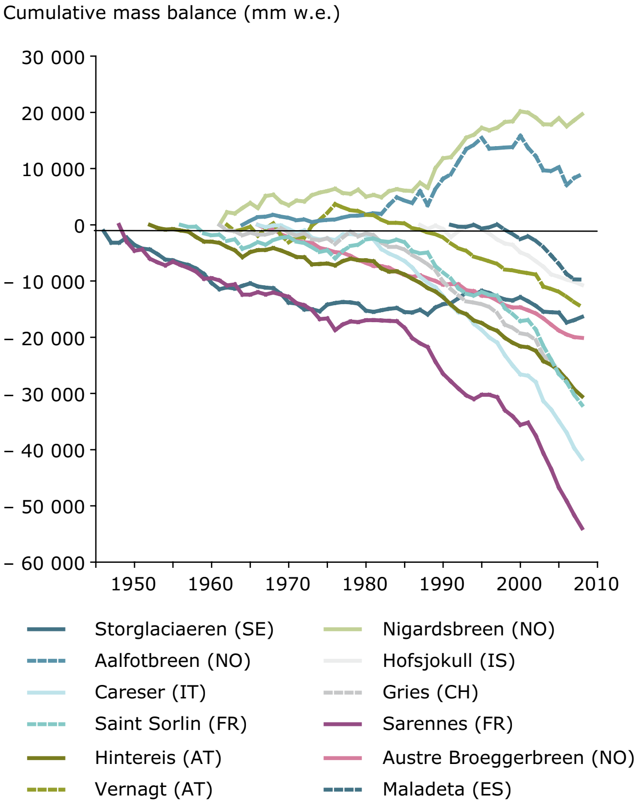
2.6 European glaciers

The vast majority of glaciers in the European glacial regions are in retreat (Figure 2.10). The temperature increase in the Alps was more than twice the global average — about 2 °C from the late 19th century up until the early 21st century (EEA, 2009). Glaciers in the Alps lost about half their total volume — roughly 0.5 % per year — between 1850 and 1975. Loss of glacier volume has accelerated since then. About 20–25 % of the remaining amount vanished between 1975 and 2000 (updated after Haeberli et al., 2007) and again 10 % vanished in 2000–2009 — corresponding to about 2 % per year of the remaining volume. Thus glaciers in the Alps lost about two-third of their volume between 1850 and 2009. The year 2003 showed exceptional mass loss with a decrease in mean ice thickness of almost 3 m over nine measured Alpine glaciers. This rate was four times higher than the mean between 1980 and 2001 and exceeded the previous record of the year 1996 by almost 60 % (Zemp et al., 2009). Glacier retreat is projected to continue.

Using different modelling approaches, the glacierised area in the Alps is projected to decrease to about one-third of the present area for a further rise in Alpine summer temperature of 2 °C (Zemp et al., 2006, Le Meur et al., 2007, Jouvet et al., 2009) (Figure 2.11).

Whereas small glaciers are expected to disappear in the next few decades, considerable amounts of 'left-over' ice, thick ice bodies originating from colder conditions, from large glaciers would persist throughout the 21st century.

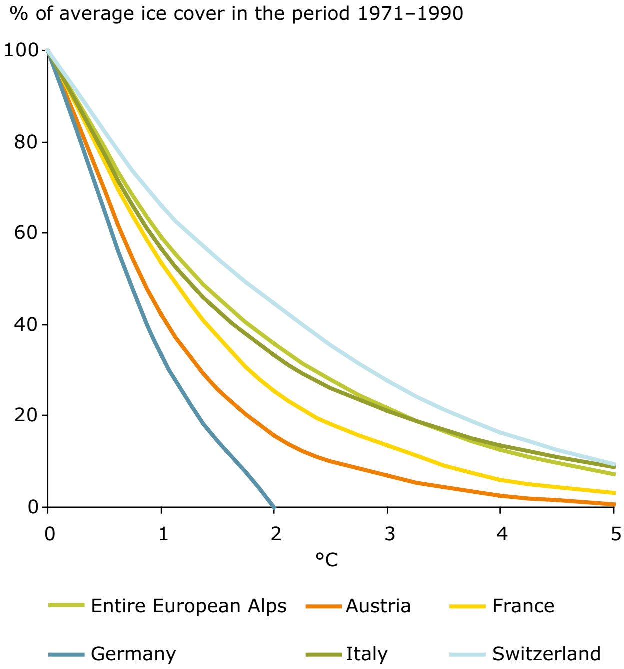
Figure 2.10 Cumulative specific net mass balance of selected glaciers from European glaciated regions, 1946–2008



Note: Positive values mean ice growth; negative values mean ice loss

Source: World Glacier Monitoring Service, 2010.

Figure 2.11 Modelled remains of the glacier cover in the European Alps for an increase in regional average summer air temperature of 1–5 °C



Source: Zemp et al., 2006.

3 Risks of global climate change

3.1 Different types of risk

Water, ecosystems, food, coastal areas and health are key vulnerable sectors in the world with increasing impacts at increasing projected temperature levels. The kind of dominant impacts and associated risks are different in different regions. From a global perspective, the most vulnerable regions are in developing countries, many of which have a low capacity to adapt. Impacts in those regions are likely to have spill-over effects for Europe, through global linkages of economic systems and also possibly through increasing migration of people. The most severe consequences of climate change could be avoided if global warming remained less than 2 °C above pre-industrial levels (Figure 3.1). An increase of less than 2 °C above pre-industrial levels may allow adaptation to climate change for many human and natural systems at affordable economic, social and environmental costs. Some of the global aspects are further presented in the cross-cutting assessment on adapting to climate change.

The so-called 'burning embers diagram' (Figure 3.2) shows the increasing risk of various types of climate impacts with an increase in global average temperature based on the scientific knowledge available in 2001 when the IPCC third assessment report was published (IPCC, 2001) and in 2009 (University of Copenhagen, 2009; Smith et al., 2009).

Five types of risk, or reasons of concern, are considered:

- risk to unique and threatened systems;
- risk of extreme weather events;
- risk of distribution of impacts;
- risk of aggregate impacts; and
- risk of risk of large-scale discontinuities.

The reasons for concern are analysed over temperature increases ranging from 0–5 °C above 1990 levels and assigned values represented by the intensity of colours running from white as no threat or risk, to yellow as some to moderate risk, and finally to deep red as high risk or very negative effects.

Risks of adverse climate change impacts appear at significantly lower levels of global average temperature rise in the most recent (2009) analysis. The 2 °C guardrail, which was thought in the 2001 analysis (IPCC, 2001) to avoid serious risks for all five reasons for concern, could in 2009 be assessed to be less adequate to avoid serious risks to many unique and threatened ecosystems and to avoid a large increase in the risks associated with extreme weather events.

The risks of large-scale discontinuities, or also called tipping elements, were considered to be very low in 2001 for a 2 °C increase but in 2009 are considered to be moderate for the same increase.

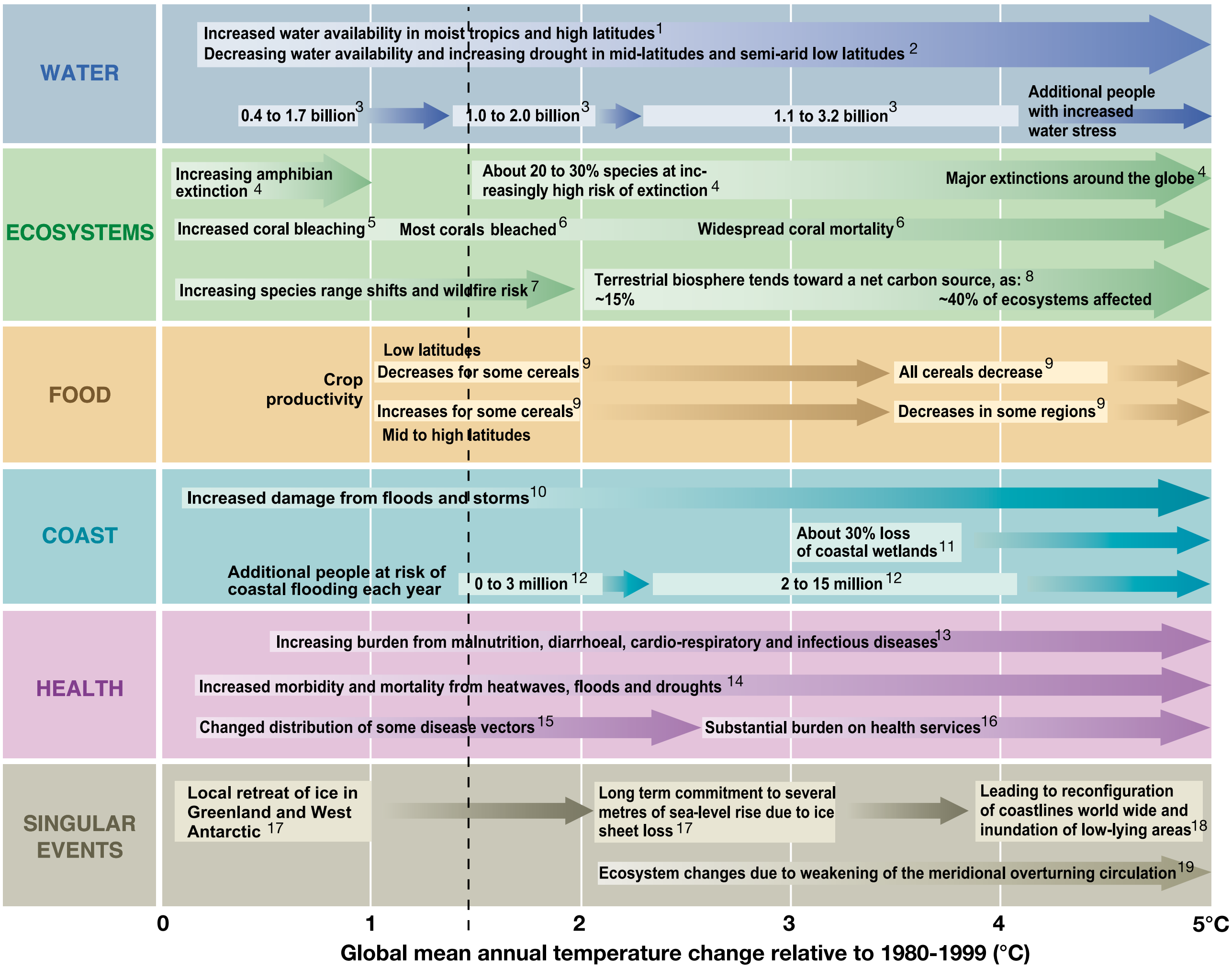
3.2 Risk of tipping elements

A special kind of risks, particularly important but difficult to deal with from a policy point of view, are climate events that have a low or unknown likelihood of occurrence but potentially very large consequences for the world, including Europe. Many of these climate events involve positive feedbacks such that the process can no longer be stopped once a threshold is crossed. However, limited understanding of the physical mechanisms involved, as well as a lack of observational data, implies large uncertainty about the likelihood of these events and about possible thresholds. These climate events are generally denoted in the scientific community as 'large scale discontinuities' (IPCC, 2007a), 'tipping elements and tipping points' (Lenton et al., 2008; Schellnhuber, 2009; Allison et al., 2009; UNEP, 2009) or 'climate eventualities' (Kattenberg et al., 2009; PBL, 2009).

Table 3.1 shows 'climate eventualities' and their key characteristics:

- already expected or ongoing climate change becomimg stronger or weaker and thus showing acceleration or deceleration of change;
- conditions that make the change stronger or weaker with positive or negative feedback leading to acceleration or deceleration of change;
- having characteristics of a tipping system (element) with a tipping threshold (or tipping point);
- level of global temperature increase above 1990 level at which the change may start to take occur;
- timescale: will the change be gradual or abrupt; how long might the change take once the event has begun;
- the main primary consequence of an event, and the spatial scale of these primary effects — regional, continental or global.

Figure 3.1 **Examples of global impacts in various sectors projected for changes in climate associated with different increases in global average surface temperature in the 21st century**



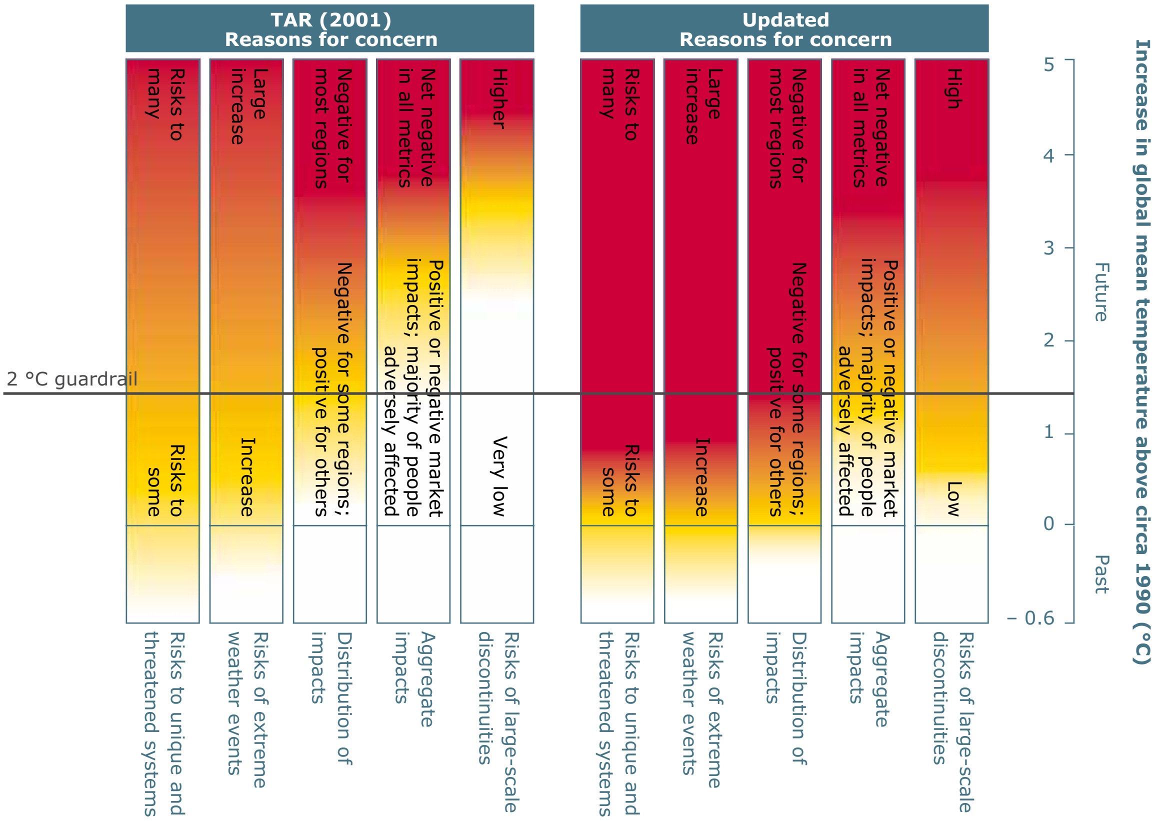
Note: Boxes indicate the range of temperature levels to which the impact relates. Arrows indicate increasing impacts with increasing warming. Adaptation to climate change is not considered in this overview. The black dashed line has been added by EEA to indicate the EU Council conclusions and UNFCCC Copenhagen Accord objective of 2 °C maximum temperature increase above pre-industrial (1.4 °C above 1990 because of about 0.6 °C temperature increase from the pre-industrial period to 1990). Numbers in superscript are the figure sources included in the individual sections of the Working Group II Report 'Impacts, Adaptation and Vulnerability' (IPCC, 2007c).

Source: IPCC, 2007c. Published with the permission of the IPCC.

In this section we mainly use the term 'tipping elements/ tipping points' (EEA, 2010b). Tipping elements are regional-scale features of the climate that could exhibit a threshold ('tipping point') behaviour in response to climate change — that is, a small shift in the climate system can trigger a large-scale and/or abrupt shift towards a different state of the system. Some of these non-linear changes are related to feedbacks in the climate system, which accelerate global climate change. When a 'tipping point' is crossed, the changes in the system can be much faster than the external forcing, for example, the increase in GHG concentrations, that initiated the changes. Some tipping elements would be reversible, others irreversible. Reversible means that when the forcing is returned to its original level below the tipping point the system recovers its original state; irreversible means that the system cannot be returned to its original state.

Figure 3.3 shows that some of the large-scale consequences of climate change could be avoided if global warming were be kept to less than 2 °C above pre-industrial levels. However, it is unclear whether, and how rapidly, the Greenland ice sheet would disintegrate in a global climate 2 °C warmer than in pre-industrial times. Changes that are already taking place, such as ocean acidification (see below), slow release of CH_4 from permafrost and ocean

Figure 3.2 Reasons for concern about climate change for different levels of global mean temperature increase



Notes: Zero on the temperature scale corresponds approximately to the 1990 average temperature, and the bottom of the temperature scale to pre-industrial average temperature. The level of risk or severity of potential impacts increases with the intensity of the red. The 2 °C guardrail, the global objective in the Copenhagen Accord, is shown for reference (1.4 °C above 1990 because of a temperature increase of about 0.6 °C from the pre-industrial period to 1990).

Source: Smith et al., 2009 (adapted by EEA).

regions, and rapid melting of Arctic sea ice in summer, are already causing impacts at current temperature levels, which may further increase with future temperature increases.

Several key tipping elements with potentially large consequences for Europe are further discussed below.

Current understanding suggests that the tipping elements of most direct relevance for Europe (Map 3.2), and with potentially large impacts at relatively low global temperature increases, are the loss of the summer Arctic sea ice, the Greenland ice sheet and Alpine mountain glaciers.

Summer Arctic sea ice is disappearing faster than anticipated by current climate models. As sea ice melts, it exposes a much darker ocean surface which absorbs more radiation than white sea ice — the ice-albedo feedback — thus amplifying warming. There is no clear evidence of the existence of a critical threshold for summer Arctic sea ice loss above which the ice would further reduce and eventually collapse. However, model studies suggest that Arctic summer sea ice will vanish at an additional global warming of 1–2 °C.

The retreat of **Alpine glaciers** is amplified by several feedback mechanisms. The reduction in snow and ice-covered areas induces increased regional warming and ice melt through the ice-albedo feedback. Enhanced dust accumulation also significantly decreases surface albedo — reflectivity — leading to accelerated ice melt. Over recent decades an increase in the melt season by one month and reduced precipitation as snow have

Table 3.1 Overview of characteristics and effects of 13 large-scale discontinuities or eventualities of the climate system

Climate event	Character	Threshold	Global warming	Transition timescale	Onset possible in	Primary effect	Scale
Rapid permafrost CO_2 and methane release	Accelerated change/ positive feedback	Not known	Not known	Not known	Not known	Extra warming	Global
Rapid sea bed methane release	Accelerated change/ positive feedback/ tipping point?	Not known	Not known	10 000–20 000 years	Centuries-Millennia	Extra warming	Global
Estimated climate sensitivity too low	Positive feedback/ accelerated change			Centuries	Years	Extra warming	Global
GIS disintegrates	Accelerated change/ positive feedback	~ 3 °C local warming	1–2 °C	Centuries	Decades-Centuries	Extra sea-level rise	Global
WAIS disintegrates	Accelerated change/ positive feedback/ tipping point	~ 5–8 °C local warming	3–5 °C	Centuries	Centuries-Millennia	Extra sea-level rise	Global
MOC collapses	Tipping point	0.1–0.5 Sv mass transport	3–5 °C	Decades/ centuries	Centuries	Shifts in regional climate	Several regions/ continental
ENSO changes in character	Unknown				Decades	Shifts in regional climate	Several regions
Amazon forest collapses	Tipping point	1.1 m/year prec. 40 % deforest	3–4 °C	Decades	Decades	Shifts in regional climate	Several regions/ continental
Boreal forest dieback	Accelerated change/ tipping point	~ 7 °C local warming	3–4 °C	Decades	Decades	Shifts in regional climate	Several regions/ continental
Ice-free Arctic in summer	Positive feedback/ accelerated change	None	Current	Decades	Decades	Extra warming/ shifts in regional climate	Several regions/ continental
Solar induced cooling	Decelerated/ accelerated change	None	None	Decades/ century	Years-decades	Less warming	Continental/ global
Estimated climate sensitivity too high				Centuries	Years	Less warming	Global
Ocean acidification	Gradual change	None	Current	Decades/ century	Years		Global

Note: GIS: Greenland ice sheet; WAIS: West Antarctic ice sheet; MOC: meridional overturning circulation; ENSO *El Niño*/Southern Oscillation; Sv: Sverdrup, 10^6 cubic metres per second. These climate eventualities illustrate the large uncertainties around the climate issue.

Source: PBL, 2009.

strongly reduced glacier mass and led to disintegration of glaciers into smaller parts. An increase in global mean air temperature of 2 °C above present, corresponding to an increase of 3–4 °C locally, could lead to an almost complete loss of glacier ice mass in the Alps (see also Section 2.6).

It is expected that there will be at least partial deglaciation of the **Greenland ice sheet** at 1–2 °C of global warming above present levels, corresponding to about 2–3 °C above pre-industrial levels (IPCC, 2007a). Recent estimates suggest that tipping of the Greenland ice sheet can only be avoided with long-term stabilisation at less than 2°C above pre-industrial temperatures. Without such stabilisation, the Greenland ice sheet may reach a tipping point within decades.

The **West Antarctic ice sheet** (WAIS) could lose large amounts of ice abruptly in response to ocean warming but currently there are no reliable estimates for associated temperature thresholds. The WAIS is currently assessed to be further from a tipping point than the Greenland

Map 3.1 **Potential climatic tipping elements**

Note: Tipping elements are regional-scale features of the climate that could exhibit threshold-type behaviour in response to human-driven climate change — that is, a small amount of climate change at a critical point could trigger an abrupt and/or irreversible shift in the tipping element. The consequences of such shifts for societies and ecosystems are likely to be severe. Question marks indicate systems whose status as tipping elements is particularly uncertain. There are other potential tipping elements that are missing from the map, for example, shallow-water coral reefs threatened in part by ocean acidification (Veron et al., 2009).

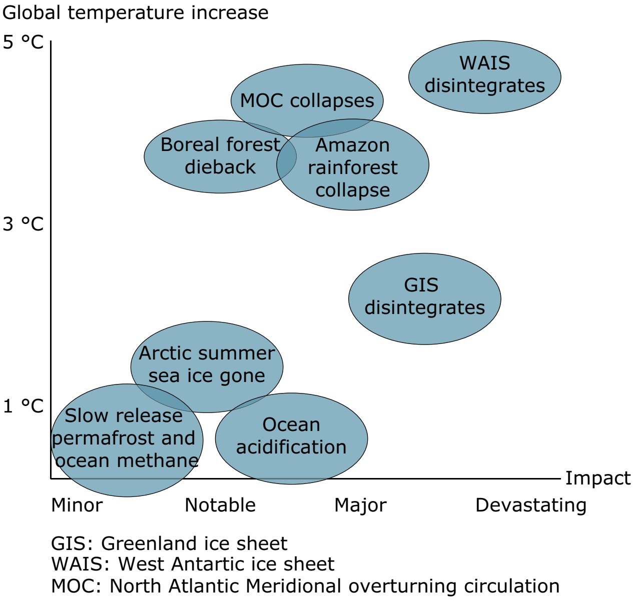
Source: Schellnhuber, 2009; University of Copenhagen, 2009.

ice sheet but the uncertainties around WAIS are larger. One study (Lenton et al., 2008) estimates tipping to be possible at global warming of about 3–5 °C above present levels. Several ice shelves around the Antarctic Peninsula, such as Larsen B, have collapsed recently, followed by the acceleration of glaciers they were buttressing. These observations highlight a mechanism that could threaten parts of the WAIS.

The total melting of the Greenland and West Antarctic ice sheets could cause a sea-level rise of about 7 m and 5 m, respectively, over the next 1 000 years. This would alter the world's coastlines completely and would have enormous societal, environmental and economic impacts. Sea-level rise would not be evenly distributed around the globe because of associated changes in ocean circulation patterns, land movements, and density and gravitational factors.

There is less confidence about other potential tipping elements. The **Atlantic thermohaline circulation** (THC) is a large-scale ocean circulation system driven by warm and salty surface water from tropical and subtropical

Figure 3.3 **Estimated global warming above 1990 level at which the onset of the events could occur and the potential scale of the impacts**



Note: Estimated temperature increase above 1990 level at which the various events could occur and an estimate of their impact. The impact scale has subjective qualifications — minor, notable, major and devastating — which were assigned on the basis of the geographical scale — from regional to continental and global — and the character of the damage — light, moderate, heavy or extreme. The level of scientific understanding for most of these events is low. The shapes and sizes of the ovals do not represent uncertainties in impact and threshold temperature, which may be significant.

Source: Lenton, 2008; PBL, 2009.

oceans that flows to the North Atlantic and then cools and sinks at high latitudes. It transports heat towards the Nordic Seas and thus contributes to milder winters in northern Europe compared to regions of similar latitudes in North America and Asia. Without this heat transport Europe would not only be much colder but also much drier. If the inflow of freshwater to the North Atlantic from rivers, extra precipitation or melting glaciers were to increase significantly, the density of the surface water would decrease. This could drastically reduce or even stop the deep-water formation that propels the THC. Simulations suggest that a THC collapse would increase sea level at European coasts by up to 1 m, in addition to global sea-level rise. A slow-down of the THC may counteract global warming trends in Europe but may have unexpected serious consequences for the behaviour of the world's climate system and exacerbate impacts elsewhere. There is no scientific consensus yet of a potential tipping point for a possible THC collapse.

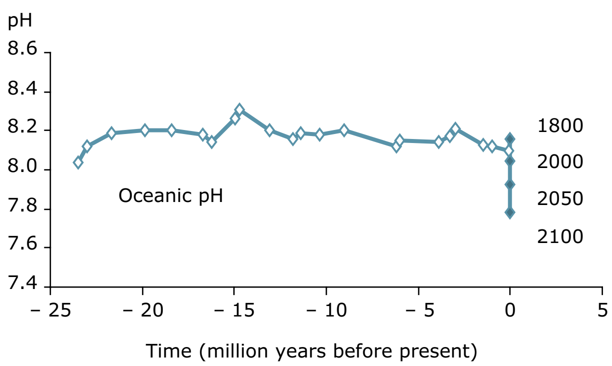
About one-third of the CO_2 emitted into the atmosphere from the burning of fossil fuel is absorbed by the oceans, resulting in acidification of oceans — lowering the pH — and a reduction in the concentration of carbonate ions (CO_3^{2-}) used for the shell of many marine organisms that are made of calcium carbonate. This has caused a decrease in surface ocean pH by an average of 0.1 units — from 8.2 to 8.1 — compared to pre-industrial levels, which is an increase in acidity by more than 30 % (Turley, 2006; CBD, 2009).

Near the surface, the ocean water is saturated with calcium carbonate used by marine organisms to build their shells and skeletons. Coral reef substrates, in shallow tropical waters along the shores of islands and continents, are mainly composed of calcium carbonate. Coral reefs have extremely high productivity and biodiversity. With increasing acidity of the ocean, the depth of the saturated zone decreases, that is, it becomes shallower, with detrimental effects on the formation of shells and coral.

Temperature-induced mass coral bleaching on a wide geographic scale started when atmospheric CO_2 levels exceeded 320 ppm. When CO_2 levels reached 340 ppm, sporadic but highly destructive mass bleaching occurred in most reefs worldwide, something more usually associated with El Niño events. At today's level of 387 ppm, most reefs around the world are committed to an irreversible decline.

The rate of change in ocean chemistry is very high, faster than previous ocean acidification-driven extinctions in Earth's history. Ocean acidification will continue in line

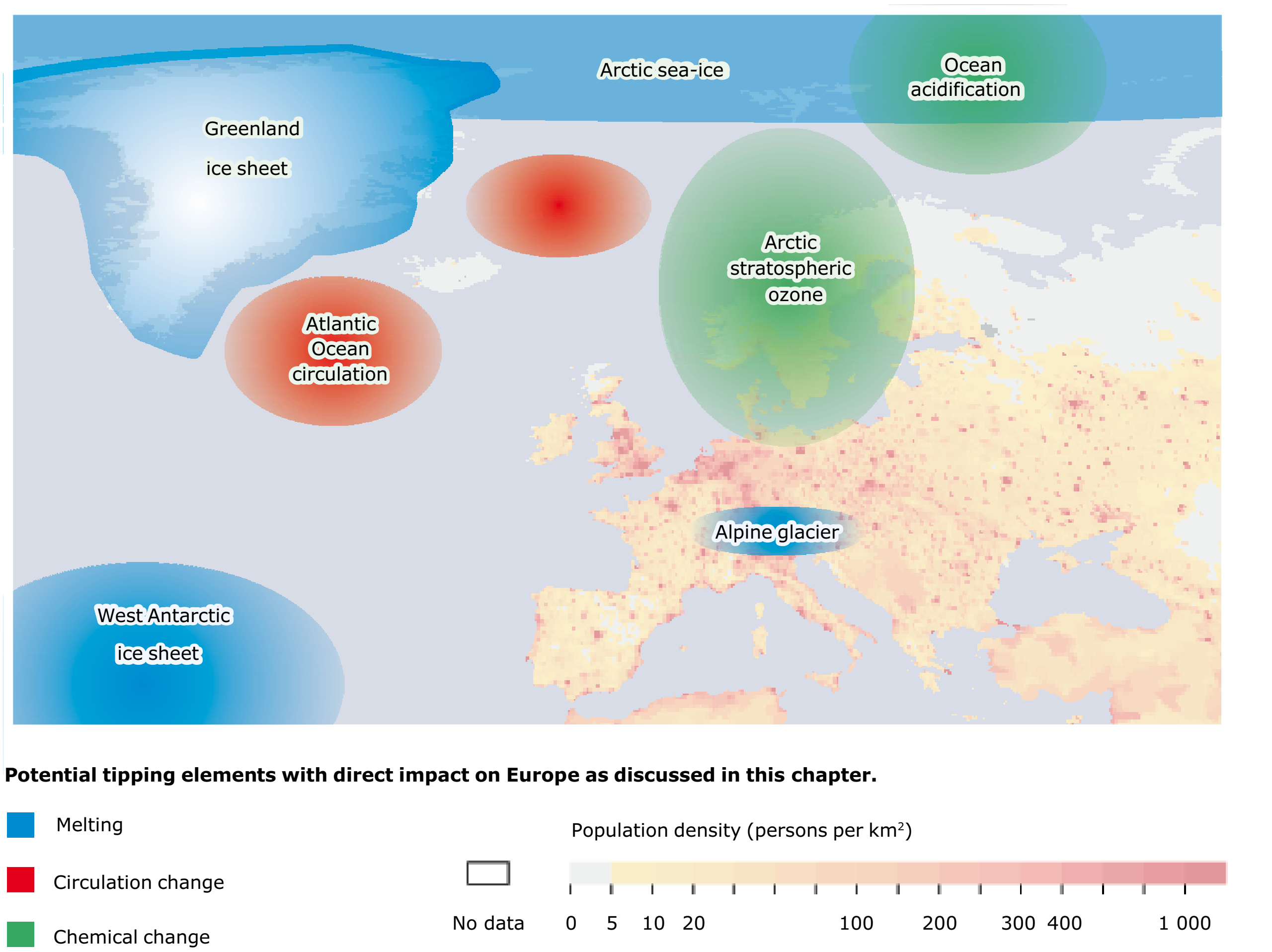
Figure 3.4 **Ocean acidity over the past 25 million years and projected to 2100**



Note: The pH is a measure of acidity — the lower the number the more acidic the ocean becomes. On a geological timescale, ocean pH has been relatively stable. Recently, oceans have been acidifying fast and this is projected to continue at a rate unprecedented for millions of years.

Source: University of Copenhagen, 2009; CBD, 2009.

Map 3.2 Potential tipping elements with direct impacts on Europe



Note: Colours on the land mass indicate population density.

Source: EEA, 2010b.

with increasing CO_2 concentrations in the atmosphere and if atmospheric CO_2 concentration were to reach 450 ppm, large areas of the polar oceans, especially the Arctic, would become corrosive to shells of key marine calcifiers. Mass bleaching of coral reefs, which currently has a 4–7 years return time in line with El Niño events, is expected to become an annual phenomenon. By 2100 pH could drop to 7.8, which corresponds to an increase in ocean acidity by 150 % compared to the pre-industrial pH of 8.2. The acidity of the ocean would be higher than at any time in the past 20 million years, and the increase in acidity would be at least 100 times faster than any change experienced in the marine environment over the past 100 000 years. Such a change could trigger an accelerated change in marine ecosystems that are already affected by global warming, pollution and (over)fishing (CBD, 2009; Veron et al., 2009).

Other tipping elements are the emission of CH_4 from permafrost melting and the destabilisation of methane hydrates in the ocean, and rapid degradation of large-scale ecosystems, such as a collapse of the Amazon rainforest and a boreal forest dieback. The understanding of these processes is as yet limited and the probability of major impacts in the current century is generally considered to be low.

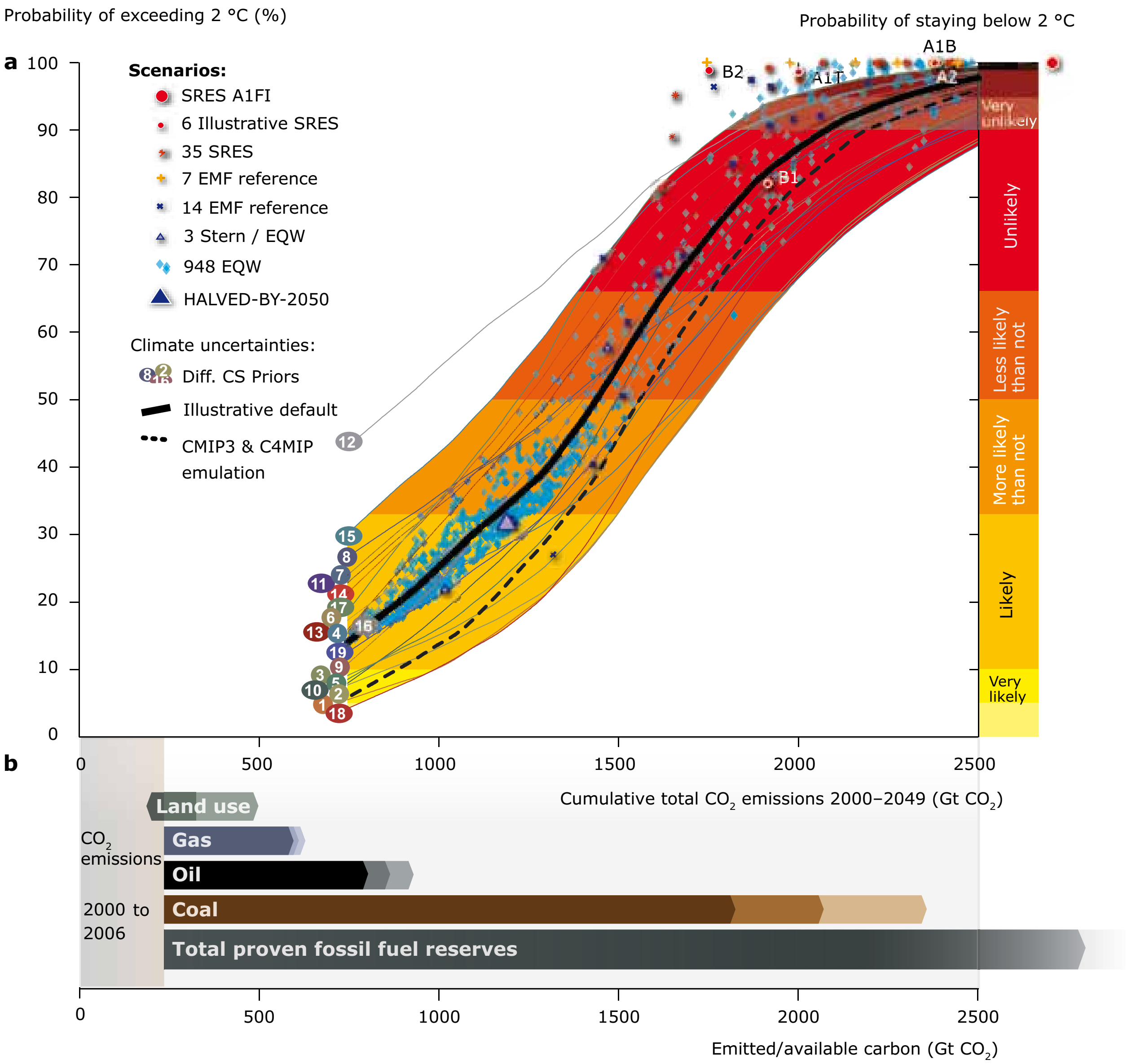
Detection of early warning signals of climate tipping points requires the development or improvement of climate monitoring systems. Detection of slowing down of variability before abrupt climate changes of the past offers a possible clue about tipping elements and thresholds. However, timely detection of threshold crossing is difficult because the observed phenomenon may be hidden for decades by natural climate variations.

3.3 Temperature and greenhouse gas concentration objectives

According to the IPCC (2007) and subsequent studies (PBL, 2009), the concentration of GHGs in the atmosphere would need to be stabilised at 445–490 ppm CO_2 equivalent — about 350–400 ppm CO_2 only — to have a 50 % chance of limiting global mean temperature increase to 2 °C above pre-industrial levels. To achieve this stabilisation, global emissions would need to peak at the latest in 2015–2020 and then decline by 50–80 % below 2000 levels by 2050.

Recent studies (Meinshausen et al., 2009) have shown that both cumulative emissions up to 2050 and emission levels in 2050 are robust indicators of the probability that 21st century warming will not exceed 2 °C above pre-industrial temperatures. Limiting cumulative CO_2 emissions over 2000–2050 to 1 000 Gt CO_2 would result in a 25 % probability that global warming exceeds 2 °C — and a limit of 1 440 Gt CO_2 in a 50 % probability. Global 2000–2006 CO_2 emissions were 234 Gt CO_2. Thus only less than half the proven economically recoverable oil, gas and coal reserves could be used up to 2050 to stay within these limits (assuming no carbon capture and storage). Halving

Figure 3.5 The probability of exceeding 2 °C global warming versus CO_2 emitted from 2000–2049



Note: a) Individual scenarios' probabilities of exceeding 2 °C for our illustrative default (dots; for example, for SRES B1, A2, Stern and other scenarios and smoothed (local linear regression smoother) probabilities for all climate sensitivity distributions (numbered lines). The proportion of CMIP3 AOGCMs and C4MIP carbon-cycle model emulations exceeding 2 °C is shown as black dashed line. Coloured areas denote the range of probabilities (right) of staying below 2 °C in AR4 terminology, with the extreme upper distribution (12) being omitted.
b) Total CO_2 emissions already emitted between 2000 and 2006 (grey area) and those that could arise from burning available fossil fuel reserves, and from land use activities between 2006 and 2049 (median and 80 % ranges).

Source: Meinshausen et al., 2009.

global GHG emissions by 2050, assuming 1990 as emission base year, would lead to an estimated 12–45 % probability of exceeding 2 °C.

To limit impacts and guide policy development, the Copenhagen Accord recognised a long-term climate limit of 2 °C global mean temperature increase, although without specifying the base year. The Accord also mentions the need for a review in 2015 to consider a possible goal of limiting temperature rise to 1.5 °C on the basis of new scientific insights.

The EU first proposed a temperature limit of not more than 2 °C above pre-industrial levels in 1996, which was reaffirmed subsequently by a number of Environment Councils and European Councils (EU, 1996; EC, 2008; EU, 2010). It was originally deduced from the evidence available at the time, including the temperature variation during the Holocene during which human civilization has developed, and from considerations of the adaptation rates of ecosystems. Significantly improved understanding of the vulnerability of societies and ecosystems to climate change has strengthened the scientific basis of this objective. However, the establishment of the political goal of limiting global warming to 2 °C also took into account technical feasibility and the cost of measures necessary to achieve the objective.

The EU has further stated in many Environment Council conclusions, for example in March 2010, that to stay below 2 °C requires GHG emissions to peak by 2020 at the latest and then be reduced by at least 50 % by 2050 compared with 1990 levels and continue to decline thereafter. In addition, the EU has stated that developed countries as a group, and the EU, should reduce their GHG emissions by 80 % to 95 % by 2050 below 1990 levels (see also the SOER 2010 mitigating climate change assessment (EEA, 2010c).

As shown above there are recent scientific indications that dangerous climate change, due to gradual climate change or to tipping phenomena, could even occur at temperature increases below 2 °C. Some experts and countries are therefore promoting lower stabilisation objectives, for example, limiting global warming to 1.5 °C above pre-industrial levels or limiting CO_2 concentration to 350 ppm (Hansen et al., 2008) which is below the current CO_2 concentration of 387 ppm. Achieving such low stabilisation would require substantial technical and socio-economic changes worldwide since it would imply a reduction in GHG emissions of at least 80 % globally by 2050 and negative emissions thereafter. Negative emissions imply that CO_2 removal is greater than CO_2 emissions, which can only be achieved by large-scale enhancement of global carbon sinks, for example by afforestation, combined with a carbon-free global energy system.

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