1 Introduction

1.1 Purpose and scope

Recent decades have seen notable changes in global and European climate. Sea levels and temperatures are rising, precipitation is changing, and the intensity and frequency of weather extremes in many regions is increasing.

This report presents an indicator-based assessment of recent and projected climate changes and their impacts in Europe. Its objectives are to:

- present past and projected climate change and its impacts through easily understandable, scientifically sound and policy-relevant indicators;
- identify the sectors and regions most vulnerable to climate change with a high need for adaptation;
- increase awareness of the need for global, EU and national action on both mitigation (to achieve the EU global temperature target) and adaptation;
- highlight the need to enhance monitoring, data collection and dissemination, and reduce uncertainties in climate and impact modelling.

The aim is to provide short but comprehensive indicator information covering all the main impact categories, where feasible across Europe (EEA's 32 member countries). However, for categories for which no Europe-wide data were available, indicators have in some cases been developed and presented for smaller scales, providing data was available for at least several countries.

The report updates a previous EEA report on climate change impacts in Europe (2004). It is intended for a broad audience consisting of policy-makers at the EU and national and sub-national level, and the interested public and non-governmental organisations (e.g. environmental, businesses).

1.2 Background and policy framework

The consequences of climate change include an increased risk of floods and droughts, losses of biodiversity, threats to human health, and damage to economic sectors such as energy, forestry, agriculture, and tourism. In some sectors, some new opportunities may occur, at least for some time, although over a longer period and with increasing temperatures, effects are likely to be adverse worldwide if no action is taken to reduce emissions or adapt to the consequences of climate change.

The United Nations Framework Convention on Climate Change (UNFCCC) came into force in 1994. Its ultimate objective is 'to achieve stabilisation of greenhouse gas concentrations in the atmosphere at

Box 1.1 IPCC Fourth Assessment (2007)

The 2007 Fourth Assessment Report from the UN Intergovernmental Panel on Climate Change (IPCC) 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' (IPCC Synthesis Report, SPM, 2007).

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 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' (IPCC Synthesis Report, SPM, 2007).

a level that would prevent dangerous anthropogenic interference with the climate system'. To avoid 'dangerous climate change' the EU has proposed a target of a maximum global temperature increase of 2 °C above the pre-industrial level. This will require global emissions to stop rising within the next 10 to 15 years and then to be reduced to less than 50 % of 1990 levels by 2050. Within UNFCCC an international post-2012 international agreement is being negotiated, with the aim of reaching an agreement at the climate conference planned in Copenhagen at the end of 2009.

However, there is growing awareness that, even if GHG emissions were stabilised today, increases in temperature and associated impacts will continue for many decades. Even if the EU target is achieved, the global warming already incurred and embedded in unavoidable economic development will lead to climate change impacts to which countries worldwide will need to adapt. Within the UNFCCC and other UN organisations increasing attention is being given to climate change adaptation, especially in developing countries, since these, often poor, countries will suffer the earliest and most damaging effects, even though their GHG emissions are low and thus have contributed least to the problem (UNDP, 2007).

The most vulnerable regions and sectors vary across Europe, but the need to adapt to climate change has been recognised in all countries. The European Commission's Green Paper on Adaptation (2007) started the EU adaptation policy process, and actions are already taking place at the national level. A Commission White Paper on adaptation will be published by the end of 2008. Integration of climate change into other EU and national policy areas is already taking place, e.g. the Water Framework Directive (aimed at improving water quality), the Floods Directive (aimed at reducing damage from floods) and the European Commission's Communication on Water Scarcity and Droughts.

Policy-makers and the public need reliable information, and a key challenge is to further develop the scientific understanding of climate change and impacts on a regional scale so that the best possible adaptation options can be developed and deployed. Some countries are developing or have finalised national vulnerability assessments and/or national adaptation plans. However, more vulnerability and adaptive capacity assessments across key economic sectors and environmental themes are needed. There is very little quantified information on adaptation costs and further work is needed to facilitate informed, cost-effective and proportionate adaptation in Europe. There are many EU and national projects on climate change impacts, vulnerability and adaptation. However results from such research programmes have often not been fully shared with policy-makers and other stakeholders in a form that they can understand. There is a need for more projects that can help provide the right policy guidance and tools and which will help to build effective trans-national and sub-national networks.

The European Environment Agency, the Commission's Joint Research Centre and the World Health Organization (European office) have therefore joined forces to prepare this report. The Agency also cooperated closely with several of its European topic centres (ETCs), including the ETC on Air and Climate Change; the ETC on Water and the ETC on Biological Diversity.

The report presents results of key recent national and EU-wide research activities (FP5-7 projects) and also builds on the fourth assessment of the IPCC (2007), and other recent key international assessments, including the Arctic Climate Impact Assessment (2004, and its 2007 follow-up) and UNEP's Global Outlook for Ice and Snow (2007). The report also uses information from national assessments from various European countries. The main added value compared to these other reports is the inclusion of the most recent scientific information and the specific focus on Europe.

Compared with the previous (2004) EEA indicator report, this report includes a number of additional indicators, while some of the previous indicators have not been retained, for various reasons including the insufficiently clear relevance of the indicator regarding impacts of climate change.

All indicators are also available on the web through the EEA web site indicator management system. This will allow easy regular updating on the web of those indicators for which regular (possibly annual) new data becomes available and for which trends are changing significantly in a relatively short period of a few years.

1.3 Outline

Chapter 2 sets out the scientific background of climate change, its causes and its impacts. It also provides an overview of the linkages between the various indicator categories.

Chapter 3 provides an introduction and brief overview of observed climate change in Europe.

Chapter 4 gives an overview of projected climate change and also discusses possible irreversible climate change with large potentially catastrophic risks. It also includes some background on climate-change scenarios and projected climate-change indicators.

The main part of the report is in Chapter 5. The state of climate change and its impacts in Europe are described by means of about 40 indicators, divided into eight different categories:

- Atmosphere and climate;
- Cryosphere (glaciers, snow and ice);
- Marine biodiversity and ecosystems;
- Water quantity;
- Freshwater quality and biodiversity;
- Terrestrial ecosystems and biodiversity;
- Soil;
- Agriculture and forestry;
- Human health.

The indicators in Chapter 5 provide selected and measurable examples of climate change and its impacts, which are already showing clear trends in response to climate change. Mainly indicators for which data are available for about 20 years have been selected, although in some cases this period was shorter and the reasons for including the indicator are explained. The responses of the selected indicators can be understood as being representative of the more complex responses of the whole category. Furthermore, the results can give an indication of where, to what extent and in which sectors Europe is vulnerable to climate change, now and in the future. Each indicator is presented in a separate sub-chapter containing a summary of the key messages, an explanation of the relevance of the indicator for the environment, society and policy, a short description of main uncertainties, and analysis of past, recent and future trends.

Chapter 6 discusses climate change adaptation strategies and actions and reviews current experience.

Chapter 7 addresses the effects of climate change on economic sectors, based on the limited knowledge available. Complete Europe-wide information is available for almost no sectors, so information for many sectors is therefore provided either from only a few countries or over a relatively limited period.

Finally, Chapter 8 evaluates the causes of uncertainties and discusses data availability and quality. It also proposes potential indicators which could broaden future climate impact assessments, given appropriate monitoring and data.

2 The climate system and human activities

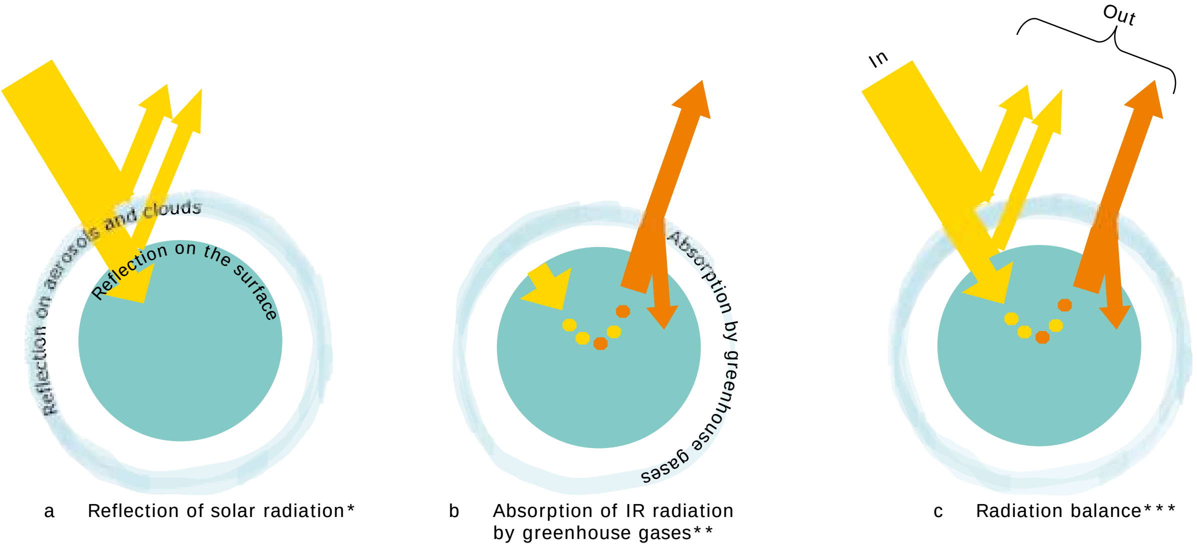
2.1 Introduction

The earth's climate is changing. More changes are foreseen, having many effects. Climate change has drawn much attention from scientists, policymakers and the general public and has hit the headlines of newspapers around the world. The Intergovernmental Panel on Climate Change received the Nobel Prize. People have come to realise that they are responsible for climate change and that it is very likely to have significant effects on the way future generations live.

The climate can be described in terms of the temperature at the earth's surface, the strength of the winds and ocean currents and the presence of clouds and precipitation, and has relationships with many aspects of the earth like sea level, snow cover and the biosphere. Climate can be described as weather averaged over a large geographical area and often over a long time-period, but information about events that deviate from the average ('extreme events') is also important.

The climate system evolves in time as a result of many factors including the amount of energy that the earth receives from the sun in the form of radiation. There are two main ways by which the amount of radiation that reaches the earth's surface and is absorbed changes. First, it depends on the amount of incoming radiation, which depends on the position of the earth with respect to the sun and the sun's activity. Second, it depends on the composition of the earth's atmosphere. Certain atmospheric constituents, like aerosols (i.e. smoke, dust and haze) and clouds, prevent solar radiation from reaching the surface by reflecting it back into space (Figure 2.1a). Finally, very bright surfaces on the earth, like snow and ice fields, reflect light. The fraction of the incoming radiation that is eventually absorbed by the surface will heat up the earth; the increased temperature will set the atmosphere into motion, creating winds, clouds

Figure 2.1 The 'greenhouse effect'



a Reflection of solar radiation*

b Absorption of IR radiation by greenhouse gases**

c Radiation balance***

Note:
* Incoming solar radiation is partly reflected by aerosols and clouds in the atmosphere and by the surface of the earth and partly absorbed by the earth surface.
** Heat radiating from the earth's surface in the form of infrared radiation will be partly absorbed by greenhouse gases in the atmosphere.
*** When the incoming radiation equals the outgoing radiation for several hundreds of years, the earth surface reaches a constant mean temperature.

Source: Produced by Frank Raes (Joint Research Centre (JRC)) for this report.

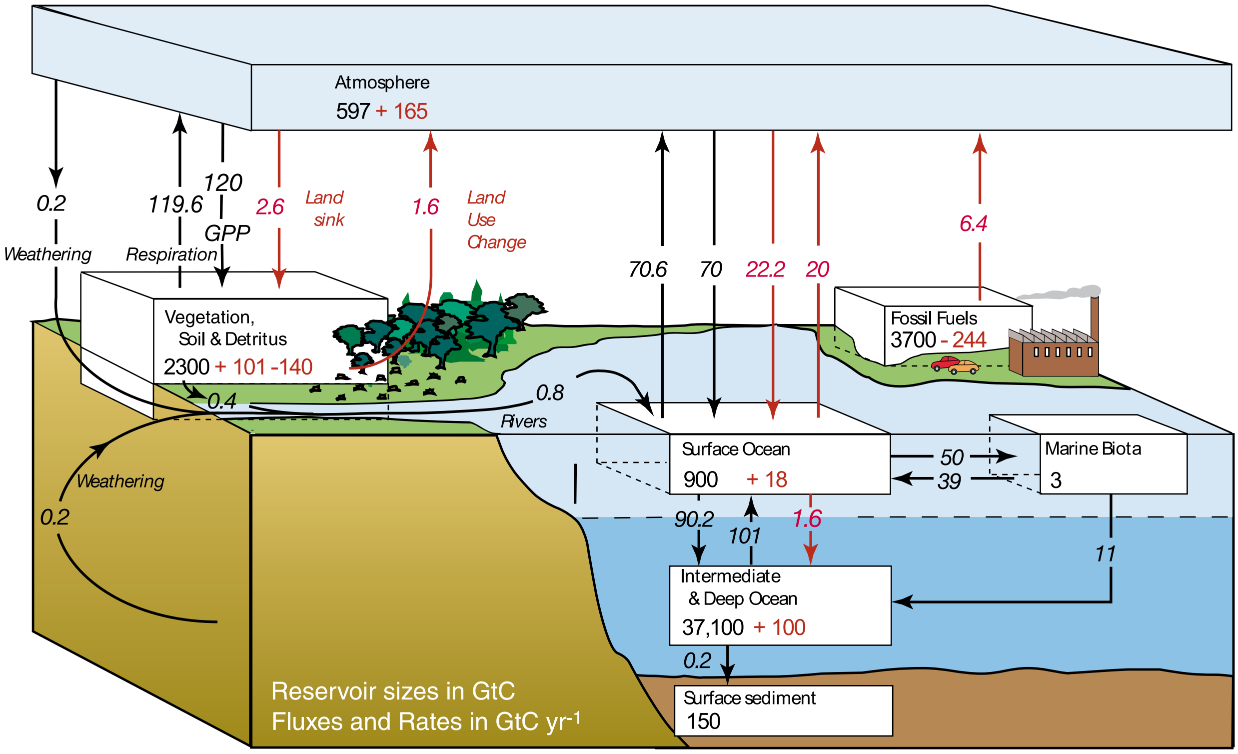
and precipitation, and will also help to maintain the currents in the oceans.

Invisible infra-red radiation from the earth has to pass again through the atmosphere before it is lost to space. Gases like water vapour, carbon dioxide, methane and others absorb this radiation partly, and therefore keep the heat in the system (Figure 2.1b). These are called greenhouse gases, because they act in a way somewhat similar to the glass of a greenhouse. The earth, like a greenhouse, will have a constant 'equilibrium' temperature when the amount of radiation that comes in equals the amount of radiation that goes out (Figure 2.1c). If, however, the amount of greenhouse gases and aerosols change, then the temperature also changes.

The chemical composition of the atmosphere is controlled by natural processes like volcanic eruptions, and human activities like fossil-fuel burning. Both natural and human processes drive the exchange of specific substances, like water, carbon (see Figure 2.2), nitrogen, and sulphur, between the atmosphere, the oceans and land. It is important to understand these cycles in order to understand climate change and how it will develop.

The complex interactions between the cycling of substances, radiation and other processes lead to feedback loops. These can either amplify (positive feedback) or dampen (negative feedback) the increase in atmospheric greenhouse gas concentrations and temperature. An example of a negative feedback is more CO_2 in the air favouring the growth of vegetation, leading to a larger uptake by that vegetation of CO_2 from the atmosphere. An example of a positive feedback is a warming of the ocean enhancing the transfer of CO_2 from the ocean to the atmosphere, leading to an additional greenhouse effect and further warming. Warming will also lead to more evaporation of water from the ocean, and since water vapour is a greenhouse gas, this will amplify the initial warming. This is an important mechanism that will amplify, indeed nearly double, any initial global warming, including that caused by man. Another positive feedback is the possible melting of soils which are currently permanently frozen, e.g. in Siberia or

Figure 2.2 The global carbon cycle for the 1990s



Note: The atmospheric CO_2 concentration is the result of many processes that produce and/or remove CO_2. These are part of the carbon cycle, which describes the cycling of carbon through the various compartments of the earth system. During the past 10 000 years until about 150 years ago, the atmospheric CO_2 concentration has been roughly constant. Since then the burning of fossil fuels and man-made forest burning (red arrows) have led to a steady increase in the concentration of CO_2, an enhancement of the greenhouse effect and climate change.

Source: Denman *et al.*, 2007. Published with the permission of the Intergovernmental Panel on Climate Change.

Northern Canada. When this happens, methane, which is trapped in these soils, will be released and cause even more warming. A further example is the melting of ice and snow by increases in temperature. This reduces the reflectivity of the earth's surface, increasing the absorption of incoming solar light, leading to even more warming.

Looking at the 4.5-billion-year history of the earth, a constant temperature has been an exception rather than a rule. The global mean temperature of the Earth has always been changing, because of natural variability, i.e. changes in the natural factors mentioned above.

2.2 The past 800 000 years

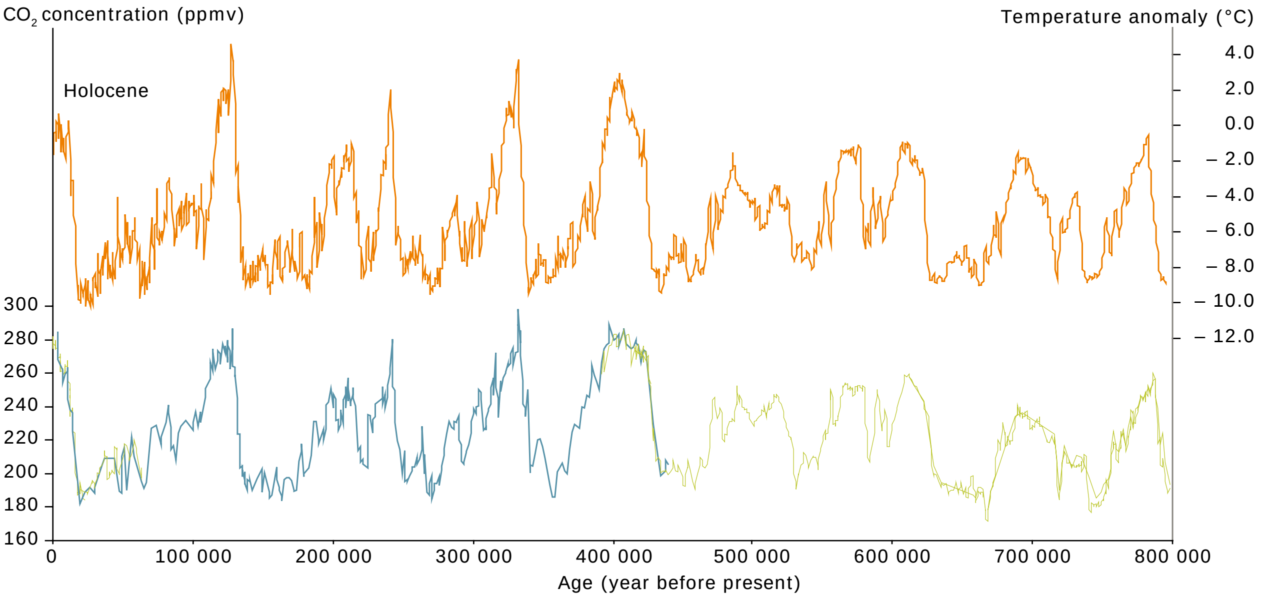
Figure 2.3 shows that the climate on earth has been oscillating about every 100 000 years between glacial periods, during which the global mean temperature was about 5 °C lower than today, and inter-glacial periods, during which the global mean temperature was about equal to that of today. These transitions were triggered by predictable changes in the position of the earth's axis with respect to the sun, followed by mechanisms within the earth system which can amplify the initial changes. The oscillations in global mean temperature between ice ages and inter-glacial periods correspond with changes in the carbon dioxide concentration as expected from the greenhouse effect.

2.3 The past 10 000 years until 150 years ago

The earth is currently in an inter-glacial period that started about 10 000 years ago. A range of observations, including ice-cores and tree rings, have shown that the concentrations of greenhouse gases and aerosols in the atmosphere have been relatively stable during this period (left end of Figure 2.3). The rate of CO_2 production in the atmosphere, through natural processes such as respiration by vegetation and soils, natural fires, respiration from marine vegetation, and volcanism, has been roughly equal to the rate of CO_2 removal, through photosynthesis by terrestrial vegetation and uptake by the oceans. The atmospheric CO_2 concentration has therefore been constant. It is likely that this stable climate triggered the development of agriculture and consequently the building of permanent settlements and civilization.

Over the past 1 300 years the northern hemisphere mean temperature stayed within a range of only

Figure 2.3 **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, i.e. the present inter-glacial (left end of the graph) is very stable.

Source: Lüthi *et al.*, 2008.

0.5 °C (Figure 2.4). Variability within that range is explained by changes in the output of the sun, volcanic eruptions emitting large amounts of dust particles into the atmosphere, and natural variations in the exchange of carbon dioxide between atmosphere, oceans and biosphere.

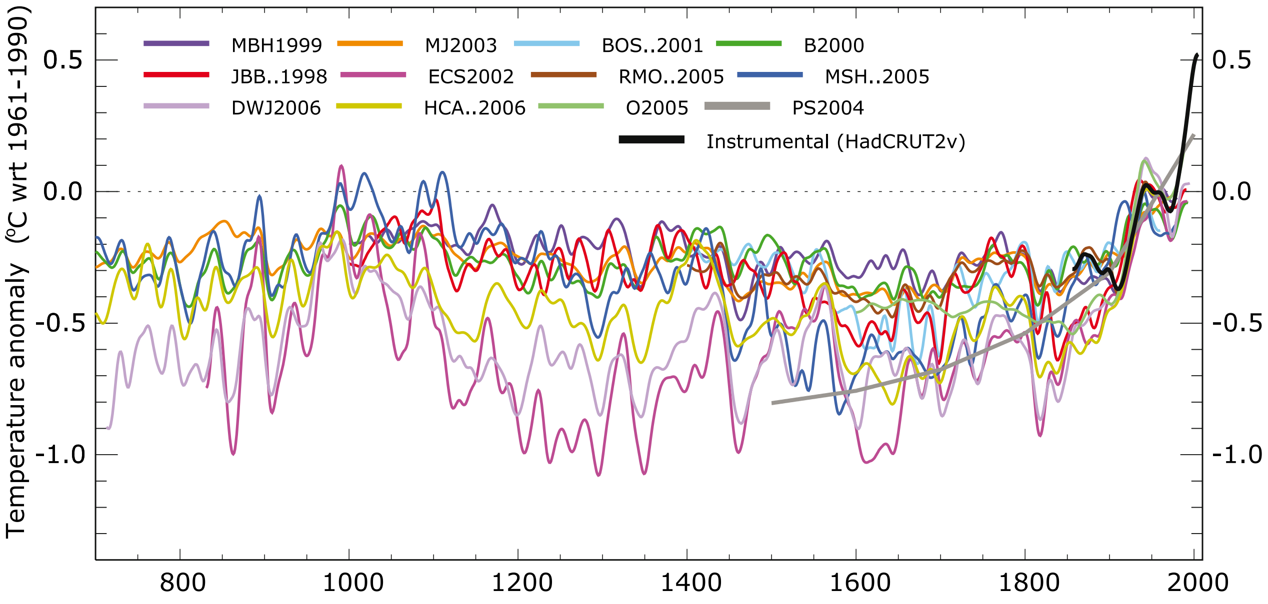
2.4 The past 150 years

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 and the use of synthetic fertilisers, have increased emissions and the atmospheric concentration of both (warming) greenhouse gases and aerosol particles (some of which have a cooling effect), resulting in a very clear net effect of warming.

During the past 150 years many climate variables have changed, like temperature, precipitation, and extremes (see Section 5.2). Figures 2.4 and 2.5 show the exceptional increase in temperature, especially during the past 50 years, together with the observed sea-level rise and change in snow cover. The Intergovernmental Panel on Climate Change concludes in its fourth assessment report (IPCC, 2007) that: '(there is) a very high confidence (i.e. 90 % certainty) that the globally net effect of human activities since 1750 has been one of warming'. The report shows that the recent temperature increase was triggered mainly by man-made CO_2 and other greenhouse gas emissions. Nature plays a certain role, but there are insufficient natural changes to explain the changes. This has led scientists to define a new geological epoch: the Anthropocene (Crutzen *et al.*, 2000).

The CO_2 concentration in the atmosphere has now reached a level of 387 ppm. According to the ice records this is well above the regular level of the past 800 000 years. Global mean temperature might have been somewhat higher at times during the past 800 000 years than today, but projections of CO_2 and global mean temperature to the end of the century push the earth system, and humanity with it, definitely out of the regular patterns and into uncharted terrain.

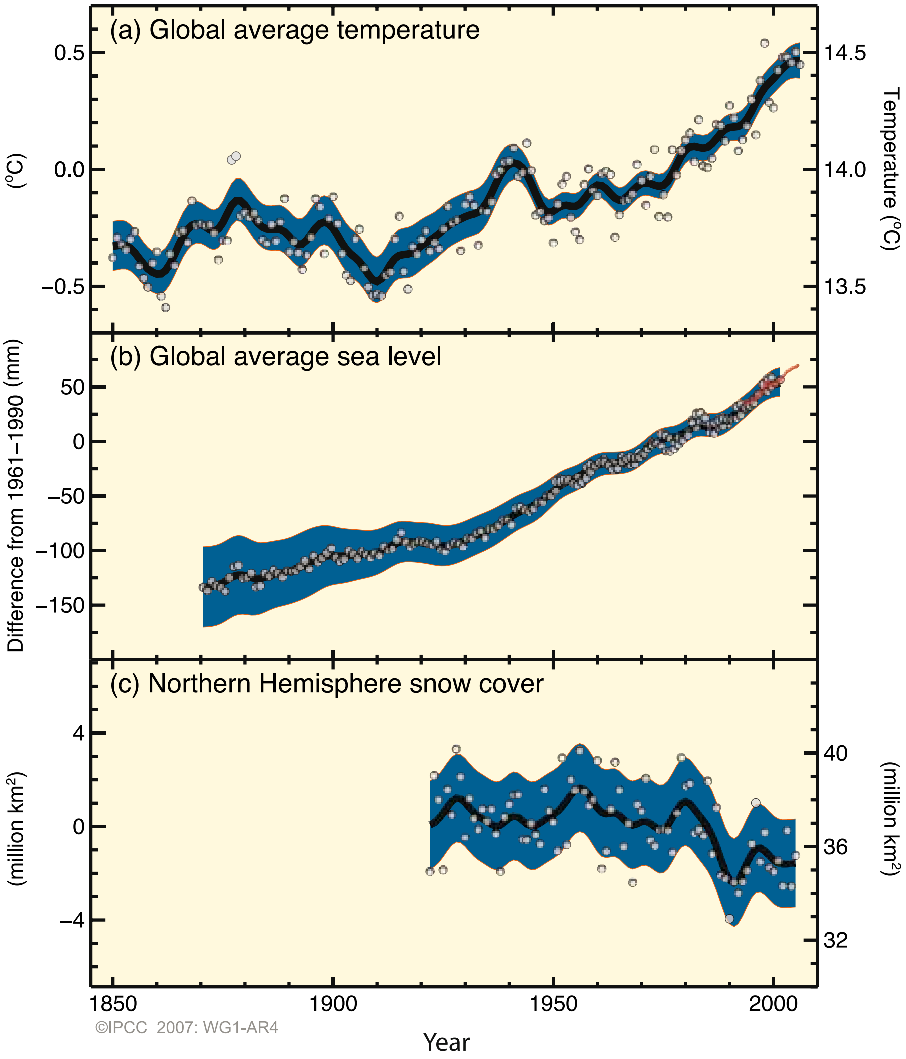
Figure 2.4 Records of northern hemisphere temperature variation during the last 1 300 years



Note: Based on 12 reconstructions using multiple climate proxy records shown in colour (e.g. ice-cores, lake sediments, tree-rings, etc.). Instrumental records are shown in black. All temperatures represent anomalies (°C) from the 1961 to 1990 mean.

Source: Jansen *et al.*, 2007. Published with the permission of the Intergovernmental Panel on Climate Change.

Figure 2.5 **Observed changes in (a) global average surface temperature, (b) global average sea level and (c) northern hemispheric snow cover for March–April**



Note: All changes are relative to the period 1961–1990. Circles show yearly average values, smoothed curves are based on 10-year averaged values and shaded area show the uncertainty.

Source: IPCC, 2007. Published with the permission of the Intergovernmental Panel on Climate Change.

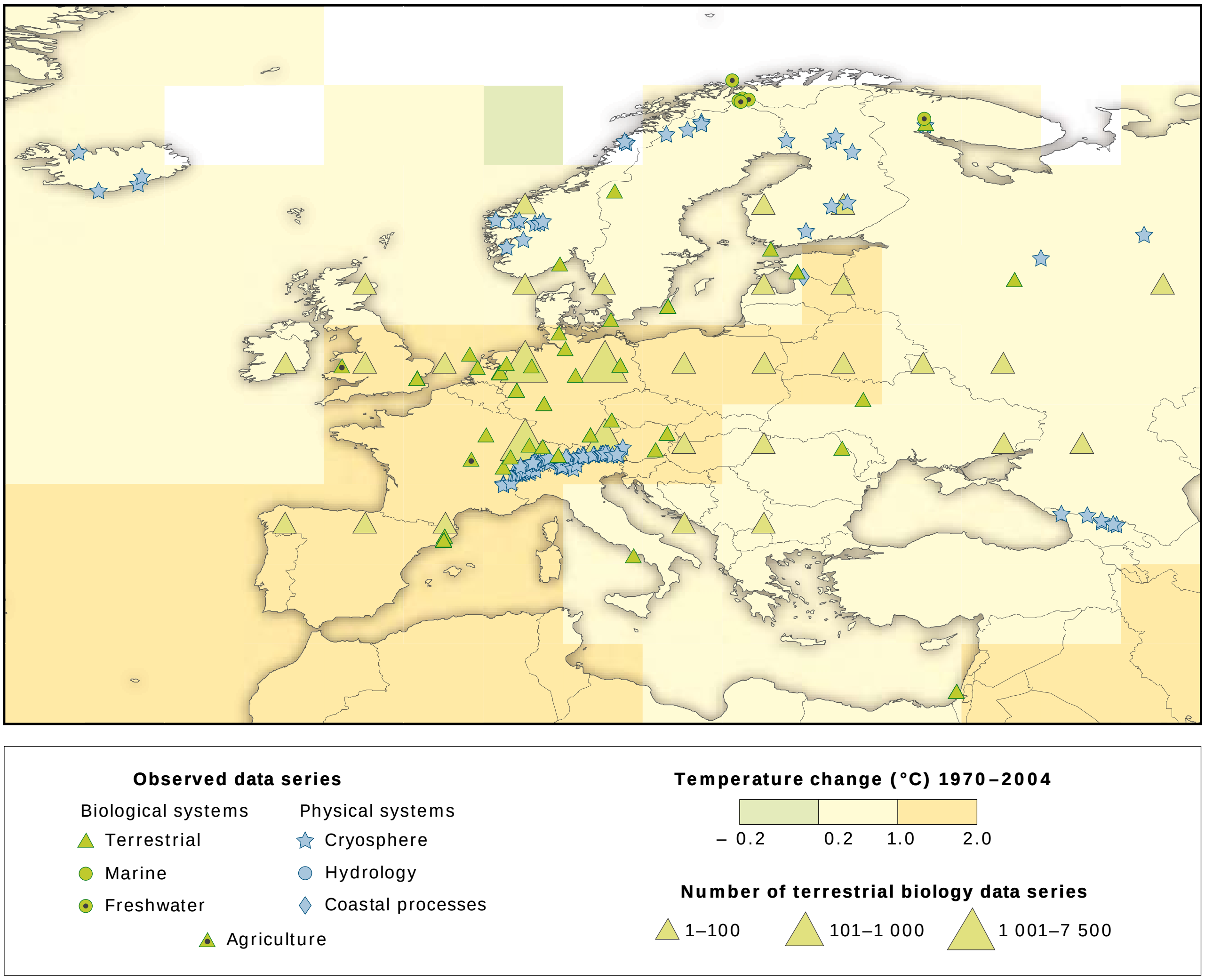
3 Observed climate change impacts

More and earlier impacts of climate change have been observed in many parts of the world (Map 3.2) and understanding of these impacts has increased. Changes in biological and physical systems have also been observed in Europe, 89 % and 94 % of which, respectively, are consistent with those expected as a result of warming (IPCC, 2007b). The impacts vary across regions and sectors (Map 3.1).

The impacts are presented in detail in the main body of this report, in terms of observed and projected impacts.

The change in atmospheric composition and the resulting climate change have a cascade of impacts with many linkages (see Figure 3.1 for some selected aspects of the whole cascade). Many impacts

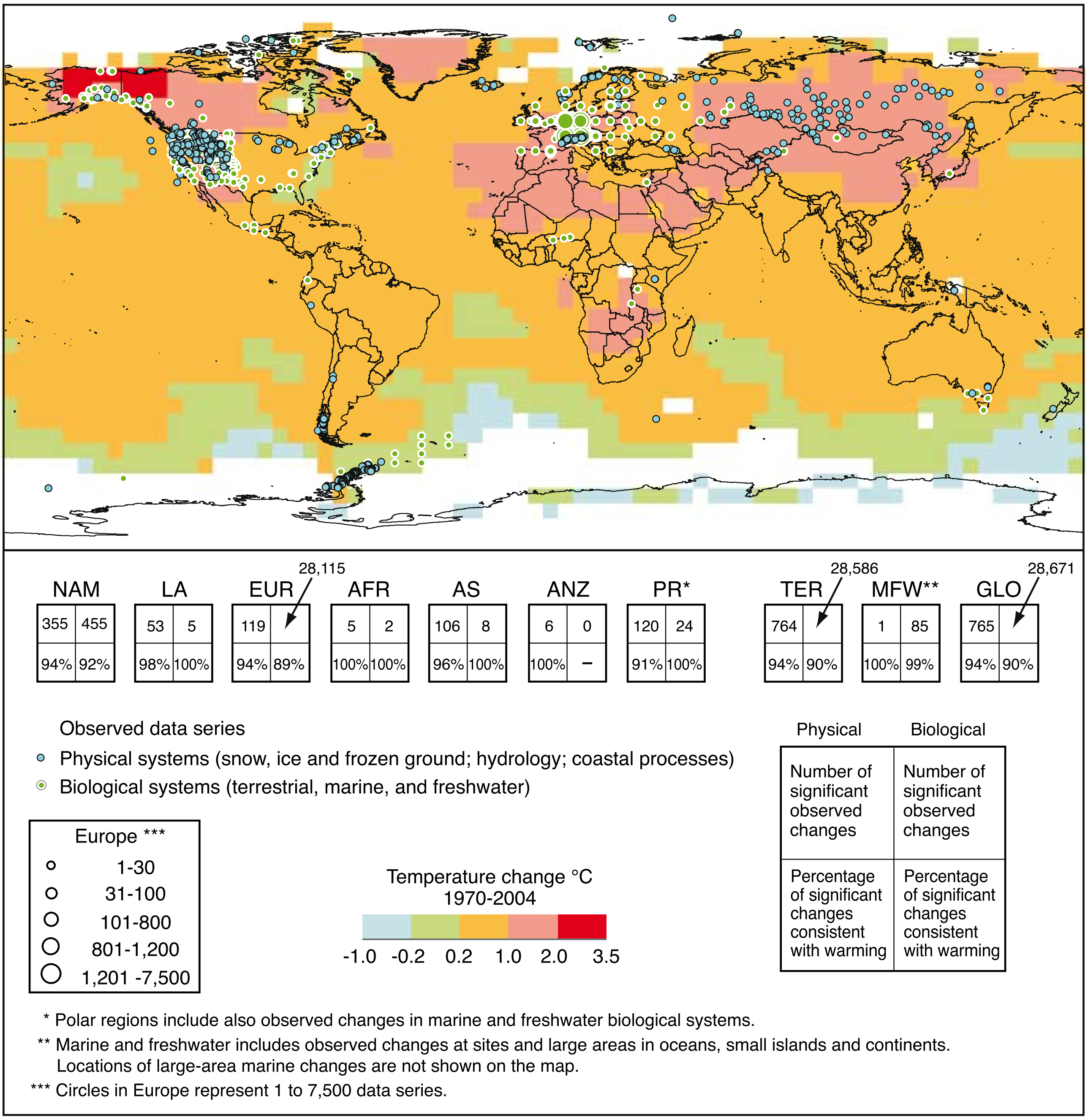
Map 3.1 Locations of significant changes in physical and biological systems in Europe between 1970–2004



Note: Presented together with the surface air temperature changes in Europe during the period 1970–2004. Most of the changes are consistent with the observed warming. Based on IPCC Working Group II Fourth Assessment Report Chapter 1.

Source: Rosenzweig *et al.*, 2008, based on Rosenzweig *et al.*, 2007.

Map 3.2 Locations of significant changes in data series of physical and biological systems, shown together with surface air temperature changes over the period 1970–2004



* Polar regions include also observed changes in marine and freshwater biological systems.

** Marine and freshwater includes observed changes at sites and large areas in oceans, small islands and continents. Locations of large-area marine changes are not shown on the map.

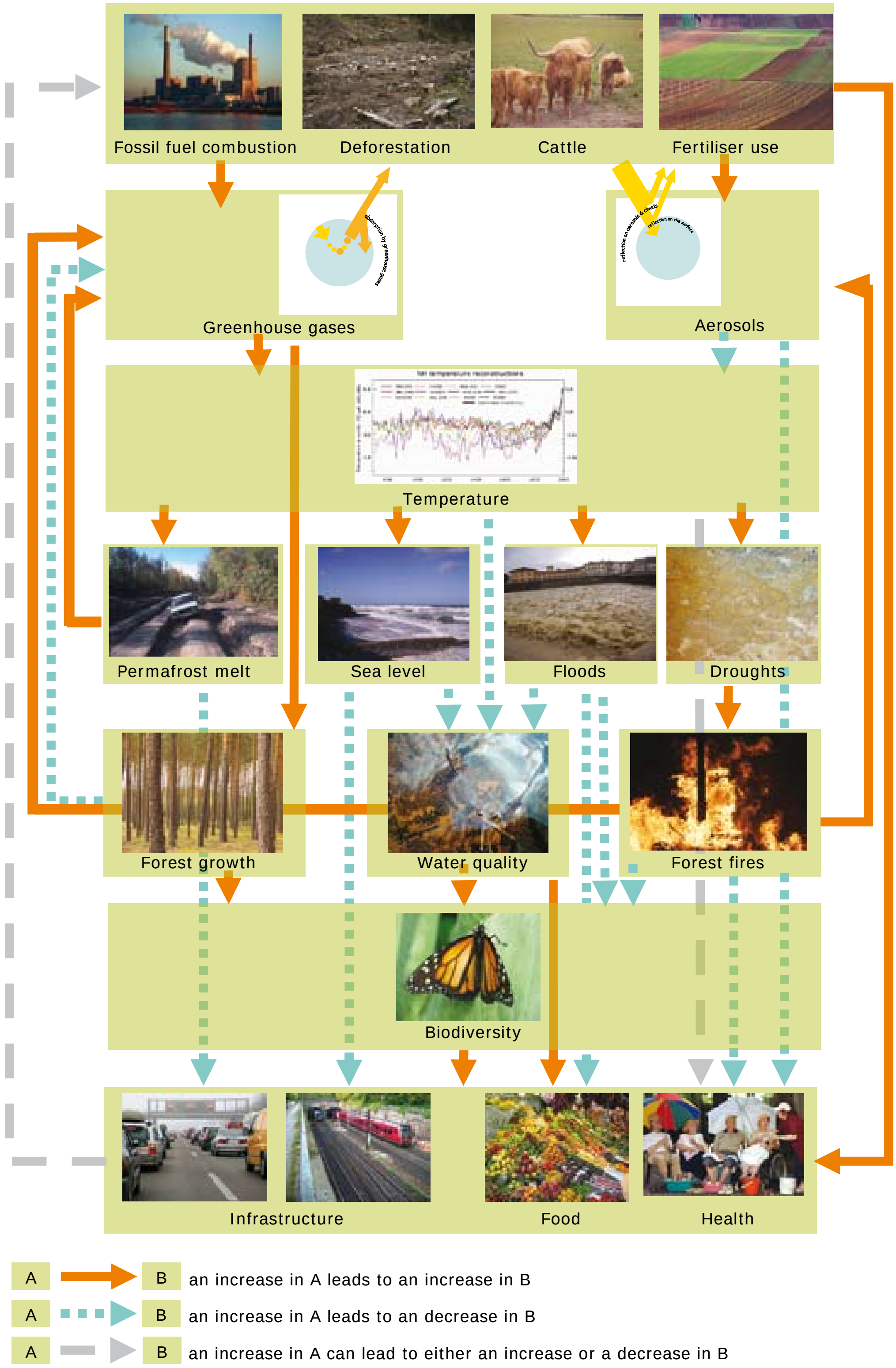
*** Circles in Europe represent 1 to 7,500 data series.

Note: Based on HadCRUT3 data. A subset of about 29 000 data series was selected from about 80 000 data series from 577 studies. These met the following criteria: (1) ending in 1990 or later; (2) spanning a period of at least 20 years; and (3) showing a significant change in either direction, as assessed in individual studies. Note that 28 000 of the 29 000 data series are from European studies. White areas do not contain sufficient observational climate data to estimate a temperature trend. The 2 x 2 boxes show the total number of data series with significant changes (top row) and the percentage of those consistent with warming (bottom row) for (i) continental regions: North America (NAM), Latin America (LA), Europe (EUR), Africa (AFR), Asia (AS), Australia and New Zealand (ANZ), and Polar Regions (PR) and (ii) global-scale: Terrestrial (TER), Marine and Freshwater (MFW), and Global (GLO). The numbers of studies from the seven regional boxes do not add up to the global (GLO) totals because numbers from regions except Polar do not include the numbers related to Marine and Freshwater (MFW) systems. Locations of large area marine changes are not shown on the map.

Source: Parry *et al.*, 2007. Published with the permission of the Intergovernmental Panel on Climate Change.

and linkages are now increasingly confirmed by observations such as those presented in this report. Figure 3.1 also shows the existence of positive and negative feedback loops. The main relevant indicators of climate change impacts in Europe are presented in Chapter 5.

Figure 3.1 Selected relationships between climate change impacts included in this report



Note: The availability of cheap fossil fuels and the mass production of food has led directly to a higher quality of life, improved health, and better infrastructures. (orange arrows to the right). However fossil-fuel use (in electricity generation, transport, heating, and industry), deforestation, and agriculture emit greenhouse gases leading to climate change with several impacts and positive and negative feedbacks (various orange and blue arrows). A successful global warming mitigation policy would be a negative controlling feedback (grey arrow to the left), however also adaptation actions are needed in vulnerable sectors and regions.

Source: Produced by Frank Raes (Joint Research Centre (JRC)) for this report.

4 Climate change impacts: what the future has in store

4.1 Scenarios

Because of the better understanding of observed climate change and processes and feedbacks, the future impacts and associated risks can now be assessed systematically for different sectors and regions and different levels of projected increases in global annual average temperatures (IPCC, 2007b).

Both worldwide and for Europe, recent assessments of climate change impacts are mostly based on the Special Report on Emissions Scenarios (SRES) (Nakićenović *et al.*, 2000) (see Box 4.1). These scenarios describe different ways in which the world may develop. Note that all these scenarios are without explicit climate policies.

The projected changes in temperature and precipitation 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.

Note that many of the indicators included in this report show the projected impacts for Europe for the A1B, A2, B1 or B2 scenarios. Differences in the projected changes in temperature and precipitation (and associated impacts) are also due to the use of different climate models. In general, climate models are based on well-established physical, chemical and biological principles and have been demonstrated to reproduce observed features of recent climates and past climate change. However, climate models differ in complexity and assumptions. As a result, climate projections can differ considerably, especially on the regional scale and also over the seasons. Furthermore, confidence in the projections is higher

Box 4.1 The IPCC Special Report on Emissions Scenarios (SRES)

A1. The A1 scenario family describes a future world of very rapid economic growth, global population that peaks in the mid-century and declines thereafter, and a rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 family develops into three groups that describe alternative directions of technological change in the energy system, distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (**A1B**) (where balanced is defined as not relying too heavily on one particular source, on the assumption that similar improvement rates apply to all energy-supply and end-use technologies).

A2. The A2 family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than in other scenarios.

B1. The B1 family describes a convergent world with the same global population, which peaks in the mid-century and declines thereafter, as in A1, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in B1 and A1. While these scenarios are also oriented towards environmental protection and social equity, they focus on local and regional levels.

Source: IPCC, 2001.

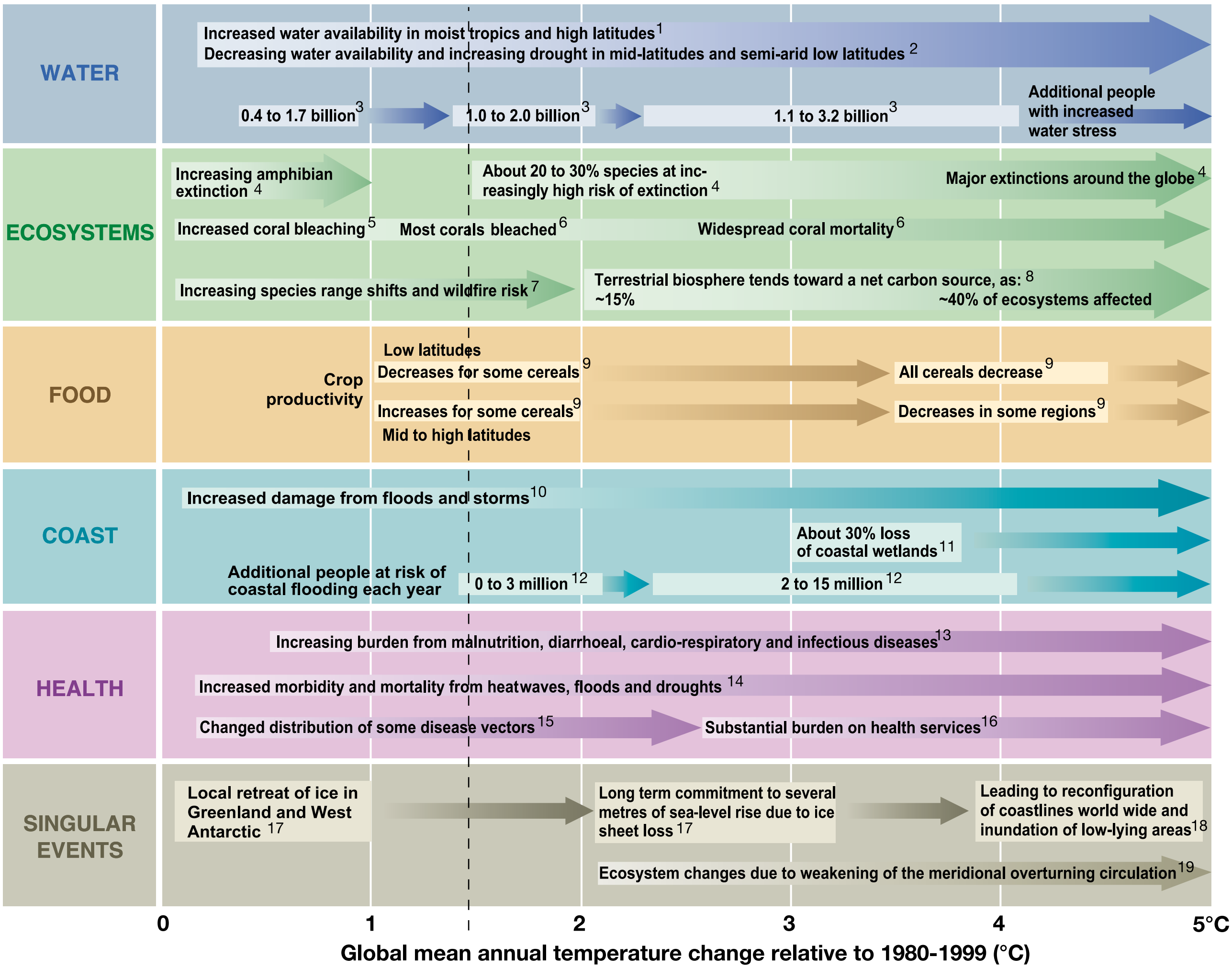
for some climate variables (e.g. temperature) than for others (e.g. precipitation) (IPCC, 2007a). The uncertainties in climate modelling, in particular for Europe and for the indicators presented in this report, are explained in more detail in Chapter 8.

4.2 Projected global climate change impacts

Water, ecosystems, food, coastal areas and health are key vulnerable sectors in the world with increasing impacts at increasing projected temperature levels (see Figure 4.1). The kind of dominant impacts and associated risks are different in different regions (Figure 4.2). From a global perspective, the most vulnerable regions are in the developing world, which has the lowest capacity to adapt. Impacts in those regions are likely to have spill-over effects for Europe, through the interlinkages of economic systems and migration. These effects have not been quantified and are not further discussed in this report.

To limit impacts and guide policy development, the EU has adopted a long-term climate goal of

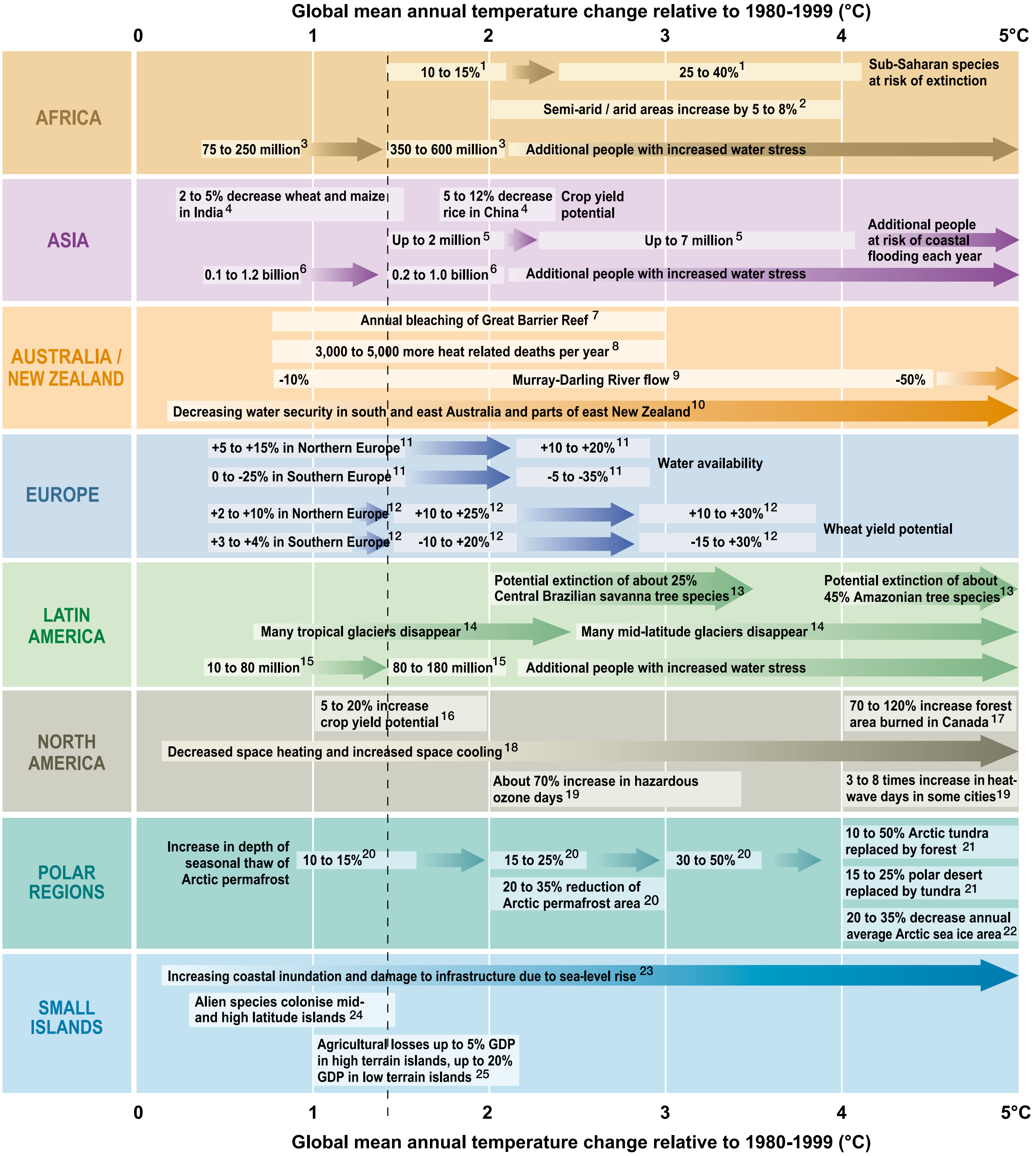
Figure 4.1 Examples of global impacts in various sectors projected for changes in climate associated with different amounts of increase in global average surface temperature in the 21st century



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 indicates the EU objective of 2 °C maximum temperature increase above pre-industrial (or 1.5 °C above 1990 levels). Numbers in superscripts are the figure sources, included in the individual sections of the Working Group II Report 'Impacts, Adaptation and Vulnerability' (IPCC, 2007b)

Source: Parry *et al.*, 2007. Published with the permission of the Intergovernmental Panel on Climate Change.

Figure 4.2 Examples of regional impacts projected for changes in climate associated with different amounts of increase 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 indicates the EU objective of 2 °C maximum temperature increase above pre-industrial (or 1.5 °C above 1990 levels). Numbers in superscripts are the figure sources, included in the individual sections of the Working Group II Report 'Impacts, Adaptation and Vulnerability' (IPCC, 2007b).

Source: Parry *et al.*, 2007. Published with the permission of the Intergovernmental Panel on Climate Change.

Box 4.2 EU target of limiting global temperature rise to 2 °C above pre-industrial level

The EU global temperature limit of 2 °C above the pre-industrial level was first established in 1996 before the Kyoto negotiations, and reaffirmed subsequently by the Environment Council (2003) and the European Council (2005 and 2007). It was deduced from the evidence available at the time and from the concern that adaptation rates of ecosystems are limited. Since 1996, understanding of vulnerability to and impacts of climate change has improved significantly. According to the IPCC 4th assessment report, some impacts are now projected to be stronger and occur at lower temperatures than assessed in the IPCC Third Assessment Report (2001). Furthermore, for some cases the increase in impacts will be relatively smooth, while for others, such as heat wave mortality, coral reef losses and thawing of permafrost, a critical temperature limit or threshold may be identified. The projected climate changes and impacts vary regionally, making some thresholds regional rather than global. Both kind of impact should be taken into consideration when evaluating the EU's goal.

Temperature increases can trigger climate feedbacks that strongly accelerate climate change, initiate irreversible changes to the climate system, or result in sudden and rapid exacerbation of certain impacts, requiring unachievable rates of adaptation. The temperature changes at which these thresholds would be exceeded are not yet clearly understood. At a temperature rise of more than 2 °C above pre-industrial levels, there is an increase in the risk of a range of severe large-scale events, such as shutdown of the thermohaline circulation. But some thresholds may be passed with a global average temperature increase of less than 2 °C, for example the melting of the Greenland ice sheet, which could be initiated by a global temperature rise between 1 and 2 °C and could be irreversible if the temperature rise is sustained for a sufficient period.

Also in Europe, the magnitude of impacts is projected to increase as global temperatures rise. An increase of less than 2 °C above pre-industrial levels is likely to allow adaptation to climate change for many human systems at moderate economic, social and environmental costs. The ability of many natural ecosystems to adapt to rapid climate change is limited and may be exceeded well before 2 °C is reached. Beyond 2 °C one can expect major increases in vulnerability, considerable impacts, very costly adaptation needs, an unacceptably high and increasing risk of large-scale irreversible effects, and a substantial increase in the uncertainty of the impacts.

Further research is needed to better quantify the risks of exceeding the 2 °C target and define ways of achieving it (see also next section). For now, the target remains a reasonable level beyond which the risk of severe impacts would increase markedly, recognising that it will not avoid all impacts.

Main sources: IPCC, 2007a, 2007b, 2007c; EC, 2008.

2 °C global mean temperature increase above pre-industrial levels (or about 1.5 °C above 1990 levels) (Box 4.2). This goal aims to limit risks, but will not avoid all global impacts (see Figures 4.1 and 4.2 in which the EU goal is indicated by a dashed line).

4.3 Risks of non-linear climate change

A special kind of risk, particularly difficult to deal with from a policy point of view, is impacts with a low likelihood of occurrence but potentially very large consequences (see Box 4.3 for examples). In general such impacts build up slowly. However, there are 'tipping points' beyond which large and rapid changes in the behaviour of natural or societal systems may occur. Some of these non-linear changes are related to positive feedbacks in the climate system and can therefore accelerate climate change. The EU target of a maximum of 2 °C above pre-industrial levels was set also from a perspective of reducing non-linear climate change with potentially very large consequences.

4.4 Limiting damage by mitigation and adaptation

Society needs to avoid the unmanageable — through the reduction of greenhouse gas emissions — and manage the unavoidable — through adaptation measures (Scientific Expert Group on Climate Change, 2007). Successful international climate change negotiations that would lead to avoiding a dangerous interference with the climate system would obviously be a controlling feedback helping to limit the unavoidable.

The EU long-term goal of 2 °C maximum global mean temperature increase above pre-industrial levels will limit risks, but not avoid all impacts. However, at the same time, if temperatures are limited to the EU goal, many serious impacts can be avoided. Most of the studies underlying the graphs (Figures 4.1 and 4.2) do not take adaptation explicitly into account, and adaptation could further reduce risks and economic costs. However there are limits to adaptation, dependent on the type, magnitude and rate of change. Furthermore, the figures end by 2100, but climatic changes

Box 4.3 What are the risks of non-linear climate change?

The risk of large-scale discontinuities or non-inearities has been identified by IPCC as one of five 'reasons for concern' and deserves special attention, because of their potentially very large consequences for the world, including Europe. What is a non-linear, or abrupt change? If a system has more than one equilibrium state, transitions to structurally different states are possible. If and when a 'tipping point' is crossed, the development of the system is no longer determined by the time-scale of the forcing, but rather by its internal dynamics, which can be much faster than the forcing (IPCC, 2007a). A variety of different tipping points has been identified. Below we discuss a few with potentially large consequences for Europe.

One of the large-scale discontinuities relevant for Europe is the possible deglaciation of the West Antarctic Icesheet (WAIS) and Greenland. There is a medium confidence that 1–2 °C of sustained global warming above present temperatures (or 2–3 °C above pre-industrial) is a threshold beyond which there will be a commitment to a large sea-level contribution due to at least partial deglaciation of both ice sheets (IPCC, 2007a, 2007b). If so, the sea level may rise over the next 1 000 years or more on average by 7 m from Greenland and about 5 m from the WAIS (IPCC, 2007a). This would alter the world's coast lines completely. Note that the sea-level rise will not be evenly distributed over the globe, because of ocean circulation patterns, land movements, and density and gravitational factors.

There is less confidence about other non-linear effects, e.g. what may happen with the ocean circulation. A slow-down of the thermohaline circulation (THC), or equivalently, the meridional overturning circulation (MOC), may counteract global warming trends in Europe, but may have unexpected serious consequences for the behaviour of the world's climate system and exacerbated impacts elsewhere. Other examples of possible non-linear effects are the progressive emission of methane from permafrost melting and destabilisation of hydrates, and rapid climate-driven transitions from one ecosystem type to another (IPCC, 2007b). The understanding of these processes is as yet limited and the chance of major implications in the current century is generally considered to be low.

and their impacts will not have stopped by that time. Because of delays in the climate system, emissions now and during the rest of this century will have persisting effects in centuries to come. These considerations, among others, illustrate the deeply ethical dimension of the climate problem in terms of impacts on current and future generations. In addition to ethical questions, economic considerations also play a role. The costs of inaction as well as those of action are very uncertain. Limits on quantification and valuation play a key role. Economic effects of climate change for Europe are uncertain, but potentially very significant (EEA, 2007). What is considered 'dangerous anthropogenic interference with the climate system' (Article 2 of the UNFCCC) is therefore more a political issue rather than a scientific one.

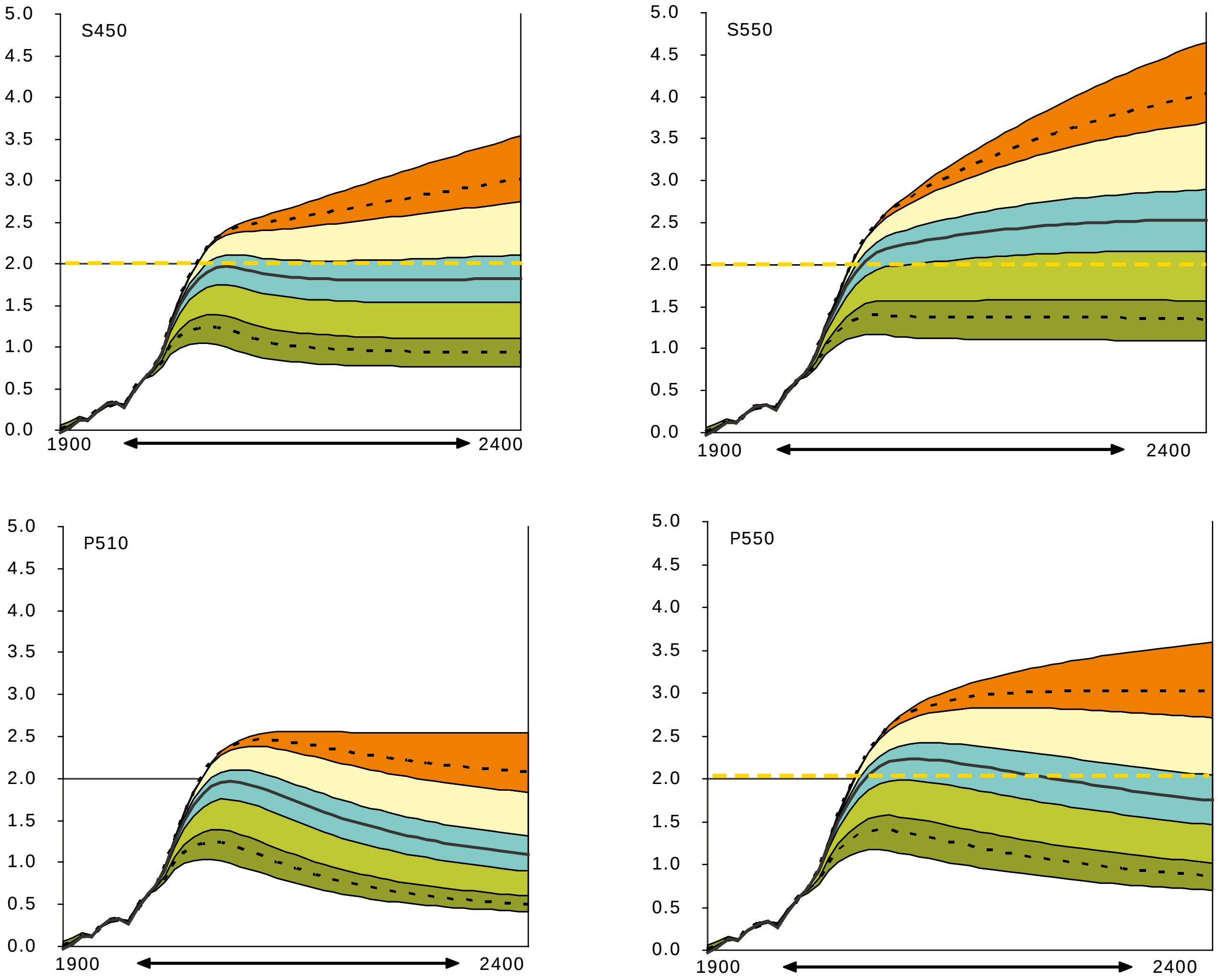
One way of looking at the rationale of different climate change response strategies is to compare mitigation efforts with adaptation actions. Mitigation aims particularly at avoiding the serious impacts associated with continuing, longer-term changes in the climate system as well as limiting the risks of large-scale discontinuities in that system. Adaptation aims particularly at reducing unavoidable negative impacts already in the shorter term, reducing vulnerability to present climate variability, and exploiting opportunities provided by climate change.

To have a 50 % chance of meeting the EU long-term climate objective, global GHG concentrations would have to be stabilised at 450 ppm CO_2-equivalent (of which about 400 ppm is CO_2; see also den Elzen and Meinshausen, 2005; van Vuuren *et al.*, 2006; den Elzen *et al.*, 2007; see Figure 4.3). The specific global emission profiles that are consistent with the EU goal are dependent on assumptions that include climate sensitivity and the possible acceptance of a temporary peaking above the objective. The achievement of a 450 ppm CO_2-equivalent stabilisation goal is generally considered to be very ambitious, but feasible from a technical and macro-economic perspective (IPCC, 2007c). Global GHG emissions will have to peak within the next 10 to 15 years, followed by substantial global emission reductions to at least 50 % below 1990 levels by 2050. To achieve those deep emissions reductions, a broad portfolio of technologies currently available or expected to be commercialised in the coming decades will need to be deployed urgently and on a large scale. Lock-in of carbon-intensive technologies needs to be avoided, requiring a large shift in investment patterns.

Mitigation costs are still uncertain. Allowing or not allowing temporary 'overshoot' of the stabilisation goal has important implications for costs and feasibility (van Vuuren *et al.*, 2006). But the costs are likely to rise quickly for lower stabilisation levels.

Costs for some sectors and regions could be high, and political, social and behavioural hurdles would have to be dealt with to allow for a world-wide, effective mitigation response. There are encouraging signs that international action is being mobilised to stave off long-term climate change impacts. These include the Bali Action Plan (UNFCCC, 2007) aimed at achieving a global post-2012 climate change agreement by the end of 2009 in Copenhagen, and the 2008 climate change and energy package of the EU: 20 % reduction of GHG emissions and a 20 % renewable energy share in total energy consumption by 2020 (EC, 2008).

Figure 4.3 The probabilistic implications for global temperature increase up to year 2400



Note: Above pre-industrial levels for pathways stabilising at 450 and 550 ppm CO$_2$-equivalent concentration levels (upper row) and the pathways that peak at 510 and 550 ppm respectively (lower row). The FAIR-SiMCaP pathways shown are those for the B2 baseline scenario based on a climate sensitivity that assumes the 1.5–4.5 °C uncertainty range for climate sensitivity (IPCC TAR), being a 90 % confidence interval of a log-normal distribution. Shown are the median (thick solid line) and 90 % confidence interval boundaries (dashed lines), as well as the 1, 10, 33, 66, 90, and 99 % percentiles (borders of shaded areas). Probability density function is based on Wigley and Raper, 2001.

Source: Den Elzen *et al.*, 2007.