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Impacts of Europe's changing climate — 2008 indicator-based assessment

Joint EEA-JRC-WHO report

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JRC European Commission
European Environment Agency

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Foreword

Climate change and its associated impacts require immediate action in order to safeguard the economy and environment of Europe and the rest of the world. This indicator report shows how temperature is increasing, sea levels are rising, glaciers, ice sheets and sea ice are melting, precipitation is changing, and the intensity and frequency of weather extremes in many regions is increasing. It also underlines the cascade of consequences including an increased risk of floods and droughts, losses of biodiversity (marine, freshwater and terrestrial), threats to human health, and damage to economic sectors such as energy, transport, forestry, agriculture, and tourism.

We are already experiencing a global average temperature increase of almost 0.8 °C above pre-industrial levels, and even higher increases in Europe and northern latitudes. There is an urgent need to stabilize the climate below a 2 °C increase above pre-industrial levels, so as to avoid major irreversible impacts on society and ecosystems. To achieve this we need both global greenhouse gas emission reductions and actions to adapt to climate change.

For the past decade the European Union has tackled climate change through international agreements under the United Nations Framework Convention on Climate Change. What is now needed is a massive scale-up in renewable energy technology development and transfer, investment in energy and resource efficiency, adaptation actions and efforts to reduce deforestation, increase the resilience of ecosystems and reduce effects on human health. A global post-2012 regime, hopefully agreed by the end of 2009, will need to include all these elements.

Tackling the climate change problem requires numerous relevant institutions to work towards the same goal. This report was prepared jointly by the European Environment Agency, including its European Topic Centres, the Joint Research Centre of the European Commission, and World Health Organization Regional Office for Europe. It builds on results of recent national and EU-wide research activities, the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC) and the Arctic Climate Impact Assessment. We consider the report a successful example of an inter-institutional collaboration.

The report highlights that more action is needed towards halting biodiversity loss and maintaining the resilience of ecosystems because of their essential role in regulating the global climate system. Enhancing ecological coherence and interconnectivity of the EU Natura 2000 network is key to the long-term survival of many species and habitats, for them to be able to adapt to a changing climate.

Climate change is also a significant and emerging threat to public health, and changes the way we must look at protecting vulnerable populations. The large number of additional deaths during the 2003 heat wave highlighted the need for adaptation actions, such as heat health action plans. A number of vector-borne, water- and food-borne and other diseases are expected to increase. The possible spread of such diseases is highly dependent on early detection and having preventive measures in place.

The report highlights that vulnerable regions and sectors vary widely across Europe. Key economic sectors, which will need to adapt through integration within sectoral policies at European and (sub-) national levels, include energy supply, health, water management, agriculture, tourism and transport. The report shows that there is a lack of information on good practices in adaptation actions and their costs.

The report shows there is a need for improved international monitoring and reporting mechanisms by countries and international organisations. A European Clearing House on climate change impacts, vulnerability and adaptation will make information widely available to users across Europe. It will be underpinned by the EU Shared Environmental Information System (SEIS), the services to be generated by the EU Kopernikus programme on global monitoring for environment and security and the WHO Climate, Environment and Health Information System (CEHAIS). Our institutes are committed to contribute to the further development of these systems and services.

The report was prepared at a time when the European Commission was discussing ideas for a European strategy on adaptation in its Green Paper on Adaptation (2007). More concrete policy actions have been developed in its White Paper on Adaptation (due at the end of 2008). This report will provide a valuable resource in the implementation phase of the White Paper and for the development of national adaptation plans by member countries. Our three organizations are committed to providing the appropriate data and information to support the efforts of European policy makers and society to develop and implement both adaptation and mitigation actions.

Hereby we would like to thank all staff that worked hard on finalizing the report, from EEA, and its European Topic Centres on Air and Climate Change, on Water and on Biological Diversity, JRC and WHO Europe, as well as the many external experts that have contributed. In particular we would also like to thank the external Advisory Group, which included representatives from various key EU and national research programmes, several international organizations, the European Commission and the EEA Scientific Committee, for their continued support for the project and their valuable advice.

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Executive summary

Introduction

Background and objective

This report is an update and extension of the 2004 EEA Report *Impacts of Europe's changing climate*. Since 2004, there has been much progress in monitoring and assessing the impacts of climate change in Europe. The objectives of this report are to present this new information on past and projected climate change and its impacts through indicators, to identify the sectors and regions most vulnerable to climate change with a need for adaptation, and to highlight the need to enhance monitoring and reduce uncertainties in climate and impact modelling. To reflect the broadening of coverage of indicators and make use of the best available expertise, the report has been developed jointly by EEA, JRC and WHO Regional Office for Europe.

Developments in science and policy

The Intergovernmental Panel on Climate Change (IPCC), in its 4th Assessment report (2007) reconfirmed and strengthened earlier scientific findings about key aspects of climate change. Increased monitoring and research efforts have enhanced understanding of climate change impacts and vulnerability. European research on impacts and vulnerability in national and EU programmes has advanced considerably, making a major contribution to international assessments of the IPCC, the Arctic Climate Impact Assessment (2004), the UNEP Global Outlook for Ice and Snow (2007) and WHO reports.

At the 2007 UN Framework Convention on Climate Change (UNFCCC) Bali conference, the urgency of responding effectively to climate change through both adaptation and mitigation activities was recognised by a larger number of countries than ever before. The EU has proposed a target of a maximum global temperature increase of 2 °C above the pre-industrial level and a number of EU mitigation targets and actions by 2020. A post-Kyoto regime that would include both adaptation and mitigation is expected to be agreed by end of 2009. There has been progress in implementing the UNFCCC work programme on impacts, vulnerability and adaptation to climate change, developed to help countries improve their understanding of climate change impacts.

This report

The main part of this report summarises the relevance, past trends and future projections for about 40 indicators (from 22 in the 2004 report). The indicators cover atmosphere and climate, the cryosphere, marine systems, terrestrial systems and biodiversity, agriculture and forestry, soil, water quantity (including floods and droughts), water quality and fresh water ecology, and human health. The report also addresses adaptation and the economics of climate change impacts and adaptation strategies and policies, and data availability and uncertainty.

Key messages

Atmosphere and climate

Recent observations confirm that the **global mean temperature** has increased by 0.8 °C compared with pre-industrial times for land and oceans, and by 1.0 °C for land alone. Europe has warmed more than the global average (1.0 and 1.2 °C, respectively), especially in the south-west, the north-east and mountain areas. Projections suggest further **temperature increases in Europe** between 1.0–5.5 °C by the end of the century, which is also higher than projected global warming (1.8–4.0 °C). Whether the EU's goal of less then 2 °C global warming (compared with pre-industrial levels) will be exceeded will depend on the effectiveness of international climate policy regarding global greenhouse gas emission reductions. More frequent and more intense **hot extremes** and a decreasing number of **cold extremes** have occurred the past 50 years and this trend is projected to continue.

Changes in **precipitation** show more spatially variable trends across Europe. Annual precipitation changes are already exacerbating differences between a wet northern part (an increase of 10 to 40 % during the 20th century) and a dry southern part (a decrease of up to 20 % in some parts of southern Europe). The intensity of **precipitation extremes** such as heavy rain events has increased in the past 50 years, and these events are projected to become more frequent. Dry periods are projected to increase in length and frequency, especially in southern Europe.

No clear trend in the frequency and intensity of **storms** has yet been observed, but the strength of the heaviest storms is projected to increase, albeit with slightly lower frequency. Uncertainties for projected annual precipitation and frequency and the intensity of extreme events continue to be larger than those for annual temperature. Climate variability and change have contributed to an increase in **ozone concentrations** in central and south-western Europe, which is projected to continue. This may result in current ozone abatement policies becoming less effective.

Cryosphere

The cryosphere (the frozen world) is important since it is affected by climate change, while changes in the cryosphere itself have a major effect on the climate system. **European glaciers** are melting rapidly: those in the Alps have lost two thirds of their volume since 1850, with loss accelerating since the 1980s, and they are projected to continue their decline. **Snow cover** has decreased by 1.3 % per decade during the past 40 years, with the greatest losses in spring and summer, and decreases are projected to continue. These various changes will cause natural hazards and damage to infrastructure and changes in river flows and seasonality, thus substantially affecting the hydrological cycle in river catchment areas.

The reduction in **Arctic sea ice**, especially in summer, has accelerated the past five decades, with a record low extent in September 2007 of about half the normal minimum in the 1950s. Arctic sea ice may even disappear at the height of the melting season in the coming decades, creating a feedback that will further increase climate change because dark open water reflects much less sunlight than white snow-covered surfaces. Species specialised for life in the ice are threatened. Less ice will ease access to the Arctic's resources. Oil and gas exploration, shipping, tourism and fisheries will offer new economic opportunities, but also increase risks to the Arctic environment.

Also **mountain permafrost** is reducing due to increasing temperatures, which is already increasing natural hazards and damage of high-mountain infrastructure. The **Greenland ice sheet** has lost ice since the 1990s, probably at an increasing rate. Hence its contribution to global sea-level rise has increased in the past decades. Accelerated flow of outlet glaciers to the sea accounts for more of the ice loss than melting. No reliable predictions of the future of the ice sheets in Greenland and Antarctica can yet be made. The processes causing the faster movement of the glaciers are poorly understood and there is a lack of long-term observations.

Marine biodiversity and ecosystems

According to satellite observations, the rate of global mean **sea-level rise** has increased to 3.1 mm/year in the past 15 years (compared with a global average of 1.7 mm/year in the 20th century). Because of ocean circulation and gravity effects, sea-level rise is not uniform but varies across European seas. An acceleration of **sea surface temperature** increases has also been observed in recent decades. Projections suggest that sea level and sea surface temperature of some European seas could rise more than the global average. IPCC (2007) sea-level rise estimates (up to 0.59 m by 2100) may be too low because of the risks of more rapid changes than so far assessed in the Greenland ice sheet (and partly in the Antarctic ice sheet). Sea-level rise can cause flooding, coastal erosion and the loss of flat and low-lying coastal regions. It increases the likelihood of storm surges, enforces landward intrusion of salt water and endangers coastal ecosystems and wetlands.

Changes in the **timing of seasonal biological phenomena (phenology**) and distribution of **marine species** have been observed, including earlier seasonal cycles (by 4–6 weeks) and **northward movements**, by up to 1 100 km over the past 40 years, which seems to have accelerated since 2000. These changes will affect marine ecosystems, biodiversity and affect fisheries, including increasing the vulnerability of North Sea cod stocks to over-fishing and a decline in seabird populations. Sub-tropical species are occurring with increasing frequency in European waters, and sub-Arctic species are receding northwards. The rate of northward movement of a particular species, the sailfin dory, has been estimated at about 50 km/year. Changes in the geographic distribution of fish may affect the management of fisheries. Fisheries regulations in the EU include allocations of quotas based on historic catch patterns, and these may need to be revised.

Water quantity, river floods and droughts

Climate change, including changes in temperature, precipitation, glaciers and snow cover, is intensifying the hydrological cycle. However, other factors such as land-use changes, water management practices and extensive water withdrawals have considerably changed the natural flows of water, making it difficult to detect climate change-induced trends in hydrological variables. In general, annual **river flows** have been observed to increase in the north and decrease in the south, a difference projected to exacerbate. Strong changes in seasonality are projected, with lower flows in summer and higher flows in winter. As a consequence, **droughts** and water stress will increase, particularly in the south and in summer.

Europe has been affected by several major droughts in recent decades, such as the catastrophic drought associated with the summer 2003 heatwave in central parts of the continent and the 2005 drought in the Iberian Peninsula. The regions most prone to an increase in drought hazard are southern and south-eastern Europe, but minimum river flows will also decrease significantly in many other parts of the continent, especially in summer.

In the past, the recorded number of **river floods** has been strongly influenced by improved monitoring and reporting systems. For example since 1990, 259 major river floods have been reported in Europe, of which 165 have been reported since 2000. For the coming decades, however, floods are projected to occur more frequently in many regions, particularly in winter and spring, although estimates of changes in flood frequency and magnitude remain uncertain.

Projected climate-induced changes in the hydrological cycle will aggravate the impact of other stresses (such as land-use and socio-economic changes) on water availability, freshwater ecosystems, energy production, navigation, freshwater supply and use (in agriculture, households, industry) and tourism. Adaptation actions will be needed such as improving water efficiency to mitigate water stress and enhancing retention to reduce flood risk.

Freshwater quality and biodiversity

Increased **temperatures of lakes and rivers** (by 1–3 °C during the 20th century) have resulted in decreases in **ice cover on lakes and rive**rs by 12 days on average in the last century in Europe. These changes can be at least partly attributed to climate change, and partly to other causes such as freshwater use for cooling processes (e.g. power plants). Lake and river surface water temperatures are projected to increase further with increasing air temperatures. Warming of surface water can have several effects on **water quality** and hence on human use and **aquatic ecosystems**. Changes include movement of freshwater species northwards and to higher altitudes, changes in life-cycle events (phenology), for example spring phytoplankton and zooplankton blooms up to one month earlier than 30–40 years ago. Climate change may thus favour and stabilise the dominance of harmful cyanobacteria in phytoplankton communities, resulting in increased threats to the ecological status of lakes and enhanced health risks, particularly in water bodies used for public water supply and bathing. This may counteract nutrient load reduction measures. Further monitoring is needed to confirm and better analyse these changes.

Terrestrial ecosystems and biodiversity

Climate change, in particular milder winters, is responsible for the observed **northward and uphill distribution shifts** of many European **plant species**. By the late 21st century, plant species are projected to have shifted several hundred kilometers to the north, forests are likely to have contracted in the south and expanded in the north, and 60 % of mountain plant species may face extinction. The rate of change will exceed the ability of many species to adapt, especially as landscape fragmentation may restrict movement. The **timing of seasonal events in plants (phenology)** is changing, for example the average advance of spring and summer between 1971 and 2000 was 2.5 days per decade. The pollen season starts on average 10 days earlier and is longer than 50 years ago. Changes in seasonal events are projected to continue.

Birds, insects, mammals and other **animal groups** are also **moving northwards and uphill**. A combination of the rate of climate change, habitat fragmentation and other obstacles will impede the movement of many animal species, possibly leading to a progressive decline in European biodiversity. Distribution changes are projected to continue. Suitable climatic conditions for Europe's breeding birds are projected to shift nearly 550 km north-eastward by the end of the century, with the average range size shrinking by 20 %. Projections for 120 native European mammals suggest that, assuming no migration, up to 9 % risk extinction during the 21st century.

Climate change has caused advancement in the **life cycles of many animal groups (phenology)**, including frog spawning, bird nesting and the arrival of migrant birds and butterflies, and these trends are projected to continue. Populations may explode if the young are not exposed to normal predation pressures. Conversely, populations may crash if the emergence of vulnerable young is not in synchrony with their main food source or if shorter hibernation times lead to declines in body condition.

Soil

Information on the impacts of climate change on soil and the various related feedbacks is very limited. Indicators with full European coverage are absent and there is a need for the establishment of appropriate monitoring schemes. Changes in the bio-physical nature of soil are likely due to projected rising temperatures, changing precipitation intensity and frequency and more severe droughts. Such changes can lead to a future decline in **soil organic carbon** stocks and a substantial increase in CO_2 emissions. Adapted land-use and management practices could be implemented to counterbalance these impacts. Projected increased variations in rainfall pattern and intensity will make soils more susceptible to **erosion**. Projections show significant reductions in summer soil moisture in the Mediterranean region, and increases in the north-eastern part of Europe. Maintaining **water retention capacity** is important, e.g. through adaptation measures. Climate change alters the habitat of soil biota, which affects the diversity and structure of species and their abundance. Ecosystem functioning is modified consequently, but quantified knowledge of these impacts is limited. Soil degradation is already intense in parts of the Mediterranean and central-eastern Europe and, together with prolonged drought periods and increased numbers of fires, is already contributing to an increased risk of desertification. In many cases, desertification is irreversible, leading to adverse social, economic and environmental effects. Projected risks for future desertification are the highest in the same areas.

Agriculture and forestry

In both agriculture and forestry, climate change affects the **growing season** and average yields while also key relevant land-use and management changes occur, making it difficult to detect climate change-induced trends. The length of the growing season of several agricultural crops has increased at northern latitudes, favouring the introduction of new species that were not previously suitable. However, there has been a shortening of the growing season locally at southern latitudes. The flowering and maturity of several species in Europe now occurs two or three weeks earlier than in the past with consequent higher risk of frost damage from delayed spring frosts. Changes in the growing season and the **timing of the cycle of agricultural crops (agrophenology)** are projected to continue.

Since the beginning of the 21st century, the **variability of crop yields** has increased as a consequence of extreme climatic events, e.g. the summer heat of 2003 and the spring drought of 2007. Since extreme events are projected to increase in frequency and magnitude, crop yields will become more variable. Increases in **water demand** for agriculture (by 50–70 %) has occurred mainly in Mediterranean areas and this is projected to continue, thus increasing competition for water between sectors and uses. There is a need for adaptation of farm practices and land management to reduce or avoid adverse impacts. Some of the adaptation options such as irrigation may however increase emissions because of increased energy consumption.

In much of continental Europe, the majority of **forests** are growing faster now than in the early 20th century, due to advances in forest management practices, increased nitrogen deposition, and reduced acidification by air pollution (sulphur dioxide) and also increasing temperatures and atmospheric CO_2 concentrations. Projected climate change will favour certain species in some forest locations, while making conditions worse for others, leading to substantial shifts in vegetation distribution. Changes in distribution and the timing of seasonal events of both pests and pollinators will further change forests, although the types of change are difficult to project. Periods of drought and warm winters are increasing pest populations and further weakening forests. Projected temperature increases will increase the **danger of forest fires** and lead to more area being burned, more ignitions and longer fire seasons, especially in southern and central Europe. Adaptation actions will also be needed in the forestry sector to limit the adverse effects.

Human health

Increased temperatures can have various effects on human health. The large number of additional deaths during the 2003 (more than 70 000 excess deaths reported in 12 European countries) **heat wave** highlighted the need for adaptation actions, such as heat health action plans. Such heat waves are projected to become much more common later in the century as the climate continues to change, with mortality risk increases by between 0.2 and 5.5 % for every 1 °C increase in temperature above a location-specific threshold. There is some evidence that winter mortality in Europe has decreased, but this could have other causes, particularly improved housing and the prevention of winter infections. A number of

vector-borne diseases are expected to increase in the near future. The tiger mosquito, a transmitter of a number of viruses, has extended its range in Europe substantially over the past 15 years and is projected to extend even further. Ticks and the associated Lyme disease and tick-borne encephalitis are moving into higher altitudes and latitudes. There is a risk of additional outbreaks of Chikungunya (a virus that is highly infective and disabling but not transmissible between people) and a potential for localised dengue to re-appear. Changes in the geographic distribution of the sandfly vector are occurring in several European countries and there is a risk of human Leishmania cases further north. The possible spread of these diseases is very dependent on early detection and the preventive measures in place. Some **water- and food-borne disease** outbreaks are expected to become more frequent with rising temperatures and more frequent extreme events. The risk is very dependent on human behaviour and the quality of health care services and their ability to detect early and act.

Adaptation to climate change

To limit adverse impacts and benefit from some positive changes, adaptation is needed. Europe has to adapt and should also assist developing countries as they are most vulnerable in terms of communities, economic sectors and ecosystems.

Adaptation involves all levels of decision-making, from municipalities to international organisations. It is a cross-sectoral and transboundary issue which requires comprehensive integrated approaches. Economic sectors that are particularly concerned with adaptation include energy supply, health, water management, agriculture, tourism and transport. **Integration of adaptation into sectoral policies** at European and national levels is important in order to reduce, in the long term, the vulnerability of ecosystems, economic sectors, landscapes, health and communities to climate change impacts.

The European Commission adopted a Green Paper 'Adapting to climate change in Europe — options for EU action' in June 2007 and is planning to publish a White Paper framing a European adaptation strategy and options for adaptation in late 2008. National adaptation strategies have been or are being developed and implemented in many member countries, usually on the basis of impact and vulnerability assessments, and/or because of the urgency deriving from extreme weather and climate events.

Economic impacts

Economic costs and potential benefits of climate impacts have been quantified in some studies, but factors other than climate change often have a dominant effect, making assessments uncertain. Furthermore the costs of adaptation actions are poorly understood for both the current situation and the future.

However, about 90 % of all natural disasters that occurred in Europe since 1980 are directly or indirectly attributable to weather and climate, representing about 95 % of the economic losses caused by catastrophic events. Overall losses resulting from weather- and climate-related events have clearly increased during the past 25 years. Even though **social change and economic development** are the main factors responsible for this increase, there is evidence that **changing patterns of weather disasters** are also drivers. However, it is still not possible to determine the proportion of the increase in damage that might be attributed to anthropogenic climate change.

Economic losses as a consequence of extreme flood events in recent years have been substantial. For example, the estimated losses in central Europe in 2002 were EUR 17.4 billion. In addition, the economic costs of coastal flooding (assuming no adaptation) are estimated in the range of 12 to 18 billion EUR/year for Europe in 2080. Adaptation could significantly reduce these costs to around 1 billion EUR/year.

The hot summer of 2003 in Europe is estimated to have led to EUR 10 billion of economic losses to farming, livestock and forestry from the combined effects of drought, heat stress and fire.

Work undertaken in the context of the initiative 'The Economics of Ecosystems and Biodiversity' tentatively indicates that at a global level the cumulative welfare losses due to loss of ecosystem services, with climate change being one of the causes, could be equivalent to 7 % of annual consumption by 2050. However, little is currently known either ecologically or economically about the impacts of future biodiversity loss, and further assessment and methodological work is needed.

Projections suggest significantly reduced space-heating demand in northern Europe and increased space-cooling demand in southern Europe, with associated costs and benefits. Hydropower production is projected to increase in northern Europe and decrease in the south. With more severe summer droughts, the availability of cooling water for power plants could be limited.

Changes in climate are starting to reduce the attractiveness of major tourist resorts in mountain areas and the Mediterranean, while improving it in other regions. The suitability of the Mediterranean for tourism is projected to decline during the key summer months, although there will be an increased suitability during spring and autumn. This can produce shifts in the major flows of tourism within the EU, which will be very important in regions where tourism is a dominant economic sector. Adaptation responses such as economic diversification will be critical to limit economic losses.

Key future challenges

Improved monitoring and reporting

In recent decades the availability of observed and projected data and information on climate change impacts across Europe has improved. However, for many impacts the information availability differs very considerable between regions. There are some national monitoring and data collection programmes for a number of the 'Essential Climate Variables' defined by WMO as part of GCOS (Global Climate Observing System), with regular international reporting obligations to the UNFCCC. Also satellite data are increasingly being used for tracking these variables. Some data depend on voluntary work by non-governmental organisations. However for many indicators the data result from a limited number of local or regional projects and national or EU-wide research projects. There are no regular Europe-wide monitoring programmes for many of the indicators presented in this report. More spatially detailed information is needed to develop adequate adaptation strategies. Through coordinated efforts by countries and the Commission, monitoring and reporting systems can be improved in a way consistent with the Shared Environmental Information System for Europe SEIS (EC, 2008). GMES (Global Monitoring and Environmental Security, EC, 2004) projects could fill key data and information gaps, along with the Environment and Health Information system (EHIS). The INSPIRE Directive will help to improve inter-operability, harmonisation and access to data. It would be useful to have a European agreement on the definition of key climate change indicators, including extreme weather events (for example 'floods' and 'droughts') and to define operational ways of tracking impacts through multiple sectors, over a variety of time and geographic scales.

Improved attribution methods for impact assessments

Even if many of the observed changes in various natural and societal systems are consistent with observed climate changes, other factors also influence system behaviour. Disentangling the climate change factor from other (e.g. societal) factors and separating anthropogenic from natural forcing for different indicators often remains a challenge (IPCC, 2007). There is a need to improve in this area, in order to have better projections of impacts and develop more focused adaptation actions.

Improved understanding of socio-economic and institutional aspects of vulnerability and adaptation

Many of the research and assessment activities to date have focused on the climatological, physical and biological aspects of climate change impacts. A better understanding of the socio-economic and institutional aspects of vulnerability and adaptation, including costs and benefits, is urgently needed. Very few studies have assessed the effectiveness of adaptation measures over a variety of time scales; today's adaptation measures may not be effective in future decades if, for example, extreme weather events become more frequent and intense.

Improved and coordinated scenario analysis of impacts and vulnerability

The scenarios for the climate change impacts and vulnerability indicators presented in this report are based mainly on global scenarios and contain spatially detailed European information for only few indicators. They are also incomplete and differ between indicators. Regular interaction is needed between the climate modelling community and the user community that is analysing impacts, vulnerability and adaptation in order to develop high-resolution, tailor-made climate change scenarios for the regional and local level at a level that is needed to define appropriate adaptation measures. It would be useful if European research projects were to adopt the same contrasting set of climate scenarios for global development, such as those used by IPCC, and make use of regional climate projections as soon as they become available. There will be a need both for explorative research for the very long term (centuries) and for analysis of climate-change impacts in the medium term (decades) for which better adaptation actions urgently need to be developed. However, despite uncertainties in existing climate change scenarios, stakeholders will have to make decisions, which could then be further improved as more detailed scenarios become available.

More information on good practices and avoiding mal-adaptation

Understanding of how to implement integration of adaptation into sectoral policies should be further improved, particularly with regard to water management, energy supply, biodiversity protection, health and agriculture. Good practices should also be developed to address the cross-sectoral and transboundary nature of adaptation, in synergy with mitigation actions, in order to enhance resilience across European countries, sectors, landscapes and communities. Future activities should also consider European neighbouring countries and overseas territories. In addition, it is important to better understand mal-adaptation e.g. by developing criteria (including social, environment, health and economic aspects). Substantial work should also be undertaken on better assessment of adaptation costs across all sectors.

Develop information exchange mechanisms

Planned research programmes both at the national and the European level will result in a rapidly increasing amount of data and information on climate change impacts, vulnerability and adaptation. A European clearing house on climate change impacts, vulnerability and adaptation could make this information widely available to potential users across Europe. The information could include data on observed and projected climate changes, information on vulnerable systems, indicators, tools for impacts assessments, and good practice adaptation measures. Such a clearing house should be developed and made consistent with the existing European environmental data centres (on climate change, water, land use, biodiversity and air) and information systems (European Community Biodiversity Clearinghouse) that are currently managed by EEA, by JRC (data centres on forestry and soil), and the WHO (Climate, Environment and Health Action and Information system, CEHAIS). This clearing house could also effectively provide important European information to international organisations such as UNFCCC.

Table S.1 Observed (obs) and projected (scen) trends in climate and impacts for northern (Arctic and boreal), temperate (maritime climate, central/eastern) and southern (Mediterranean) regions of Europe

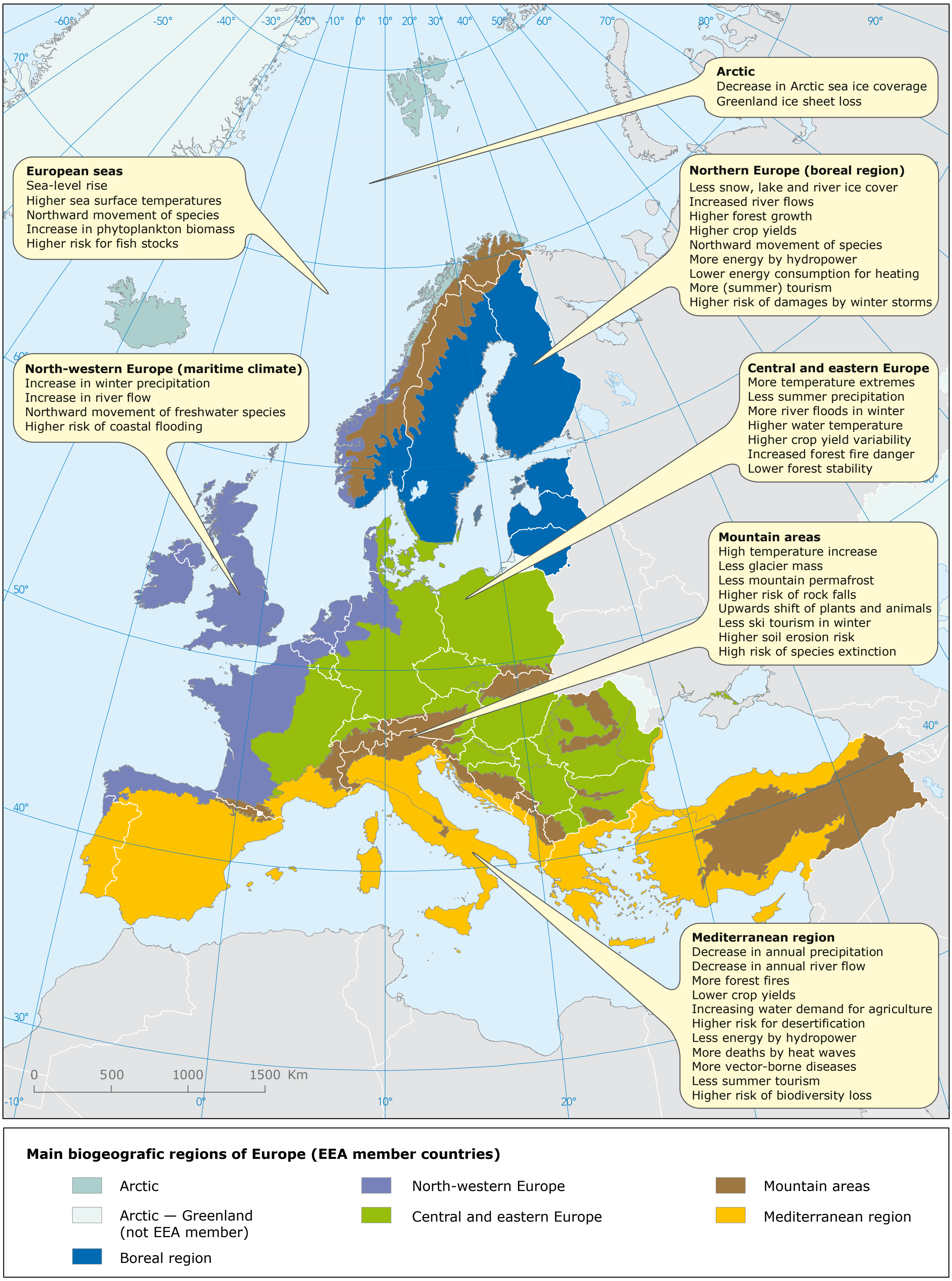
		Northern	Temperate		Southern
Section	**Indicator**	**Arctic and boreal**	**Maritime climate**	**Central/ eastern**	**Mediterranean**
		obs/scen	obs/scen	obs/scen	obs/scen
5.2	**Atmosphere and climate**				
5.2.2	Global and European temperature	+/+	+/+	+/+	+/+
5.2.3	European precipitation	+/+	+/o	o/o	–/–
5.2.4	Temperature extremes in Europe				
	Heat waves in Europe	+/+	+/+	+/+	+/+
	Number of days with frost	–/–	–/–	–/–	–/–
5.2.5	Precipitation extremes in Europe	+/+	+/+	+/+	+/+
5.2.6	Storms and storm surges in Europe	o/o	o/+	o/o	o/o
5.2.7	Air pollution by ozone	o/+	+/+	+/+	+/+
5.3	**Cryosphere**				
5.3.2	Glaciers	–/–	n.a./n.a.	–/–	–/–
5.3.3	Snow cover	–/–	–/–	o/–	+/–
5.3.4	Greenland ice sheet	–/–	n.a./n.a.	n.a./n.a.	n.a./n.a.
5.3.5	Arctic sea ice	–/–	n.a./n.a.	n.a./n.a.	n.a./n.a.
5.3.6	Mountain permafrost	–/–	–/–	–/–	–/–
5.4	**Marine biodiversity and ecosystems**				
5.4.2	Sea-level rise	+/+	+/+	+/+	+/+
5.4.3	Sea surface temperature	+/+	+/+	+/+	+/+
5.4.4	Marine phenology	+/+	+/+	n.a./n.a.	n.a./n.a.
5.4.5	Northward movement of marine species	+/n.a.	+/n.a.	n.a./n.a.	n.a./n.a.

Table S.1 Observed (obs) and projected (scen) trends in climate and impacts for northern (Arctic and boreal), temperate (maritime climate, central/eastern) and southern (Mediterranean) regions of Europe (cont.)

		Northern	**Temperate**		**Southern**
Section	**Indicator**	**Arctic and boreal**	**Maritime climate**	**Central/ eastern**	**Mediterranean**
		obs/scen	obs/scen	obs/scen	obs/scen
5.5	**Water quantity, river floods and droughts**				
5.5.2	River flow	+/+	o/+	o/+	−/−
5.5.3	River floods (number of events)	o/−	+/+	+/+	o/+
5.5.4	River flow drought	o/−	o/+	o/−	o/+
5.6	**Freshwater quality and biodiversity**				
5.6.2	Water temperature	+/+	+/+	+/+	+/+
5.6.3	Lake and river ice cover	−/−	−/−	−/−	−/−
5.6.4	Freshwater biodiversityand water quality (north and upward shift of species)	+/+	+/+	+/+	+/+
	Water quality	n.a./−	n.a./−	n.a./−	n.a./−
5.7	**Terrestrial ecosystems and biodiversity**				
5.7.2	Distribution of plant species (north-/upward shift)	+/+	+/+	+/+	+/+
5.7.3	Plant phenology	+/+	+/+	+/+	+/+
5.7.4	Distribution of animal species (north-/upward shift)	+/+	+/+	+/+	+/+
5.7.5	Animal phenology	+/+	+/+	+/+	+/+
5.7.6	Species-ecosystem relationships	−/−	−/−	−/−	−/−
5.8	**Soil**				
5.8.2	Soil organic carbon	n.a./n.a	n.a./n.a	n.a./n.a	n.a./n.a
5.8.3	Soil erosion by water	n.a./n.a	n.a./n.a	n.a./n.a	n.a./n.a
5.8.4	Water retention	n.a./+	n.a./−	n.a./−	n.a./−
5.9	**Agriculture and forestry**				
5.9.2	Growing season for agricultural crops	+/+	+/+	+/+	+/+
5.9.3	Timing of the cycle of agricultural crops (agrophenology)	+/+	+/+	+/+	+/+
5.9.4	Crop-yield variability	+/+	+/+	+/+	+/+
5.9.5	Water requirement	n.a./n.a.	−/n.a.	−/n.a.	+/n.a.
5.9.6	Forest growth	+/+	+/+	+/+	+/+
5.9.7	Forest fire danger	−/+	−/+	+/+	+/+
5.10	**Human health**				
5.10.2	Heat and health	+/+	+/+	+/+	+/+
5.10.3	Vector-borne diseases (case study)	+/+	+/+	+/+	+/+
5.10.4	Water- and food-borne diseases	n.a./+	+/+	+/+	+/+
7	**Economic consequences of climate change**				
7.2	Direct losses from weather disasters	+/+	+/+	+/+	+/+
7.3	Normalised losses from river flood disasters	+/−	+/+	+/o	+/o
7.4	Coastal areas (floods)	n.a./+	n.a./+	n.a./+	n.a./+
7.5	Public water supply and drinking water management	n.a./o	−/−	n.a./o	−/−
7.6	Agriculture and forestry (yield)	n.a./+	n.a./−	n.a./o	n.a./−
7.7	Biodiversity and ecosystem goods and services (welfare losses)	n.a./+	n.a./+	n.a./+	n.a./+
7.8	Energy				
	Heating and cooling demand	n.a./−	n.a./o	n.a./o	n.a./+
	Hydropower production	n.a./+	n.a./−	n.a./−	n.a./−
7.9	Tourism and recreation (comfort index)	n.a./+	n.a./−	n.a./−	n.a./−
7.10	Health (impacts)	n.a./+	n.a./+	n.a./+	n.a./+
7.11	The costs of climate change for society	n.a./+	n.a./+	n.a./+	n.a./+

+ = increasing; − = decreasing; o = no significant changes (or diverging trends within the region); n.a. = not available

Map S.1 **Key past and projected impacts and effects on sectors for the main biogeographic regions of Europe**



Source: IPCC, 2007; EEA.

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

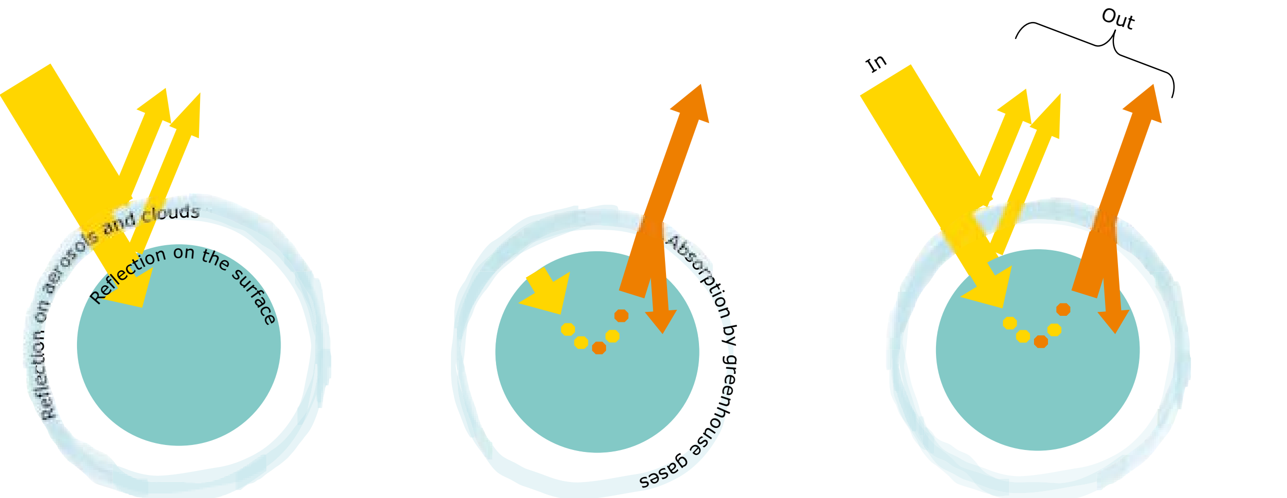
2.1 Introduction

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.

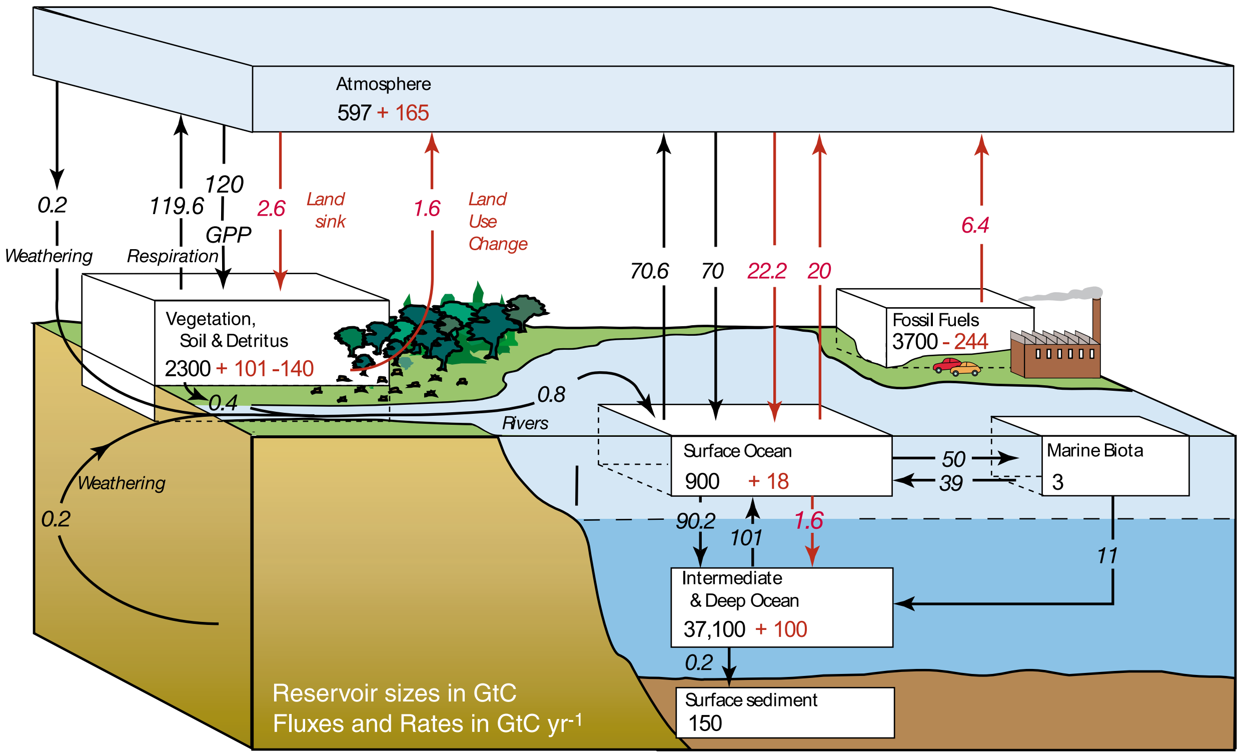
and precipitation, and will also help to maintain the currents in the oceans.

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

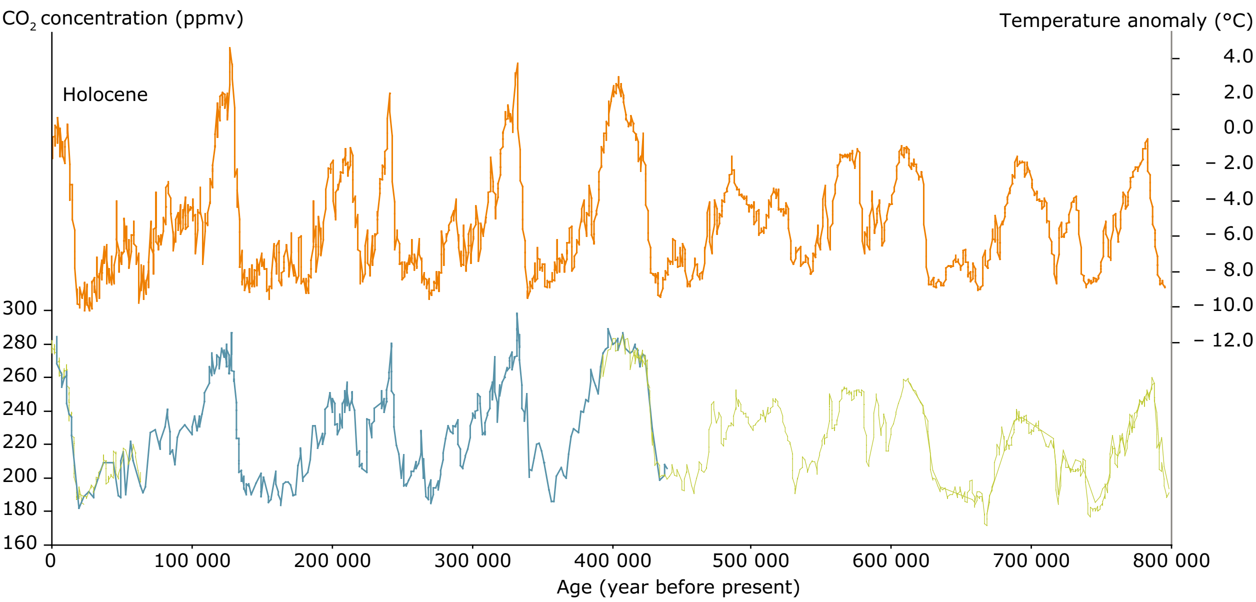
Figure 2.3 shows that the climate on earth has been oscillating about every 100 000 years between glacial periods, during which the global mean temperature was about 5 °C lower than today, and inter-glacial periods, during which the global mean temperature was about equal to that of today. These transitions 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.

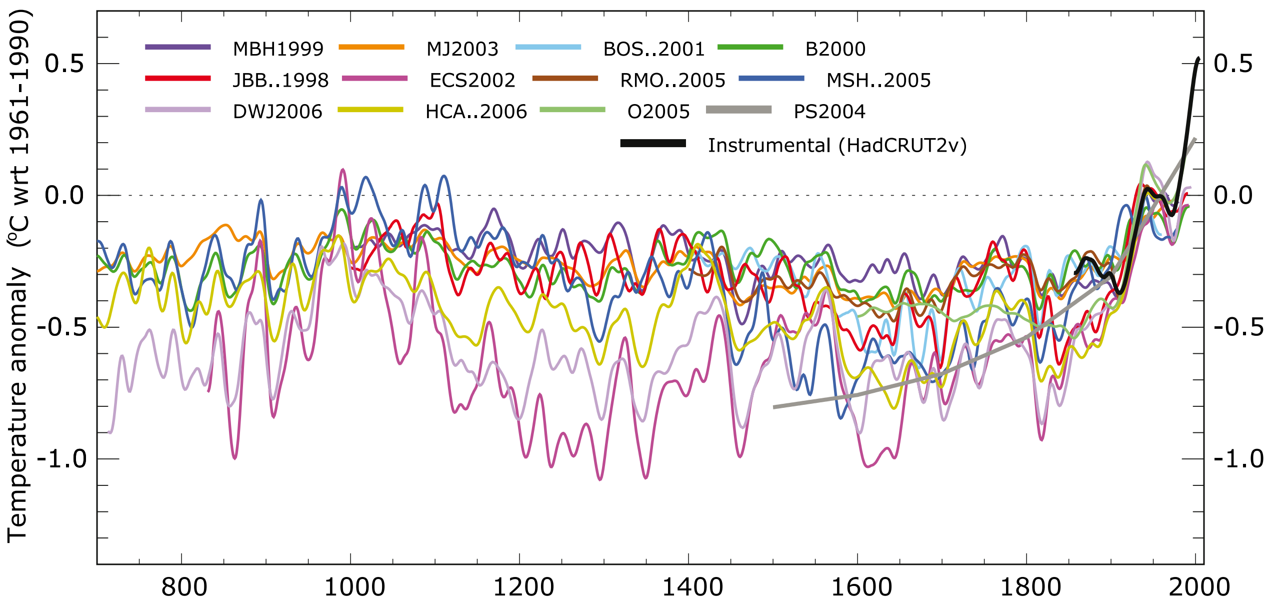
2.4 The past 150 years

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.

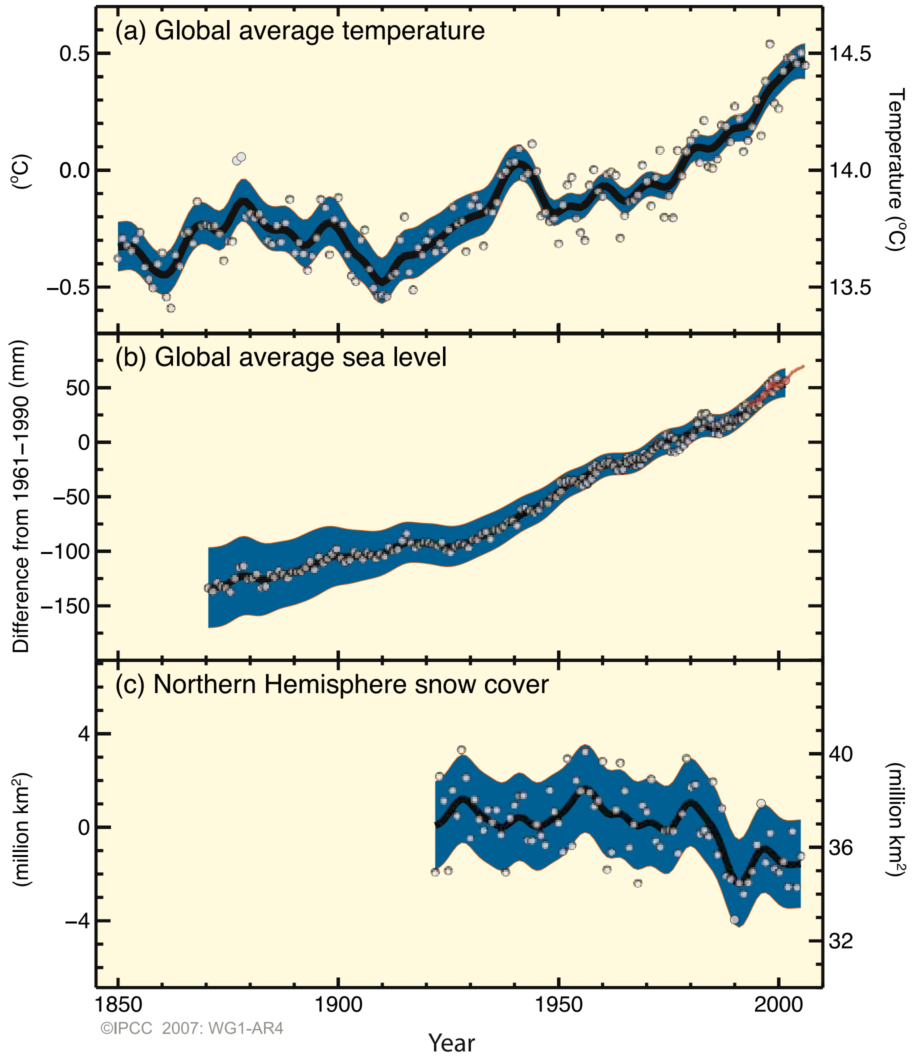
Figure 2.4 Records of northern hemisphere temperature variation during the last 1 300 years



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.

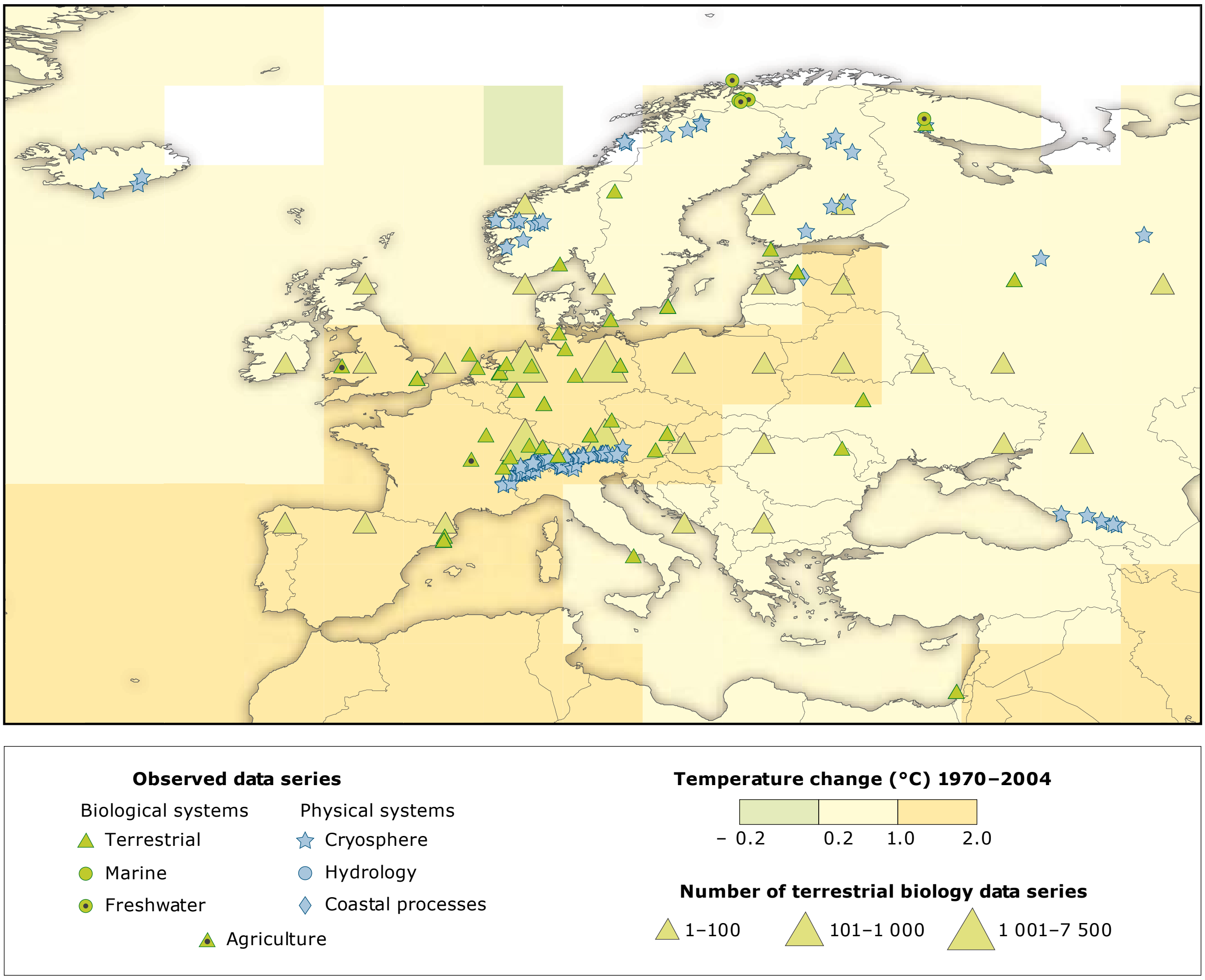
3 Observed climate change impacts

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

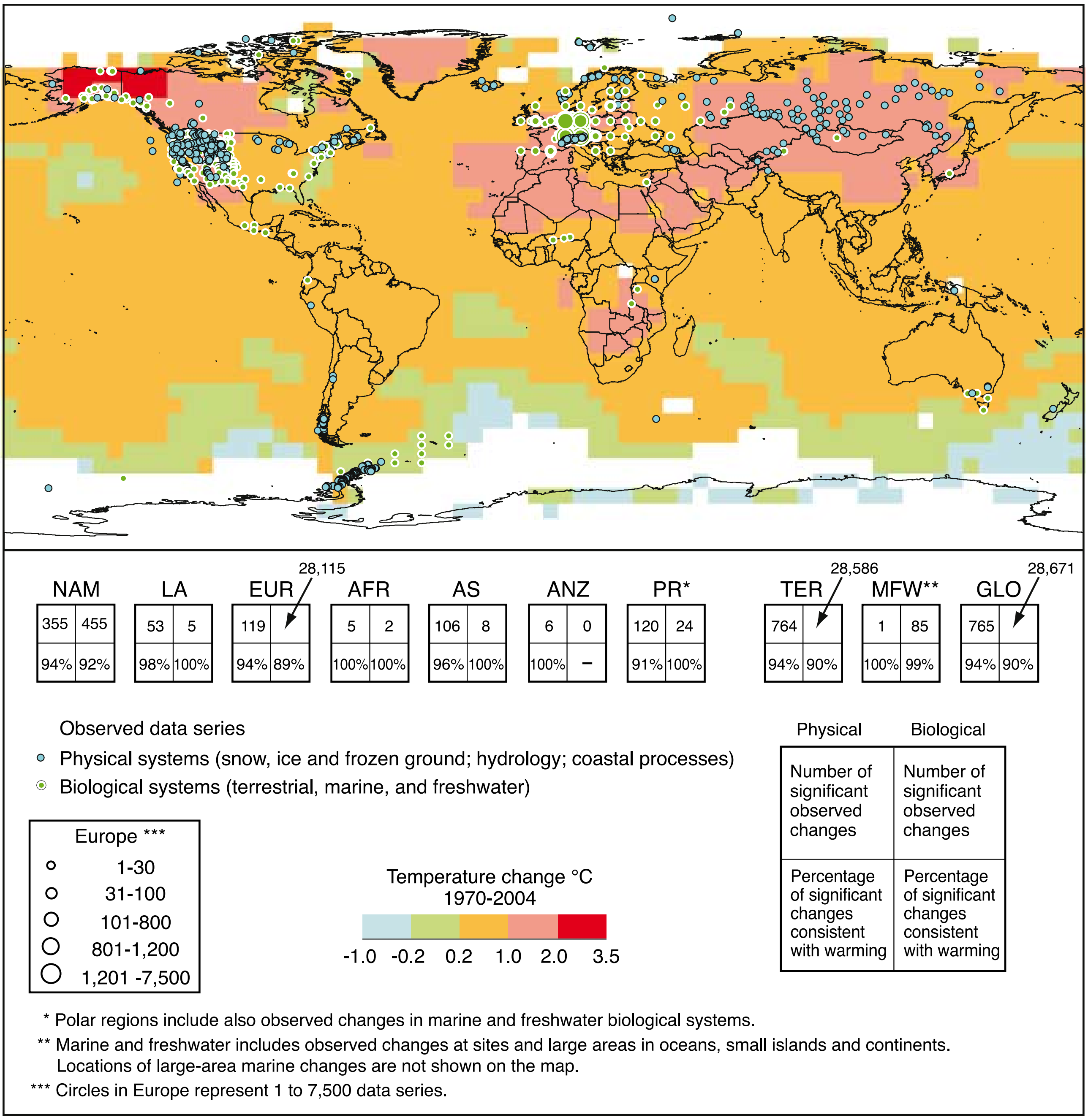
Map 3.1 Locations of significant changes in physical and biological systems in Europe between 1970–2004



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**

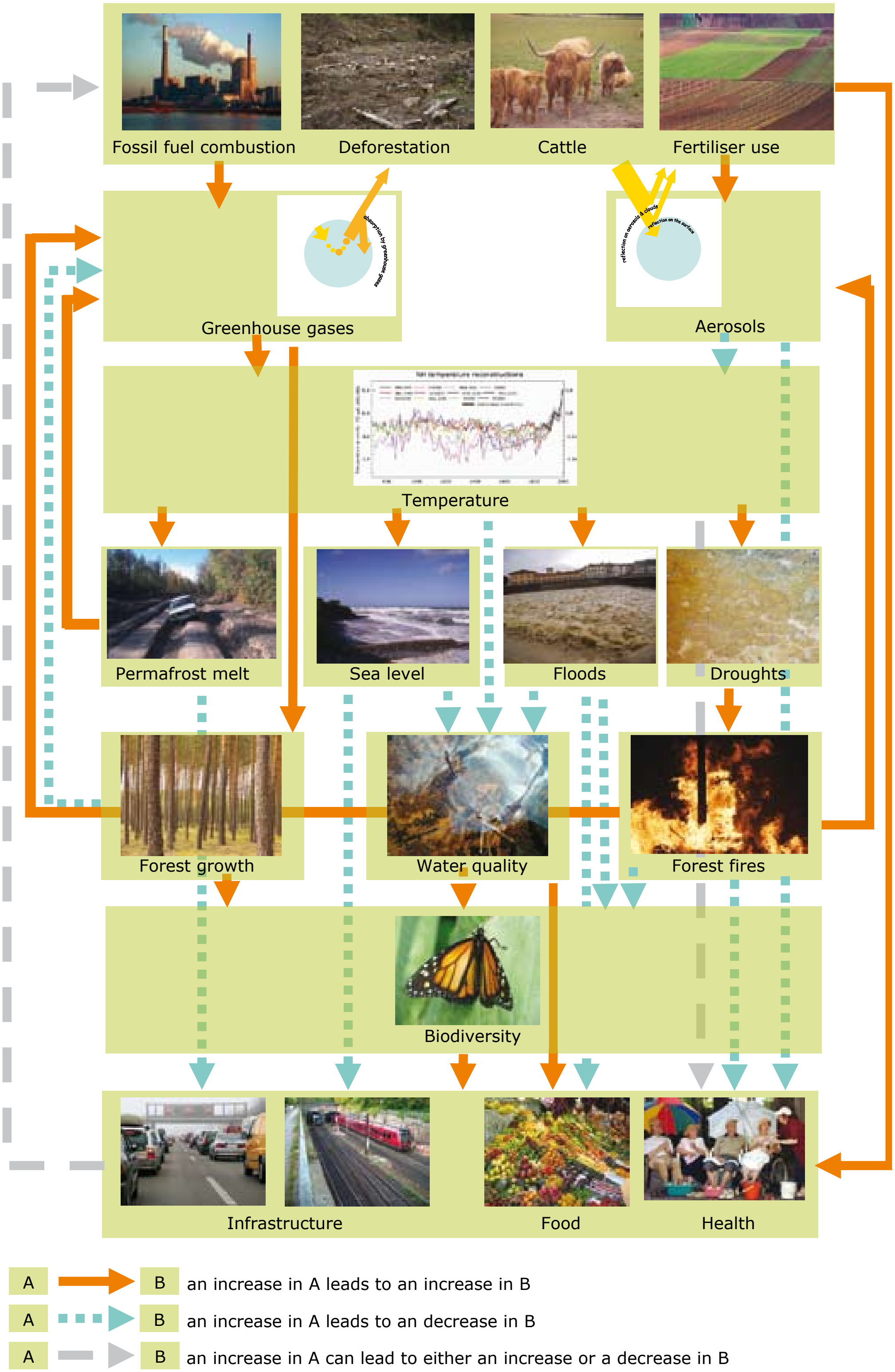


Note: Based on HadCRUT3 data. A subset of about 29 000 data series was selected from about 80 000 data series from 577 studies. These met the following criteria: (1) ending in 1990 or later; (2) spanning a period of at least 20 years; and (3) showing a significant change in either direction, as assessed 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.

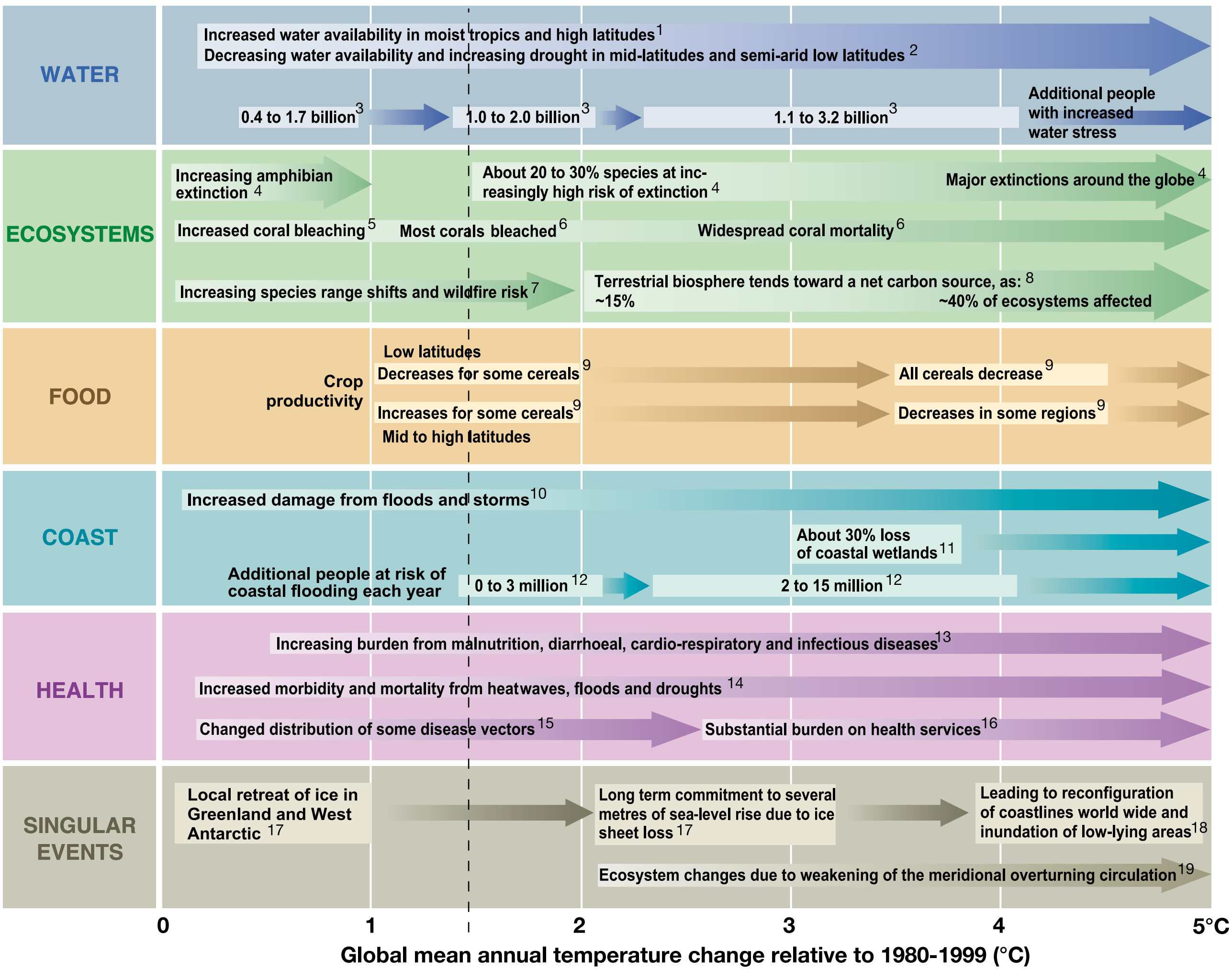
for some climate variables (e.g. temperature) than for others (e.g. precipitation) (IPCC, 2007a). The uncertainties in climate modelling, in particular for Europe and for the indicators presented in this report, are explained in more detail in Chapter 8.

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

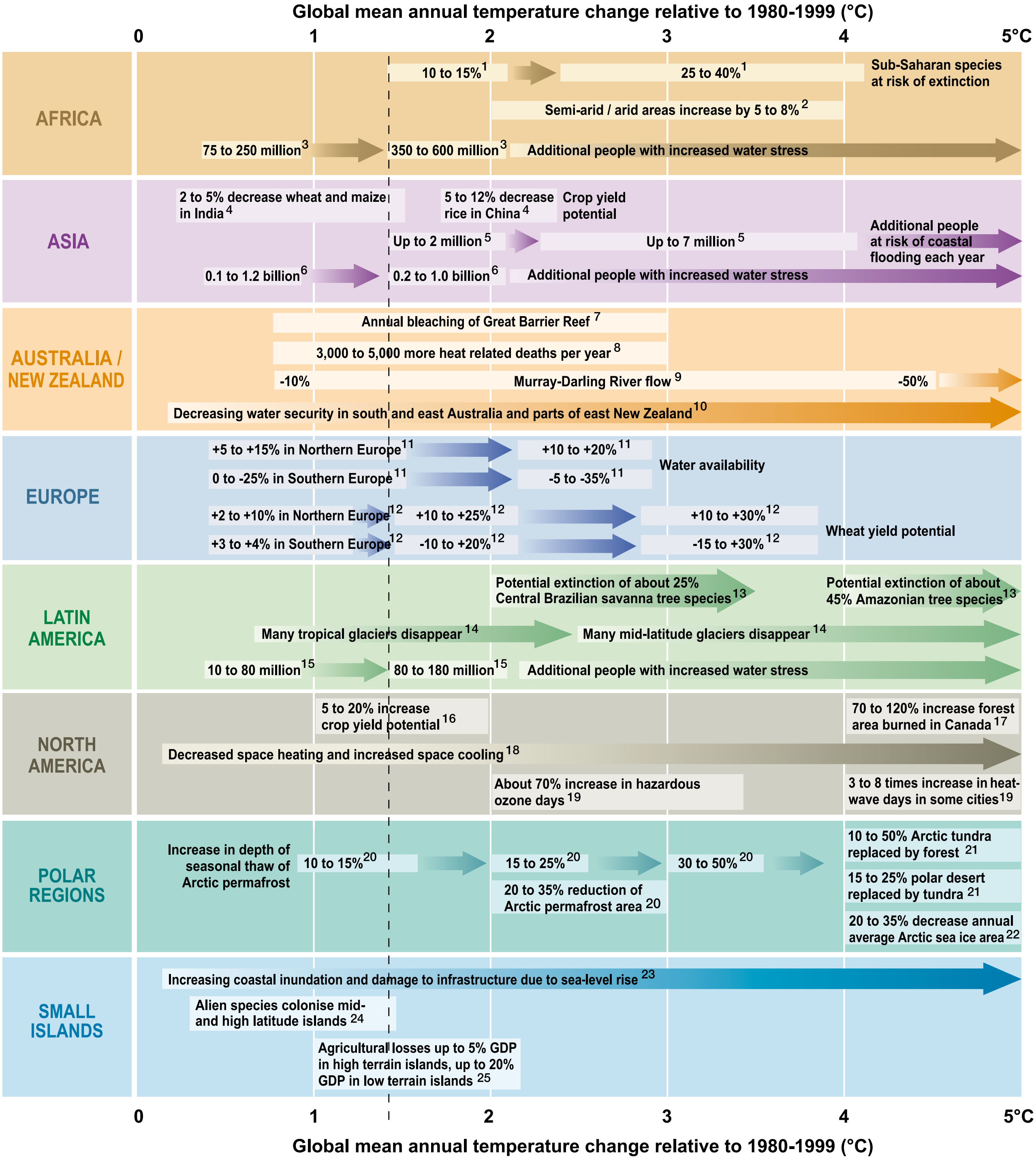
Figure 4.1 Examples of global impacts in various sectors projected for changes in climate associated with different amounts of increase in global average surface temperature in the 21st century



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.

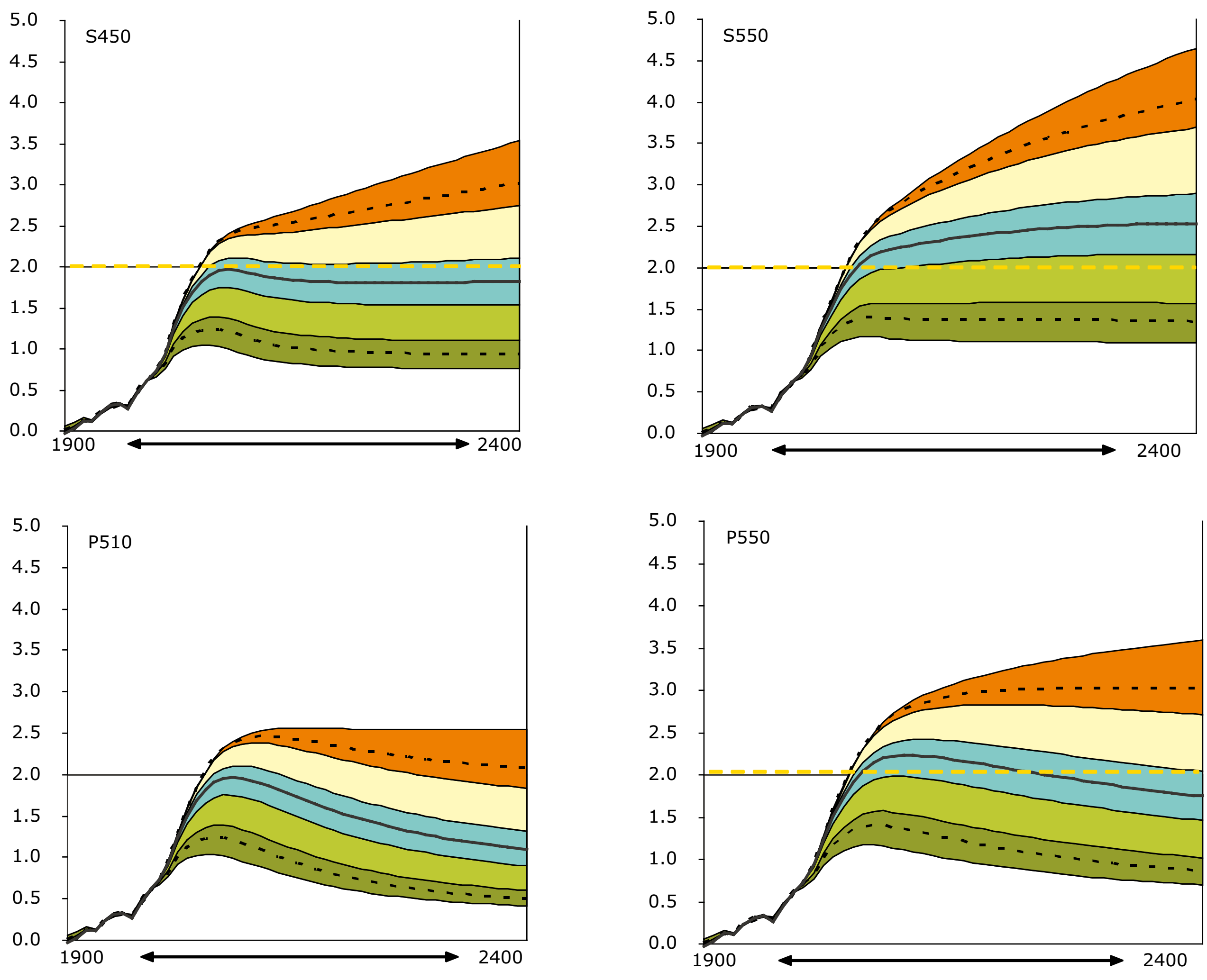
One way of looking at the rationale of different climate change response strategies is to compare mitigation efforts with adaptation actions. Mitigation aims particularly at avoiding the serious impacts associated with continuing, longer-term changes in the climate system as well as limiting the risks 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.

5 An indicator-based assessment

5.1 Introduction

General

For this report, about 40 indicators have been selected to describe the state of the climate and the impacts of climate change on various natural and societal systems in Europe. These indicators were divided into nine separate categories which are presented in this chapter:

- 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 were selected because of their measurability, their causal link to climate change, their policy relevance, the availability of historic time series (in most cases at least about 20 years), data availability over a large part of Europe (ideally they should cover all of Europe), and their transparency, i.e. they can be easily understood by policy-makers and the general interested audience.

Many other impact indicators were considered for inclusion but were rejected, often because of the difficulty of attributing an observed trend to climate change or insufficient data availability. If more information becomes available, some of these indicators might be reconsidered for inclusion in a future report, to achieve a more comprehensive picture of climate change impacts on the environment and society (see also Chapter 8).

Indicators from existing national indicator sets have been integrated where feasible. Others have been rejected because of missing data for the whole of Europe or because their relevance is limited to national issues.

Links to other EEA indicators

The indicators presented in this report can be regarded as part of a broader set of indicators that the EEA uses to present the key relationships in the causality chain for environmental and sustainability issues; from socio-economic driving forces, to pressures, state of the environment, impacts and societal response actions.

EEA has established a core set of indicators, for three main purposes: to provide a manageable and stable basis for indicator-based reporting, to prioritise improvements in the quality and geographical coverage of data flows, especially Eionet priority data flows, and to streamline EEA/Eionet's contributions to other European and global indicator initiatives, for example EU structural indicators and EU sustainable development indicators.
The EEA core set of indicators (CSI) comprises 37 indicators representing 10 different categories. The 'climate change' category contains two relevant impact-related indicators (global/European temperature and greenhouse gas concentration) which are fully consistent with the corresponding indicators in this report (for more information, see http://themes.eea.europa.eu/IMS/CSI).

Other specifically relevant indicator sets are those related to biodiversity, inland water and marine. Various indicators within these themes are related to the indicators presented in this report. For such cases the indicators included in this report have been made as consistent as feasible regarding the data sources, methodologies and key messages.

For biodiversity the key process is SEBI 2010 (Streamlining European 2010 Biodiversity Indicators). This process aims to measure and help achieve progress towards the target of halting biodiversity loss by 2010 and has compiled a first set of 26 indicators. An assessment report on Europe's progress towards the 2010 target based on these indicators will be published by the EEA in 2009 (for more information, see http://www.eea.europa.eu/themes/biodiversity/eea-activities).

For inland water, reliable, high quality information about the environmental state of surface waters is essential for water management and for improving the environmental quality of Europe's waters, especially in relation to the Water Framework Directive. EEA is preparing various state of the environment (SOE) assessments of Europe's waters: assessment of the state and trends in relation to the Water Framework Directive, using indicators like the EEA Core Set of Indicators and other more specific indicators; broader assessment of specific water-related issues, such as eutrophication, hazardous substances, water abstraction and use, hydro-morphological impacts as well as goods and services deriving from aquatic ecosystems; and assessment of the impact on water resources of specific sectors, such as agriculture, hydropower, industry, navigation, tourism and water management (for more information, see http://www.eea.europa.eu/themes/water.

For the marine topic, the EEA is leading the process for developing a common pan-European set of indicators for the marine environment which was started under the European Marine Monitoring and Assessments (EMMA) Working Group ([1]). This work will support the implementation of the Marine Strategy Framework Directive and the further development of the EEA's pan-European marine assessments. In addition to this work, the EEA has also developed indicators based on operational oceanography, such as indicators on sea-level rise and sea surface temperature.

Data and information sources for this report

This report uses recorded data and model results to assess past and future climate change and its impact. While recorded data are a good source for the description of past trends of measurable factors, models are needed for the assessment of complex parameters which cannot be measured directly and for the assessment of future trends. All information on indicators presented in this report is subject to various types of uncertainty. These can result from gaps in knowledge of climate-change processes, insufficient data availability, difficulties in attributing an observed change to climate change, and a wide range of possible future socio-economic developments and levels of emission of greenhouse gases. Data sources, projections and uncertainties are briefly addressed in the description of each indicator and explained in more detail in Chapter 8.

Presentation of indicators

The presentation of each indicator comprises:

- key messages that summarise observed and projected trends;
- a relevance section that explains the policy, socio-economic and environmental relevance, possible adaptation options and uncertainties related to the indicator;
- past trends based mainly on analysis of long time series of reliable observations;
- projections (future trends), based mainly on results from existing global IPCC models and scenarios adapted to the European situation.

([1]) More information on the work done under EMMA and follow-up can be found at: http://circa.europa.eu/Public/irc/env/marine/library?l=/workingsgroups/europeansmarinesmonitori/emma_30-31_2007/3_-_report/emma_2007_070810doc/_EN_1.0_&a=d.

5.2 Atmosphere and climate

5.2.1 *Introduction*

Europe's climate shows considerable regional variability. This is related to the continent's position in the northern hemisphere and the influence of neighbouring seas and continents, including the Arctic. Atmospheric circulation is an important driver of the temporal and regional variances (see Box 5.1).

This section describes the changing climatic and atmospheric conditions. The indicators are global and European temperature, precipitation, temperature and precipitation extremes, storms and storm surges, and atmospheric ozone concentration. Whereas most indicators focus on Europe, global temperature has been included because of the EU policy target to limit the global average temperature increase to a maximum of 2 °C above pre-industrial levels, in order to keep climate change at a manageable level and reduce the likelihood of irreversible disruptions.

Box 5.1 Atmospheric circulation patterns in Europe

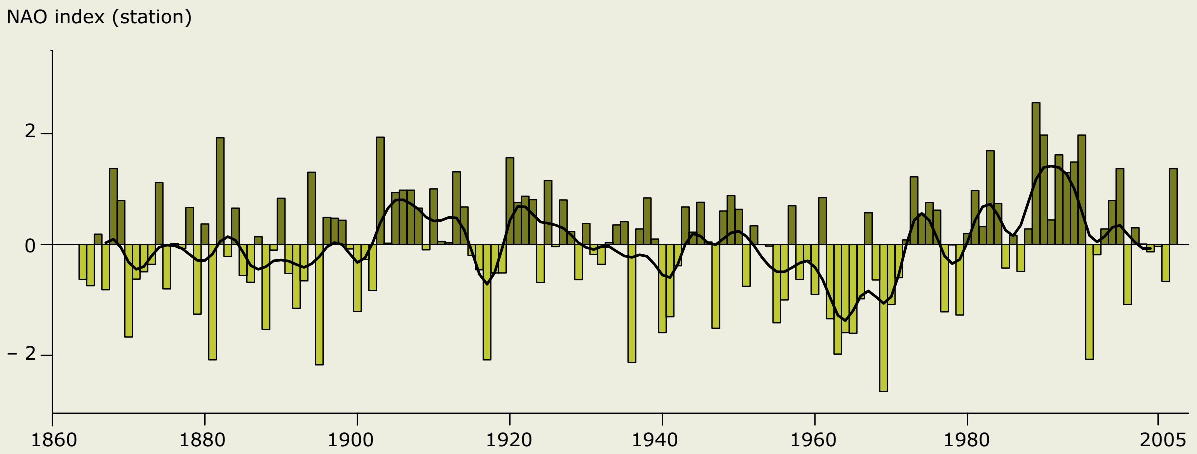
The atmospheric circulation moves air masses with their own specific characteristics, like temperature and humidity, over long distances. Important for the European climate is the prevailing western circulation at mid latitudes that directs the oceanic air masses inland over the continent. Stronger western advection brings milder and wetter weather and stronger winds to most of Europe, especially in winter. Weaker and blocked western circulation causes generally colder and drier winters and hotter and drier summers. Fluctuations in the behaviour of this circulation pattern are one of the main sources of variability in the European climate. The intensity of the western circulation in the European region is expressed by the North Atlantic Oscillation (NAO) index. NAO is the large-scale fluctuation in atmospheric pressure in the Atlantic ocean between the high-pressure system near the Azores and the low pressure system near Iceland (Figure 5.1).

The NAO is characterised by seasonal, inter-annual and inter-decadal variations. The driving mechanism of the short-term dynamics is connected with weather fluctuations. Longer time-scale variations are linked to atmosphere-ocean-ice interactions.

The seasonal anomalies have direct impacts on humans, often being associated with floods, heat-and cold-waves. The NAO appears to have been considerably more variable from year to year in the late 18th and early 19th centuries than in the 20th century. More recently, there was a large increase in the NAO index between 1970 and 1990, followed by a decrease back to about normal in 2005. The relationship with anthropogenic climate change is as yet unclear. Scenarios for future circulation patterns are very uncertain, because of the complexity of the processes and the limited ability to represent this in climate models.

The El Niño-Southern Oscillation (ENSO) in the Pacific Ocean has global impacts on decadal and longer-term variability and can cause precipitation and temperature changes over very large distances, including as far as Europe. Generally, for Europe, the effects of ENSO on precipitation and temperature are much weaker than those caused by variations in the NAO.

Figure 5.1 Mean winter (December–March) NAO index 1864–2007



Note: Positive indicates stronger western flow.

Source: Updated from Hurrell *et al.*, 2003.

The indicators represent different characteristics of the climate system that have diverse impacts on physical and biological systems and on human society; these can be independent of each other or, more often, have combined effects. High temperatures and reduced precipitation, for example, may lead to more intense droughts. Droughts are addressed in Section 5.2.5 (precipitation extremes in Europe), which gives different definitions of drought that have different consequences for the sectors involved. Temperature and precipitation extremes are both included because they have the largest impacts on society and the environment. Coastal areas are most vulnerable to storms, and damage caused by storms may be aggravated by floods related to storm surges. Within limits and at a cost, adaptation options are available for many of the consequences of changes in these extremes. If applicable, these will be mentioned in the sections on the individual indicators. Surface ozone concentrations can increase as a result of temperature increases and chemical reactions of air pollutants emitted by human activities in the lower atmosphere. Ozone is not only a greenhouse gas, higher ozone concentrations have adverse health effects — in particular the elderly — and on the environment.

Data availability and accuracy have been two of the important criteria for the selection of indicators. In general, the data availability of climate indicators is good compared with other indicators, although reliable data, particularly on the regional scale, can be scarcer. Air temperature data are the most available and reliable; precipitation and wind data are less available and — if available — more variable across different regions in Europe. Projections for precipitation and wind are more uncertain than those for temperature, and depend on future, still uncertain, atmospheric circulation patterns.

5.2.2 *Global and European temperature*

Key messages

Global

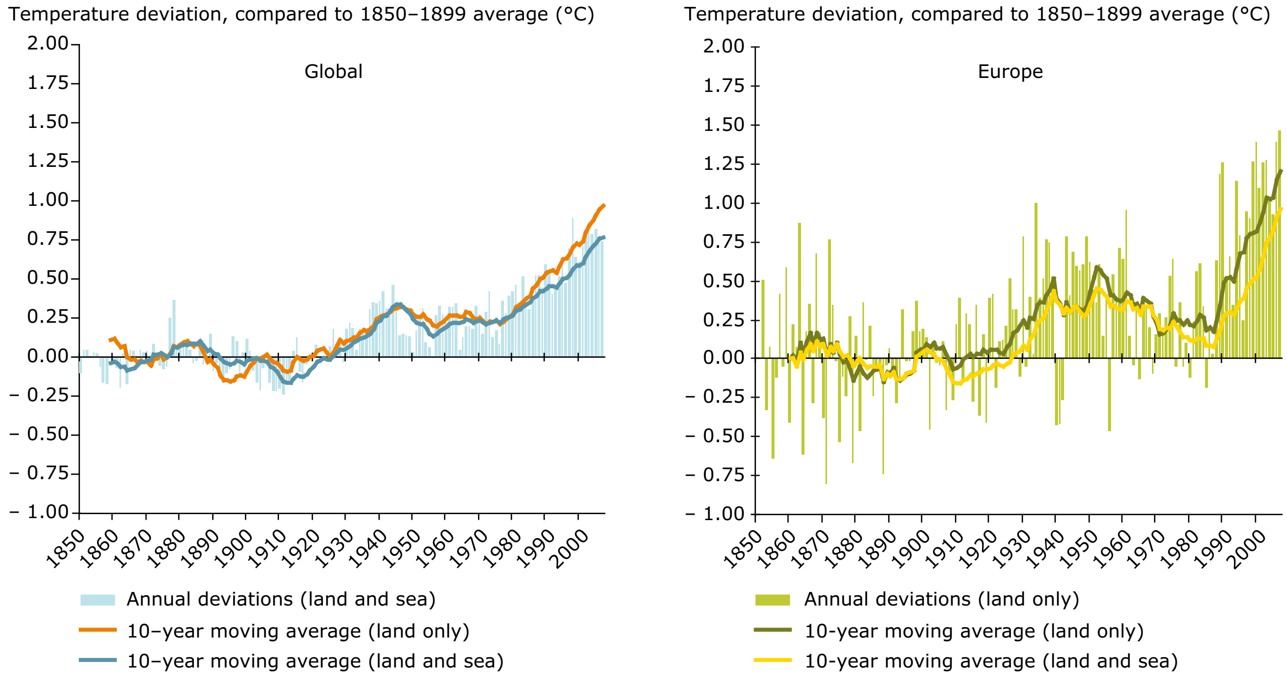
- The global (land and ocean) average temperature up to 2007 was 0.8 °C higher than pre-industrial levels (1850–1899 average). For land only, the average was 1 °C higher.
- The rate of increase of global average temperature has increased from 0.1 °C per decade over the past 100 years to 0.2 °C per decade in the past decade.
- The best estimates for projected global warming during this century are a further rise in average temperature of between 1.8 and 4.0 °C for different scenarios that assume no further/additional action to limit emissions.

Europe (*)

- Europe has warmed more than the global average. The annual average temperature for the European land area up to 2007 was 1.2 °C above pre-industrial levels, and for the combined land and ocean area 1 °C above. Eight of the 12 years between 1996 and 2007 were among the 12 warmest years since 1850.
- The annual average temperature is projected to rise this century by 1–5.5 °C (best estimate) with the largest warming over eastern and northern Europe in winter, and over south-western and Mediterranean Europe in summer.

(*) Europe is defined as the area between 35 and 70°N, – 25 and 30°E, plus Turkey (35–40°N, 30–45°E).

Figure 5.2 Observed global and European annual average temperature deviations, 1850–2007



Note: The source of the original data is the Climatic Research Unit of the University of East Anglia. The global mean annual temperature deviations are in the source in relation to the base period 1961–1990. The annual deviations shown in the chart have been adjusted to be relative to the period 1850–1899 to better monitor the EU objective not to exceed 2 °C above pre-industrial values. Over Europe average annual temperatures during the real pre-industrial period (1750–1799) were very similar to those during 1850–1899.

Sources: Climate Research Unit (http://www.cru.uea.ac.uk/cru/data/temperature/) (left); KNMI (http://climexp.knmi.nl/) (right).

Relevance

Of all the parameters used in monitoring and projecting climate change, air temperature is the nearest to our perception of 'climate'. Fortunately, air temperature data are also the most reliable climate data. There is a dense network of stations across the world — especially in Europe — with standardised measurements and often sophisticated quality control systems and homogeneity procedures. These provide high-resolution temperature information. Monthly information is available for long time-series (standardised from 1850 onwards). Time series with daily data generally start later. Furthermore, climate models have become increasingly sophisticated over recent years, with the uncertainty in the longer-term temperature projections being especially related to uncertainties in future emissions of greenhouse gases rather than uncertainties in modelling the climate system.

Temperature changes affect almost all the indicators included in this report, directly or indirectly. The projected temperature rise may have some beneficial impacts in the northern part of Europe (at least for a limited period), but the impacts in most parts of Europe are and will be adverse. In relation to climate change policy, the global temperature rise is relevant because of the EU objective of limiting global average temperature increase to a maximum of 2 °C above pre-industrial levels, as described in Section 5.1. Monitoring temperature change is thus also relevant for comparing actual developments with this target. Some other studies have proposed additional 'sustainable' targets of limiting the rate of temperature change, ranging from 0.1 °C to 0.2 °C per decade, based on the limited capability of ecosystems to adapt (Rijsberman and Swart, 1990; WBGU, 2003; van Vliet and Leemans, 2006). In this context it is important to note that land warms faster then the oceans.

Past trends

Global warming is accelerating, most probably as a result of the observed increase in anthropogenic greenhouse gas concentrations (IPCC, 2007a). Global average temperature (land and ocean) in 2007 was 0.8 °C above the pre-industrial level (defined as the 1850–1899 average (IPCC, 2007a)); the increase over land only was 1.0 °C. Eleven of the last 12 years (1996–2007) rank among the 12 warmest years (the exception being 1996). The warmest two years on record were 2005 and 1998 (see Figure 5.2). The rate of increase of global average temperature has increased from an average of 0.1 °C per decade over the past 100 years to 0.2 °C per decade over the past 10 years (all values represent land and ocean area) (IPCC, 2007a).

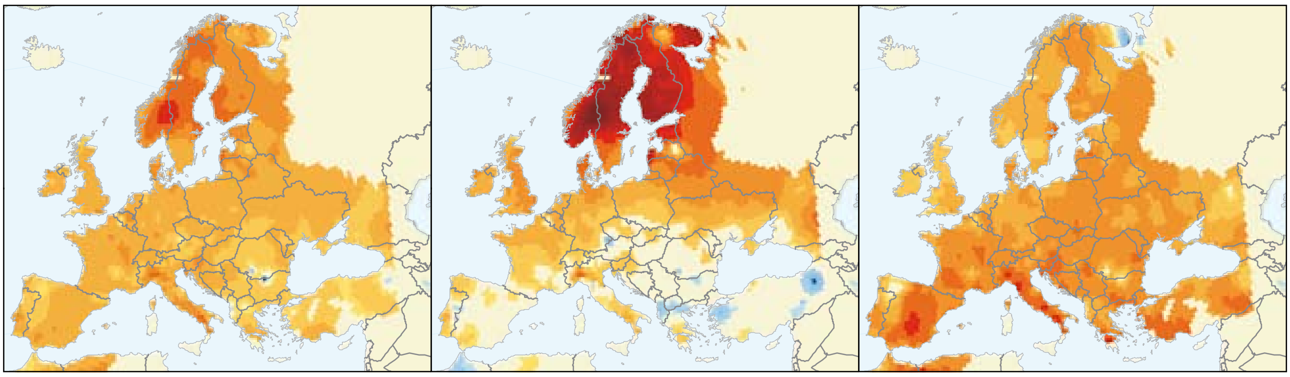
Photo: © Stockxpert

Europe has warmed slightly more than the global average. The annual average temperature for the European land area in 2007 was 1.2 °C above pre-industrial levels, and for the combined land and ocean area 1 °C above. Eight of the 12 years between 1996 and 2007 were among the 12 warmest years since 1850s in Europe. Seasonally, Europe warmed most in spring and summer. Remarkably, autumn saw almost no warming. Geographically, particularly significant warming has been observed in the past 50 years over the Iberian Peninsula, in central and north-eastern Europe and in mountainous regions (Böhm *et al.*, 2001; Klein Tank, 2004). In the past 30 years, warming was strongest over Scandinavia, especially in winter, whereas the Iberian Peninsula warmed in summer (Map 5.1).

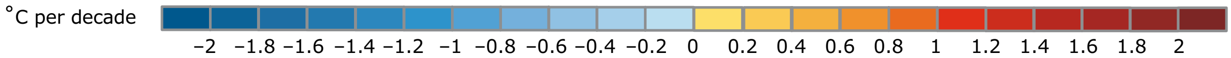
Projections

The global and European average temperature is projected to continue to increase. Globally, the projected increase in this century is between 1.8 and 4.0 °C (best estimate), and is considered likely (66 % probability) to be between 1.1 and 6.4 °C for the six IPCC SRES scenarios and multiple climate models (see Chapter 4), comparing the 2080–2100 average with the 1980–1999 average. These scenarios assume that no additional policies to limit greenhouse gas emissions are implemented (IPCC, 2007a). The range results from the uncertainties in future socio-economic development and in climate models. The EU 'sustainable' target of limiting global average warming to not more than 2.0 °C above pre-industrial level is projected to be exceeded between 2040 and 2060, for the all six IPCC scenarios.

Map 5.1 Observed temperature change over Europe 1976–2006

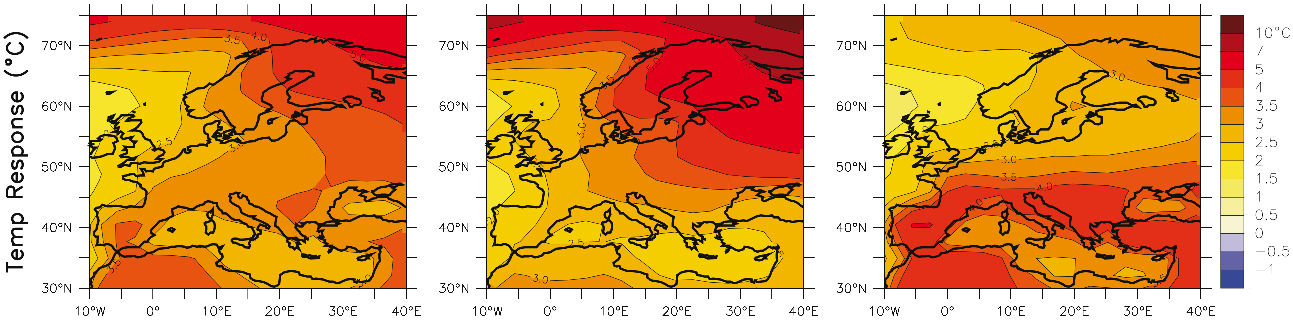


Observed temperature change over Europe during the period 1976–2006
Left: annual mean; middle: winter (DJF); right: summer (JJA)



Source: The climate dataset is from the EU-FP6 project ENSEMBLES (http://www.ensembles-eu.org) and the data providers in the ECA&D project (http://eca.knmi.nl).

Map 5.2 Modelled change in mean temperature over Europe between 1980–1999 and 2080–2099



Note: Left: annual; middle: winter (DJF); right: summer (JJA) changes in °C for the IPCC-SRES A1B emission scenario averaged over 21 models (MMD-A1B simulations).

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

The annual average temperature for Europe is projected to increase by 1.0–5.5 °C (comparing 2080–2100 with the 1961–1990 average). This range takes into account the uncertainties in future socio-economic development by including two of the IPCC-SRES scenarios (the high emissions A2 and the medium emissions A1b), and the uncertainties in the climate models (Christensen *et al.*, 2007) (Map 5.2). The warming is projected to be greatest over eastern Europe, Scandinavia and the Arctic in winter (December to February), and over south-western and Mediterranean Europe in summer (June to August) (Giorgi *et al.*, 2004; IPCC, 2007a). The temperature rise in parts of France and the Iberian Peninsula may exceed 6 °C, while the Arctic could become on average 6 °C and possibly 8 °C warmer than the 1961–1990 average (IPCC, 2007a, 2007b; ACIA, 2004).

Box 5.2 Climate reanalysis

Climate change can be monitored in different ways. In addition to the use of direct surface observations, climate variables such as near-surface temperature can also be estimated using the so-called reanalysis approach. Reanalysis uses a modern data assimilation system to combine historic data from different sources, including satellites, radiosondes, aircraft, surface data, and ships. This approach produces a comprehensive atmospheric data set, including parameters that are not well observed. The results can be used to assess climate change and climate variability.

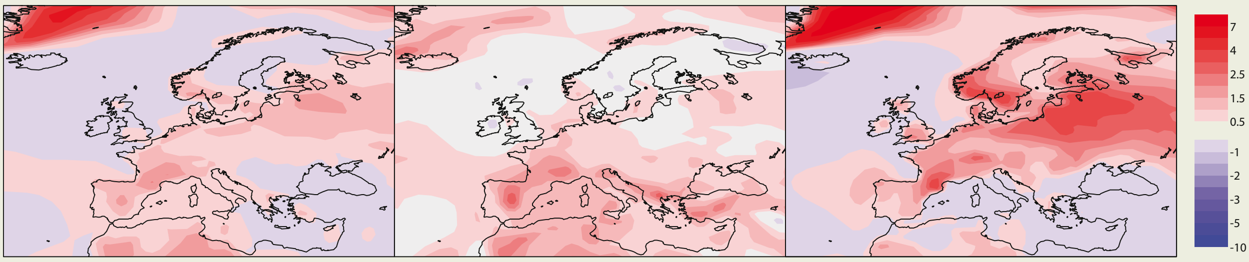
Map 5.3 is an example of the product of the latest European reanalysis, ERA-40, carried out by the European Centre for Medium-Range Weather Forecasts (ECMWF), with support from Europe's National Weather Services and the European Commission's Fifth Framework Programme. Estimated temperature changes across Europe in ERA-40 are consistent with observed changes over a similar period based on the station data (Map 5.1).

Global reanalysis provides a basis for regional reanalysis and downscaling projects (e.g. the BALTEX regional reanalysis project for the Baltic Sea). These projects can provide spatially detailed climate change data to support studies of local climate change and climate impacts.

An advantage of the reanalysis methodology is its complete temporal and spatial coverage, and the additional information that a model-based data assimilation system can provide. As such it is very useful for estimating sparsely observed climate variables such as wind speed/direction. However when a reanalysis is extended over long periods that include major changes (e.g. in the observation system), caution must be exercised when interpreting the analysed data sets, in particular in regions with insufficient observational coverage (IPCC, 2007a; Bengtsson *et al.*, 2004; Third WCRP International Conference on Reanalysis Conference Statement, 2008). For the purposes of climate analysis in particular, ERA-40 estimates of trends and low-frequency variability are more accurate for the post-satellite era from 1979 onwards than for the earlier period (Simmons *et al.*, 2004).

Overall, with the continuing development of analysis and reanalysis of climate data for the oceans, land and sea ice, and the initiatives towards providing more detailed information through regional reanalysis, there is huge potential for further progress and improved knowledge of the past climate in Europe.

Map 5.3 The linear trend in surface temperature over Europe 1958–2001



Note: Linear trend (°C/50 years) calculated from ERA-40 data for the period 1958 to 2001. The left panel is for the annual change, the central panel for summer (JJA) and the right panel for winter (DJF).

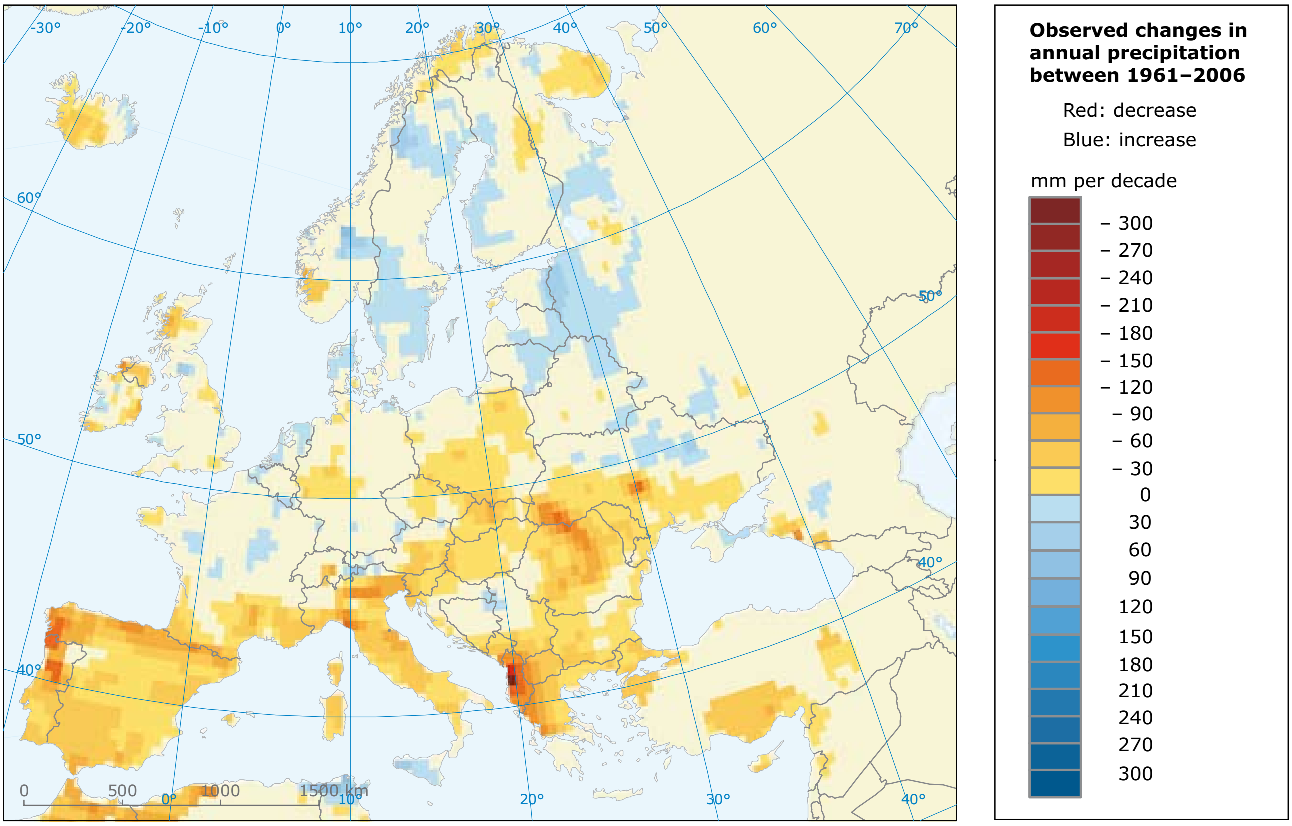
Source: European Centre for Medium-Range Weather Forecasts (ECMWF), ERA-40 Global Atmospheric Reanalysis, (http://www.ecmwf.int).

5.2.3 European precipitation

Key messages

- Annual precipitation trends in the 20th century showed an increase in northern Europe (10–40 %) and a decrease in some parts of southern Europe (up to 20 %).
- Mean winter precipitation has increased in most of western and northern Europe (20 to 40 %), whereas southern Europe and parts of central Europe were characterized by drier winters.
- Models project an increase in winter precipitation in northern Europe, whereas many parts of Europe may experience dryer summers. But there are uncertainties in the magnitude and geographical details of the changes.

Map 5.4 Observed changes in annual precipitation 1961–2006



Note: Data are in mm per decade, blue means an increase, red a decrease. The observations indicate that large decadal scale variability in precipitation amount is superposed on the long time scale trends described above. This variability is partly related to the decadal scale variability in atmospheric circulation anomalies (see Box 5.1). Calculating trends over shorter time periods may therefore lead to different results. The yellow color indicates that the trend 1961–2006 is not significant at level 25 %.

Source: The climate dataset is from the EU-FP6 project ENSEMBLES (http://www.ensembles-eu.org) and the data providers in the ECA&D project (http://eca.knmi.nl).

Relevance

Precipitation is a major component of the hydrological cycle. The amount and spatial distribution of European precipitation is strongly influenced by circulation patterns (see Box 5.1). Most precipitation over Europe is connected with the advection of maritime air masses from the

Atlantic and the Mediterranean. The combination of changes in the precipitation regime and increases in air temperature can lead to extreme hydrological evens such a flooding and droughts (see e.g. Sections 5.2.5, 5.5.3 and 5.5.4). Some systems or sectors, closely connected with the hydrological cycle, are very sensitive to the combined effects of higher temperatures and changed precipitation characteristics. Within limits and at a cost, adaptation to many of the impacts is possible. These options will be briefly mentioned in the individual indicator sections.

Homogenous time series of monthly precipitation data and interpolation and gridding methods enable analysis of various periods from 1901 on various temporal and spatial scales. However, differences between climate models for future precipitation projections indicate higher uncertainty for regional and seasonal results than for temperature projections and observed precipitation trends.

Past trends

Precipitation in Europe generally increased over the 20th century, on average 6–8 % between 1901 and 2005. Geographically, there is a variation (see Map 5.4); an increase in north-west Europe, partly due to stronger advection of wet Atlantic air masses to this part of the continent. Drying has been observed in the Mediterranean and eastern Europe and no clear trends have been observed in western Europe (Norrant and Douguédroit, 2006).

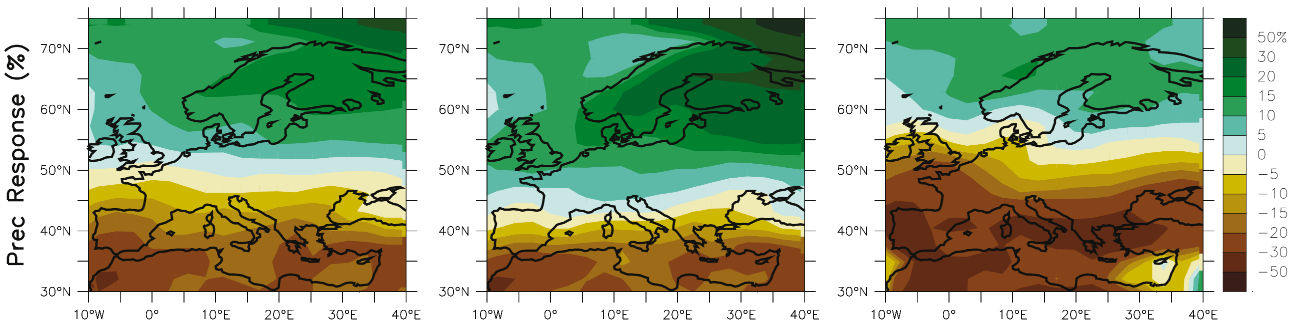
Mean winter (December–February) precipitation is increasing 20–40 % in most of western and northern Europe (Klein Tank *et al.*, 2002), because western circulation was stronger in winter. Conversely, southern Europe and parts of central Europe were characterized by a drier winter. Trends in spring and autumn were not significant.

Projections

Climate models project changes in precipitation that vary considerably from season to season and across regions. Geographically, projections indicate a general precipitation increase in northern Europe and a decrease in southern Europe. The change in annual mean between 1980–1999 and 2080–2099 for the intermediate IPCC SRES A1B projections varies from 5 to 20 % in northern Europe and from – 5 to – 30 % in southern Europe and the Mediterranean (Map 5.5). Many impact studies (see other indicators) use the high emission A2 scenario. Under this scenario the projected changes are mostly larger.

Seasonally, models project a large-scale increase in winter precipitation in mid and northern Europe. Many parts of Europe are projected to experience dryer summers (Map 5.5). Relatively small precipitation changes are projected for spring and autumn (Räisänen *et al.*, 2004; Kjellström, 2004).

Map 5.5 Modelled precipitation change between 1980–1999 and 2080–2099



Note: Left: annual; middle: winter (DJF); right summer (JJA) changes % for the IPCC-SRES A1B emission scenario averaged over 21 models (MMD-A1B simulations).

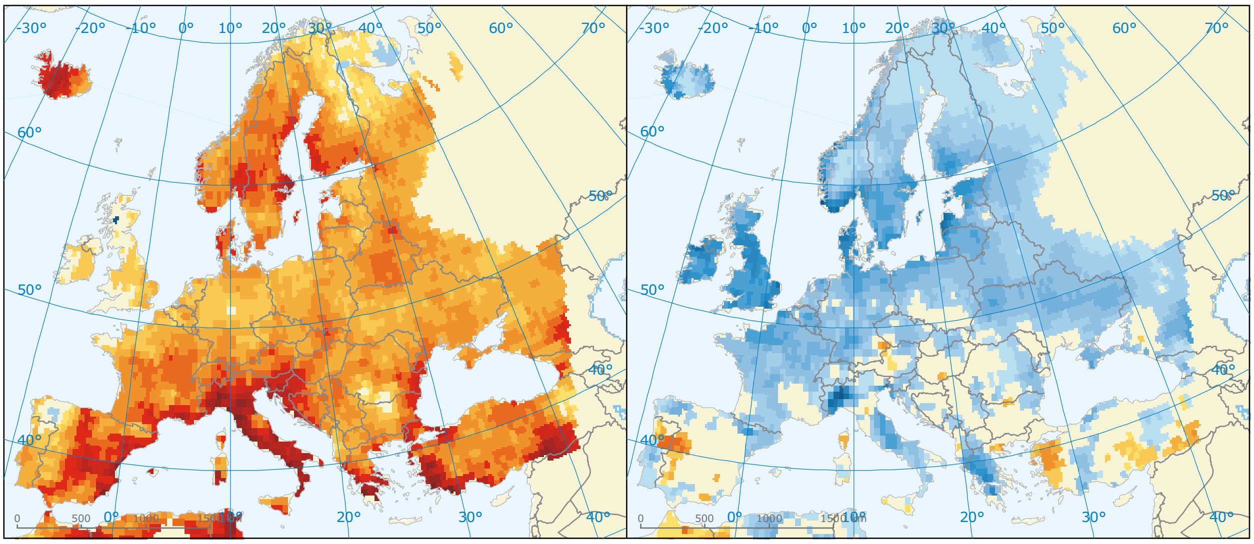
Source: Christensen *et al.*, 2007. Published with the permission of the Intergovernmental Panel on Climate Change.

5.2.4 *Temperature extremes in Europe*

Key messages

- Extremes of cold have become less frequent in Europe while warm extremes have become more frequent. The frequency of hot days almost tripled between 1880 and 2005.
- For Europe as a whole heat waves are projected to increase in frequency, intensity and duration, whereas winter temperature variability and the number of cold and frost extremes are projected to decrease further. The European regions projected to be most affected are the Iberian Peninsula, central Europe including the Alps, the eastern Adriatic seaboard, and southern Greece.

Map 5.6 Observed changes in warm spells and frost days indices 1976–2006



Observed changes in duration of warm spells in summer (left) and frequency of frost days in winter (right), in the period 1976–2006

Days per decade: − 10 − 9 − 8 − 7 − 6 − 5 − 4 − 3 − 2 − 1 0 1 2 3 4 5 6 7 8 9 10

Source: The climate dataset is from the EU-FP6 project ENSEMBLES (http://www.ensembles-eu.org) and the data providers in the ECA&D project (http://eca.knmi.nl).

Relevance

As seen by the public, climate change manifests itself most clearly through changes in the frequency of weather extremes and their impacts. Nearly all adaptation measures relate to changes in climate extremes. Extreme temperature events may lead to heat waves and intensive and long-lasting droughts, having, in turn, many impacts on natural ecosystems and society (e.g. agriculture, public health).

The time series for studying temperature extremes are based on daily data. More than 50-year of European time-series data allow detailed assessment of extreme events.

Past trends

High-temperature extremes like hot days, tropical nights, and heat waves ([2]) have become more frequent, while low-temperature extremes (e.g. cold spells, frost days) have become less frequent (Klein Tank *et al*., 2002; IPCC, 2007a; Map 5.6). The average length of summer heat waves over Western Europe doubled over the period 1880 to 2005 and the frequency of hot days almost tripled (Della-Marta *et al*., 2007).

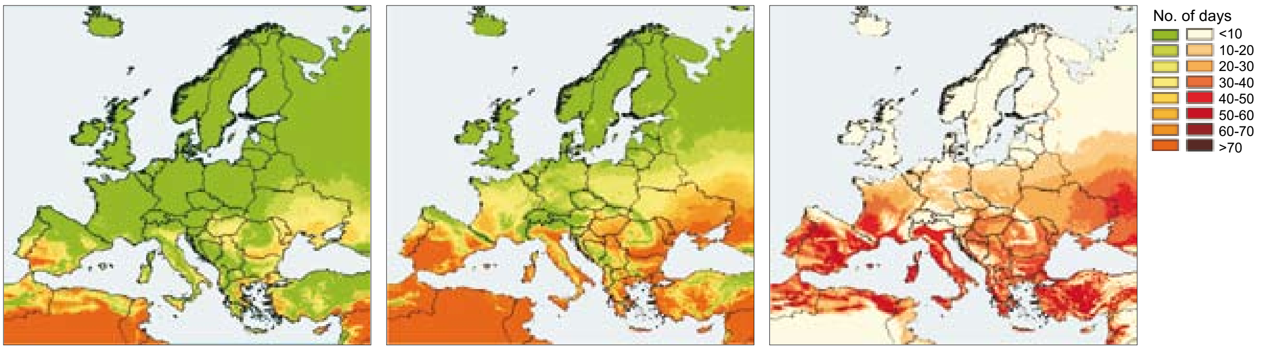
Projections

Extreme high temperature events across Europe, along with the overall warming, are projected to become more frequent, intense and longer this century (Schär *et al*., 2004; Tebaldi *et al*., 2006; IPCC, 2007a, 2007b; Beniston *et al*., 2007). Likewise, night temperatures are projected to increase considerably (Map 5.7), possibly leading to additional health problems and even mortality (Halsnæs *et al*., 2007; Sillman and Roekner, 2008), at least partly compensated by reduced mortality in winter (see Section 5.10.2).

Photo: © Stockxpert

Geographically, 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 (Kjelström *et al*., 2007; Sillman and Roekner, 2008). Under the A2 scenario, central Europe, for example, is projected to experience the same number of hot days as are currently experienced in Spain and Sicily by the end of the 21st century (Beniston *et al*., 2007).

Map 5.7 Modelled number of tropical nights over Europe during summer (June–August) 1961–1990 and 2071–2100



Note: Reference period (1961–1990) (left), scenario period (2071–2100) (centre) and change between periods (right). Data were used from the Danish Meteorological Institute (DMI) with the HIRHAM4 regional climate model with boundary conditions of the HadCM3 model and the IPCC-SRES A2 emission scenario.

Source: Dankers and Hiederer, 2008.

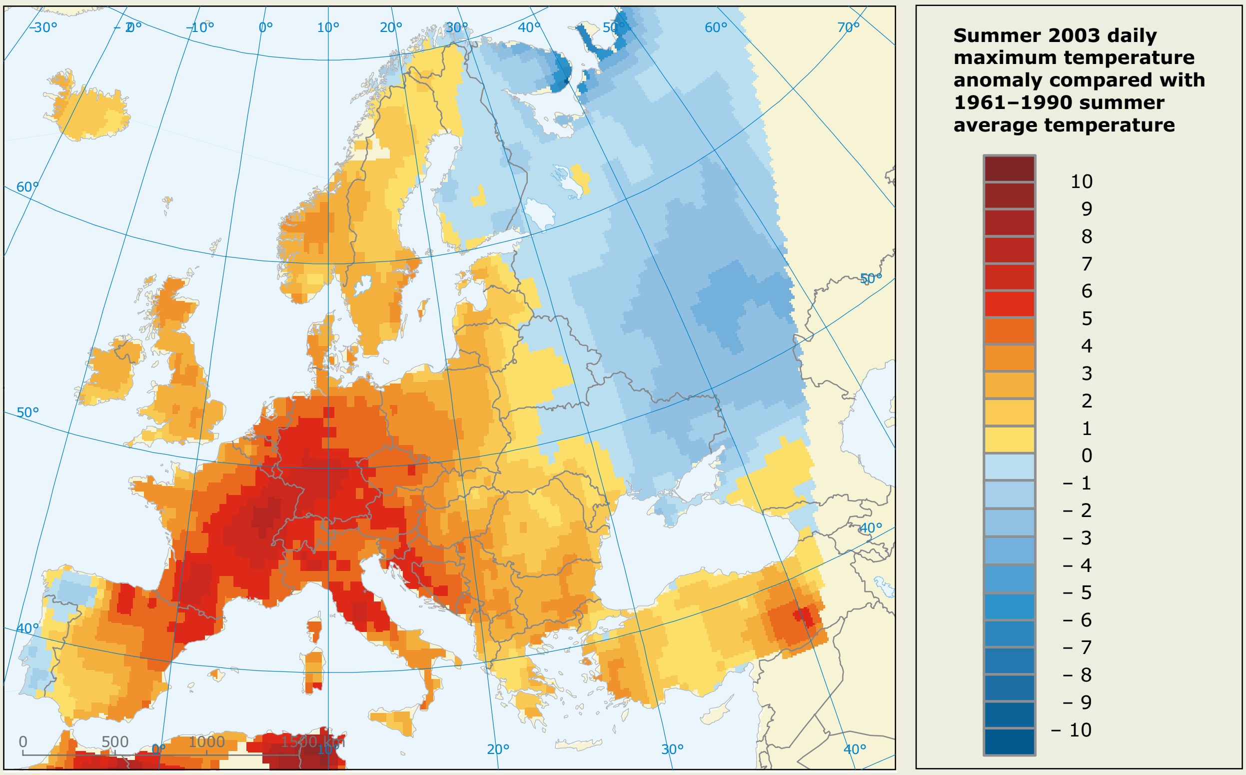
([2]) A hot day is defined as one where the daily maximum temperature exceeds the long-term daily 95th percentile of daily maximum temperature; a tropical night is one with minimum temperature > 20 °C, a heat wave is a period of at least six consecutive days with maximum temperature > 30 °C); a cold spell is a period of at least six consecutive days with minimum temperature below the 10th percentile of daily minimum temperature (e.g. for the period 1961–1990); frost days are defined as days with daily minimum temperature below 0 °C).

Box 5.3 The heat wave of summer 2003

Much of Europe was affected by a heat wave during the summer of 2003 (June, July and August). It is estimated that this was the hottest summer since at least 1500 (Luterbacher *et al.*, 2004). Seasonal temperatures were the highest on record in Germany, Switzerland, France and Spain (Map 5.8). Average summer (June–August) temperatures were far above the long-term mean, by up to five standard deviations, implying that this was an extremely unlikely event under current climatic conditions (Schär and Jendritzky, 2004). Hot summers like 2003 may, however, become much more frequent during the second part of the 21st century (Beniston, 2007; Dankers and Hiederer, 2008).

The 2003 heat wave was associated with a particular air pressure field pattern over Europe, leading to an advection of hot air from the south which reinforced the strength and persistence of the heat waves. Nearly all radiation from the sun was converted to heat because of the soil and vegetation dryness. At many locations, day-time temperatures rose to more than 40 °C. In the European Alps, the average thickness loss of glaciers reached about 3 m water equivalent, nearly twice as much as during the previous record year of 1998 (WMO, 2004; see Section 5.3.2). Annual precipitation deficits up to 300 mm caused droughts in many areas which resulted in reduced agricultural production (Section 5.6.2), more extensive forest fires (Portugal, Section 5.6.6), and record low levels of many major rivers (e.g. Po, Rhine, Loire and Danube; Section 5.7.2). In all the affected countries together, more than 70 000 additional deaths were related to the 2003 heat waves (Section 5.10.2).

Map 5.8 Summer 2003 (June–August) daily maximum temperature anomaly



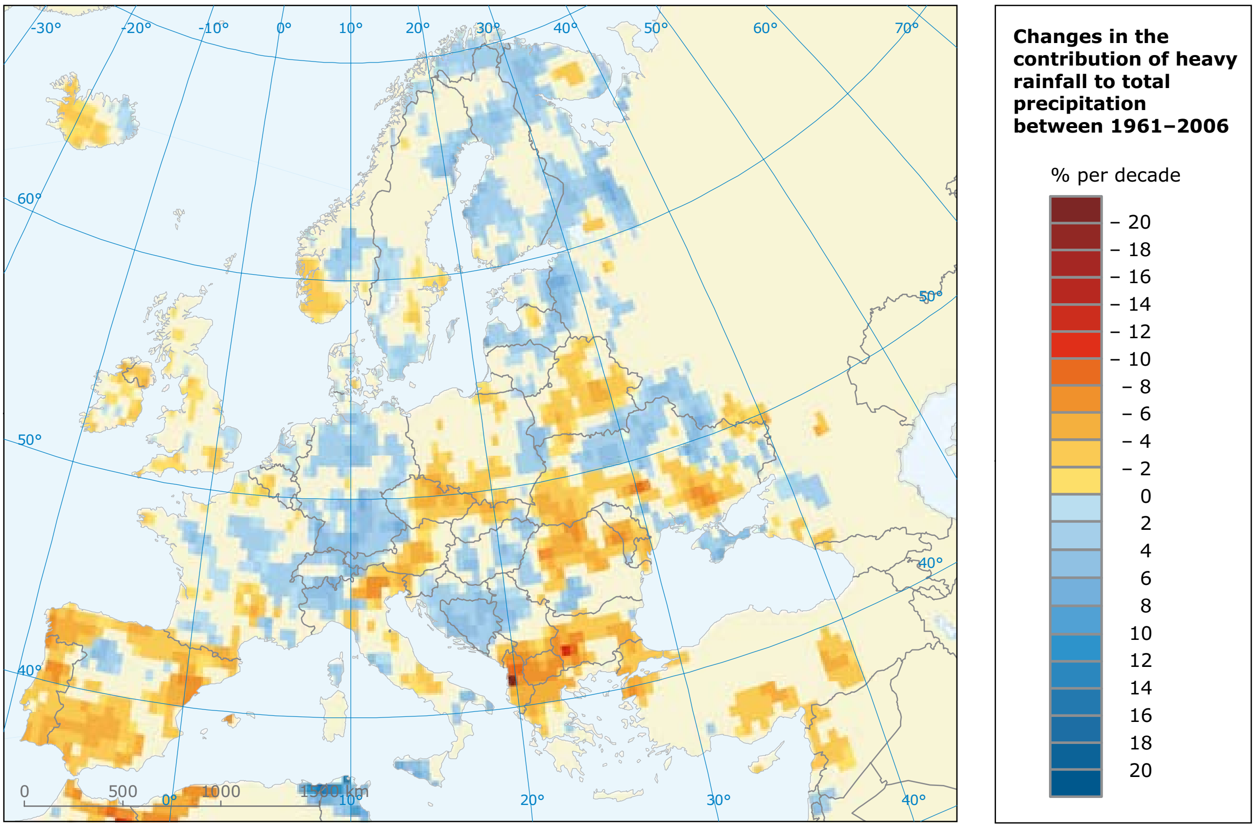
Source: The climate dataset is from the EU-FP6 project ENSEMBLES (http://www.ensembles-eu.org) and the data providers in the ECA&D project (http://eca.knmi.nl).

5.2.5 *Precipitation extremes in Europe*

Key messages

- For Europe as a whole, the intensity of precipitation extremes such as heavy rain events has increased in the past 50 years, even for areas with a decrease in mean precipitation such as central Europe and the Mediterranean.
- The proportion of Europe experiencing meteorological drought conditions did not change significantly during the 20th century.
- For Europe as whole, heavy precipitation events are projected to continue to become more frequent.
- Dry periods are projected to increase in length and frequency, especially in southern Europe.

Map 5.9 Changes in the contribution of heavy rainfall to total precipitation 1961–2006



Source: The climate dataset is from the EU-FP6 project ENSEMBLES (http://www.ensembles-eu.org) and the data providers in the ECA&D project (http://eca.knmi.nl).

Relevance

Both high and low precipitation extremes (high intensity or long-lasting rain and droughts, respectively) can lead to periods with a high amount of total precipitation or with precipitation deficit. The periods can range from minutes (e.g. in case of intense showers) to days, weeks or even months (with long-lasting rain events or absence of precipitation). Low precipitation extremes can lead to droughts (see Box 5.4). High precipitation extremes can result in fast flash floods, sewerage system failure and land-slides, or devastating floods, affecting large catchments and having longer duration.

Precipitation extremes can be described in different ways. Precipitation deficits are often expressed as the number and duration of dry periods (e.g. the number of consecutive dry days) and high precipitation events as the number of wet days, consecutive wet days, and the frequency and intensity of heavy precipitation events (Klein Tank and Können, 2003).

The time series for studying precipitation extremes are based on daily data. As for temperature extremes, there is more than 50 years of European time series data available for statistical analyses.

Past trends

The number of extreme precipitation events has increased over most of the European land area, linked to warming and increases of atmospheric water vapour. For Europe as a whole, also the intensity of extreme precipitation such as heavy rain has increased in the past 30 years, even for areas with a decrease in mean precipitation, such as central Europe and the Mediterranean. In particular, the contribution of heavy rain to total precipitation has increased (Map 5.9).

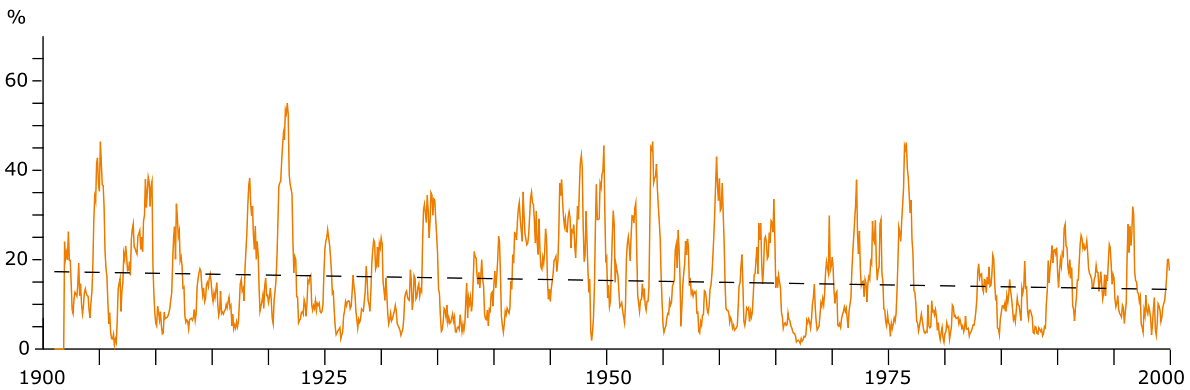
The proportion of Europe that has experienced extreme and/or moderate meteorological drought conditions did not change significantly during the 20th century (Figure 5.3) (Lloyd-Hughes and Saunders, 2002). Some drying trends were observed over central and eastern Europe, and western Russia. Similar, some trends were observed in winter/spring. Summer droughts showed no statistically significant trends in the period 1901–2002 (Robock *et al.*, 2005; van der Schrier *et al.*, 2006).

Projections

For Europe as whole it is likely (66 % probability) that heavy precipitation events will continue to become more frequent (IPCC, 2007a). In summer, the frequency of wet days is projected to decrease, but the intensity of extreme rain showers may increase. In addition, the frequency of several-day precipitation episodes is projected to increase. Geographically, there is considerable regional differentiation in the projections. Extreme precipitation events are projected to increase by 17 % in northern and 13 % in central Europe during the 21st century, with no changes projected in southern Europe (for the ECHAM 4 climate model, A1B scenario, Figure 5.4, Sillmann and Roeckner, 2008).

The combination of higher temperatures and reduced mean summer precipitation is expected to enhance the frequency and intensity of droughts across Europe. This can be illustrated, for example, by the projected number of consecutive dry days, defined as days with precipitation below 1 mm (Figure 5.5). In southern Europe, the maximum number of these days is projected to increase substantially during the 21st century. The longest dry period within a year may be prolonged here by one month at the end of 21st century. In central Europe, prolongation of longest dry period is by one week, and no prolongation is projected for northern Europe. Thus regions in Europe that are now dry are projected to become even more vulnerable.

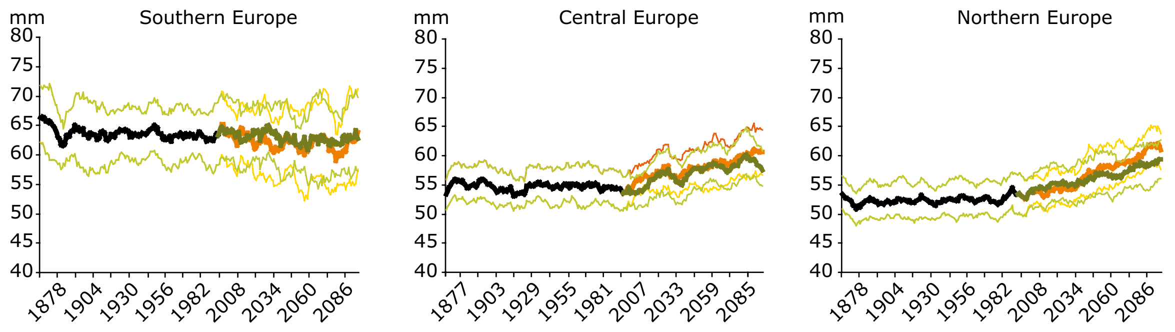
Figure 5.3 Percentage of Europe experiencing moderate drought conditions during the 20th century



Note: Expressed as standardized precipitation indices (SPI) for time scales of 12 months. The dashed line shows the linear trend. Errors are ± 2 standard errors in the gradient.

Source: Lloyd-Hughes and Saunders, 2002.

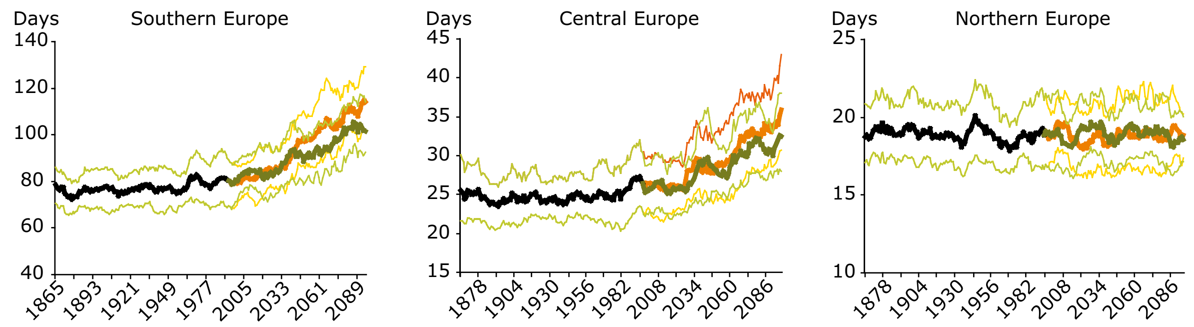
Figure 5.4 Simulated land average maximum 5-day total precipitation for different European regions (1860–2100)



Note: The 20th century (black), models simulations for IPCC SRES intermediate A1B (orange) and low B1 (green) emission scenarios. The respective ensemble means are displayed. The minimum and maximum of the ensemble members are indicated by thin green (B1) and yellow (A1B), respectively. Data are smoothed by 10-year running means.

Source: Sillmann and Roeckner, 2008.

Figure 5.5 Simulated land average maximum number of consecutive dry days for different European regions (1860–2100)



Note: The 20th century (black), models simulations for IPCC SRES intermediate A1B (orange) and low B1 (green) emission scenarios. The respective ensemble means are displayed. The minimum and maximum of the ensemble members are indicated by thin green (B1) and yellow (A1B), respectively. Data are smoothed by 10-year running means.

Source: Sillmann and Roeckner, 2008.

Box 5.4 Drought

Drought is a natural phenomenon, defined as sustained and extensive occurrence of below-average water availability. Drought should not be confused with aridity, which is a long-term average feature of a dry climate. Nevertheless, the most severe human consequences of drought can be found in arid regions, where water availability is naturally lower. Likewise, drought should not be confused with water scarcity, which reflects conditions of long-term imbalances between water supply and demands (e.g. van Lannen *et al.*, 2007).

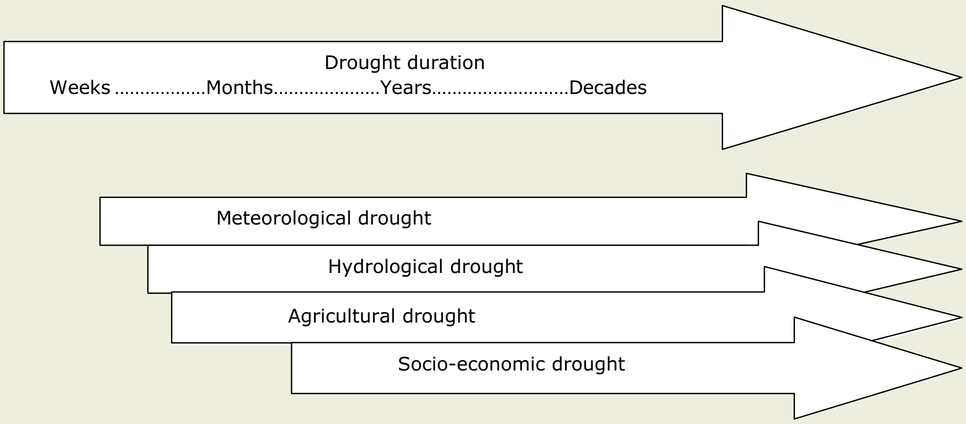
Droughts can affect both high and low rainfall areas of Europe and can develop over short periods of weeks and months or much longer periods of several seasons, years and even decades. In many cases drought develops gradually, making it difficult to identify and predict. The most common definitions and types of drought are:

- Meteorological drought: departure of precipitation from normal values for an extended period of time, the primary cause of the other types of drought.
- Hydrological drought: deficiencies in surface and subsurface water supplies, reflecting effects and impacts of meteorological droughts.
- Agricultural drought: a deficit of soil moisture affecting a particular crop at a particular time.
- Socio-economic drought: imbalance between supply and demand for an economic good, capturing both drought condition and human activities.

Precipitation is the primary factor controlling the origin and persistence of drought conditions for all types of drought. Deficiency of precipitation results in water shortage for some activity or for some group. The impacts of droughts on people and the environment result from a combination of the intensity and duration of drought events and the vulnerability of agricultural or water resources systems, including water management policies, the characteristics of regional and local water infrastructure, and social responses to drought situations. Drought is a phenomenon that is not constrained by international boundaries and can therefore grow to afflict many countries simultaneously and may stress relationships between them.

Climate projections indicate that in warmer conditions droughts may become longer-lasting and more severe in current drought-prone regions because of decreased rainfall and enhanced evaporation.

Figure 5.6 Diagram of drought types



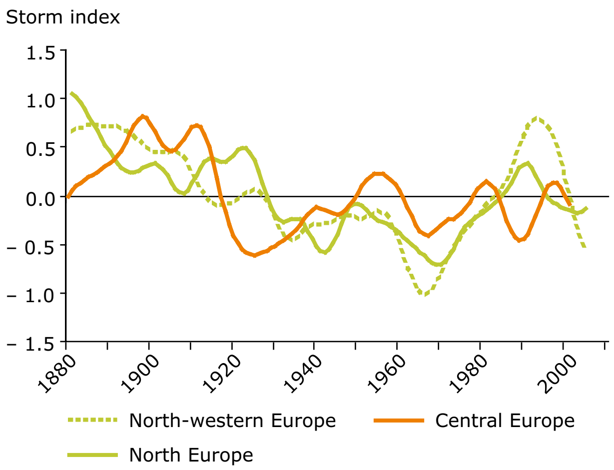
Source: Wade, 2007.

5.2.6 *Storms and storm surges in Europe*

Key messages

- There has been considerable variation, but no clear long term trend in storminess in Europe. Storm frequency was relatively high during the late 19th and early 20th century; then decreased in central and northern Europe. The recent high level is similar to the late 19th century level of storminess.
- Despite the variation in storminess, water levels along most vulnerable European coastlines of the North Sea and Mediterranean Sea have shown no significant storm-related variation.
- 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 indicate a slight decrease in the number of storms and an increase of the strength of the heaviest storms.
- Projections to the end of the 21st century show a significant increase in storm surge elevation for the continental North Sea and south-east England.

Figure 5.7 Storm index for various parts of Europe 1881–2005



Note: Positive values of the index mean higher storminess.

Source: Matulla *et al.*, 2007.

Relevance

Storms in Europe consist of extreme, near-surface damage-causing winds, associated with the passage of intense extra-tropical cyclones (Pinto *et al.*, 2007). Storms occur, in general, in north or north-western Europe all year, but in central Europe mainly between November and February. Storm surges are temporary increases in sea level, above the level of the tide, often causing coastal flooding. Storm events can have large impacts on vulnerable systems such as transport, forestry and energy infrastructures, and also on human safety.

Storm activity in Europe and the neighbouring part of the Atlantic is closely connected with atmospheric circulation (see Box 5.1). But the correlation between the NAO index and storminess across Europe varies with space and time. Direct wind observation data of sufficient quality are often lacking. Instead, storm intensity and frequency can be indirectly assessed through changes in the air pressure fields. Note that projections of changes in wind conditions are highly uncertain, mainly because of the uncertainty in atmospheric circulation projections.

Storm surges result from the combined action of atmospheric pressure and strong wind on the sea surface and occur mostly in shallow water. An increase in mean sea level will directly affect extreme levels. Changes in water depth can also influence the tidal component, modifying the extent of flooded areas. Future storm surge extremes are related both to storminess and to sea level changes.

Past trends

Storminess in Europe has shown considerable variation over the past century, but with no clear long-term trend. This is illustrated by means of the storm-index time series (Figure 5.7), based on air-pressure data. These series show that storminess in north-western, northern and central Europe was relatively high during the late 19th and early 20th century; then decreased in central Europe and northern Europe. The subsequent rise in the late 20th century was most pronounced in north-western Europe, while slow and steady in central Europe. Most recent years have shown average or calm conditions (Matulla *et al.*, 2007). On the local scale, station wind data can show different behaviour. Decreases and increases continuing over several decades can be seen at particular locations. For example a strong decrease in wind storms has been observed over the Netherlands during the past 40 years (Smits *et al.*, 2005).

Evaluating high tide levels along the North Sea in the past century showed clear changes in mean levels (related to sea-level rise) but no storm-related variations (von Storch *et al.*, 2002). Similarly, in the northern Adriatic Sea the trends for high sea levels and the subsequent occurrence of storm surges can not be associated with any trends in storminess (Lionello, 2005).

Photo: © Pavel Šťastný

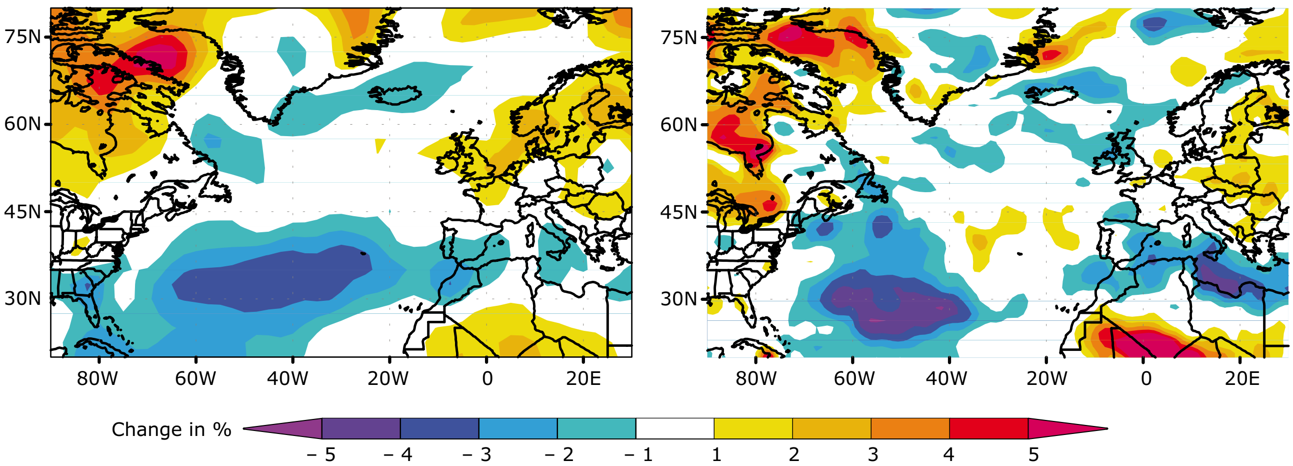
Projections

Extra-tropical storm tracks are projected to move pole-ward, with consequent changes in wind, precipitation, and temperature patterns, continuing the observed trends over the last half-century (IPCC, 2007a). The total number of storms is projected to decrease, but the strengths of the heaviest storms may increase, depending on the model used (see Map 5.10 showing different regional maximum wind distributions with different models). Note that these projections are still very uncertain and model-dependent.

During historic times, storminess and large-scale temperature variations were mostly decoupled, but the projections show a closer relationship. Some projections, based on the high emissions IPCC SRES A2 scenario, show a related increase in temperature and the frequency of heavy storms in the North Atlantic Ocean. The future storminess in this region depends on projections of sea surface temperature, retreat of Arctic ice and changes in the air pressure field (Fischer-Bruns *et al.*, 2005).

Projections of storm surges are closely connected with future storminess. The projections for the end of 21st century show a significant increase of storm surge elevations for the continental North Sea coast, by between 15 and almost 25 cm (Woth, 2005). For the UK coastline, a large increase in

Map 5.10 Projected relative change of annual maximum daily mean wind speed between 1961–2000 and 2050 using different models

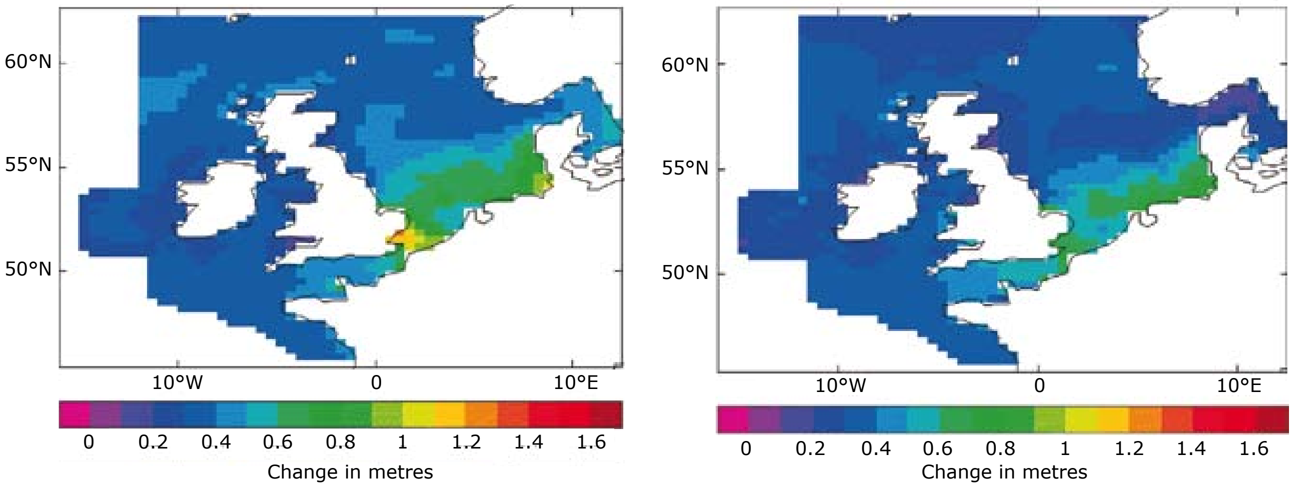


Note: Data are calculated for 10 m height using the + 2 °C scenario for 2050 (IPCC-SRES A1B emission scenarios) and the reference climate (1961–2000) from three similar models (left) and one different model, MIROCHi (right).

Source: van der Hurk *et al.*, 2006.

relative surge height is projected for the high IPCC SRES scenario A2 and the intermediate scenario B2, especially along the south-east coast of England, where the changes in storminess will have their largest effect and where the land is sinking most rapidly (Lowe and Gregory, 2005; Map 5.11).

Map 5.11 Change in the height of a 50-year return period extreme water level event for the end of 21st century for different scenarios



Note: The water level is measured relative to the present day tide, due to changes in atmospheric storminess, an increase in mean sea level and vertical land movements. Results are shown for the (left) A2 scenario and (right) B2 scenario, used model HadRM3H. A 50-year return period means the average probability of occurrence of two events in 100 years.

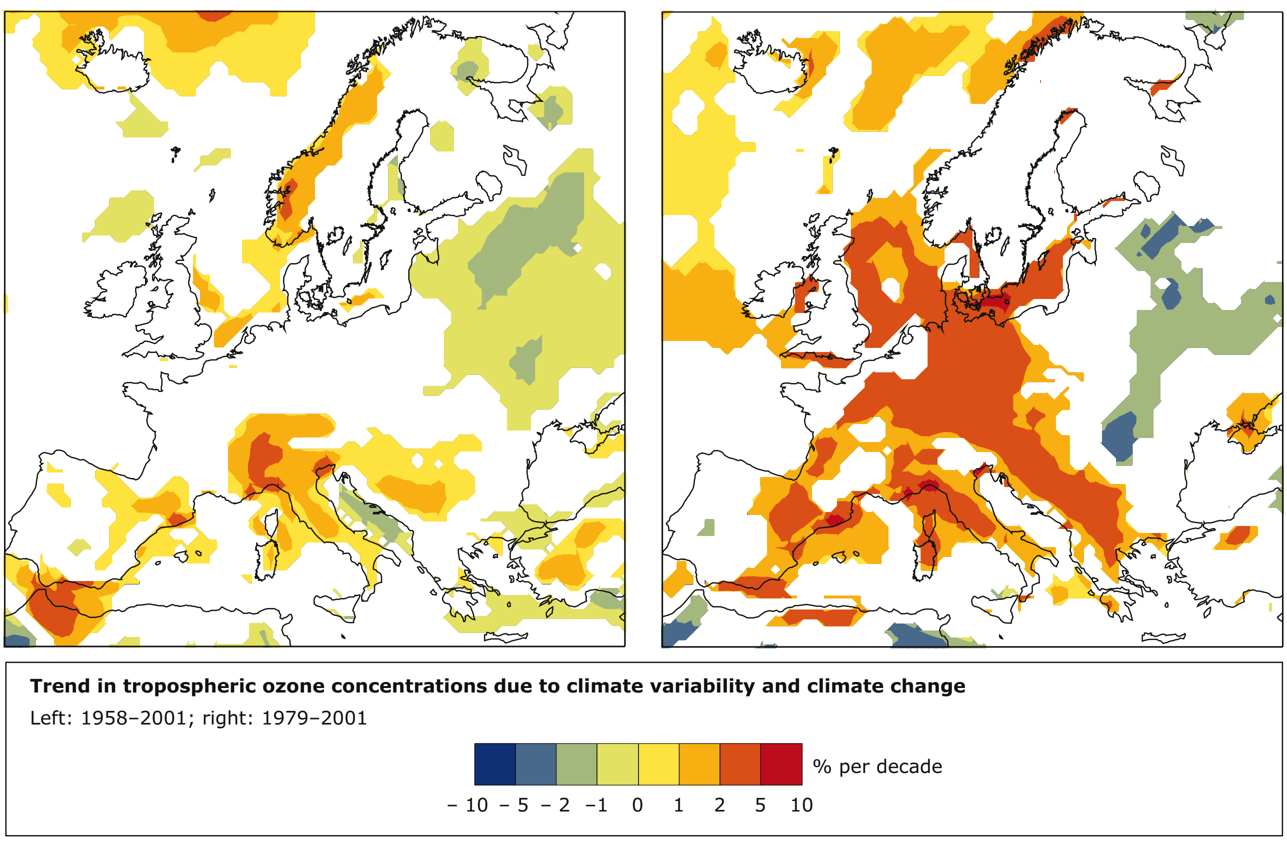
Source: Lowe and Gregory, 2005.

5.2.7 *Air pollution by ozone*

Key messages

- Climate variability and change has contributed to an increase in average ozone concentrations in central and South-Western Europe (1–2 % per decade).
- During the summer of 2003, exceptionally long-lasting and spatially extensive episodes of high ozone concentrations occurred, mainly in the first half of August. These episodes appear to have been associated with the extraordinarily high temperatures over wide areas of Europe and illustrate the expected more frequent exceedances of the ozone information threshold under projected climate change.
- The projected climate-induced increase in ozone levels may result in current ozone abatement policies becoming inadequate.

Map 5.12 Modelled change in tropospheric ozone concentrations over Europe 1958–2001 and 1978–2001



Note: The modelled changes shown are only due to climate variability and climate change. White areas have no significant trend.

Source: Andersson *et al.*, 2007.

Relevance

Tropospheric ozone is one of the air pollutants of most concern in Europe. Ozone is estimated to cause about 20 000 acute mortalities each year (European Commission, Clean Air for Europe impact assessment, 2006) and economic damage due to crop loss of EUR 4 625 million per year (Holland *et al.*, 2006). Ozone is formed in the lower troposphere as a result of complex chemical reactions between volatile organic compounds and nitrogen oxides, in the presence of sunlight. EU legislation has established ozone exceedance thresholds and national emission ceilings for ozone precursor emissions to protect human health and prevent damage to ecosystems, agricultural crops and materials.

Episodes of elevated ozone levels occur mainly during periods of warm sunny weather (Schichtel and Husar, 2001; Rao *et al.*, 2003). The projected increase in hot extremes in Europe (see Section 5.2.4) is therefore expected to result in ozone episodes that require more vigorous emission reduction measures and the use of the available adaptation measures such as improved public information and health care services.

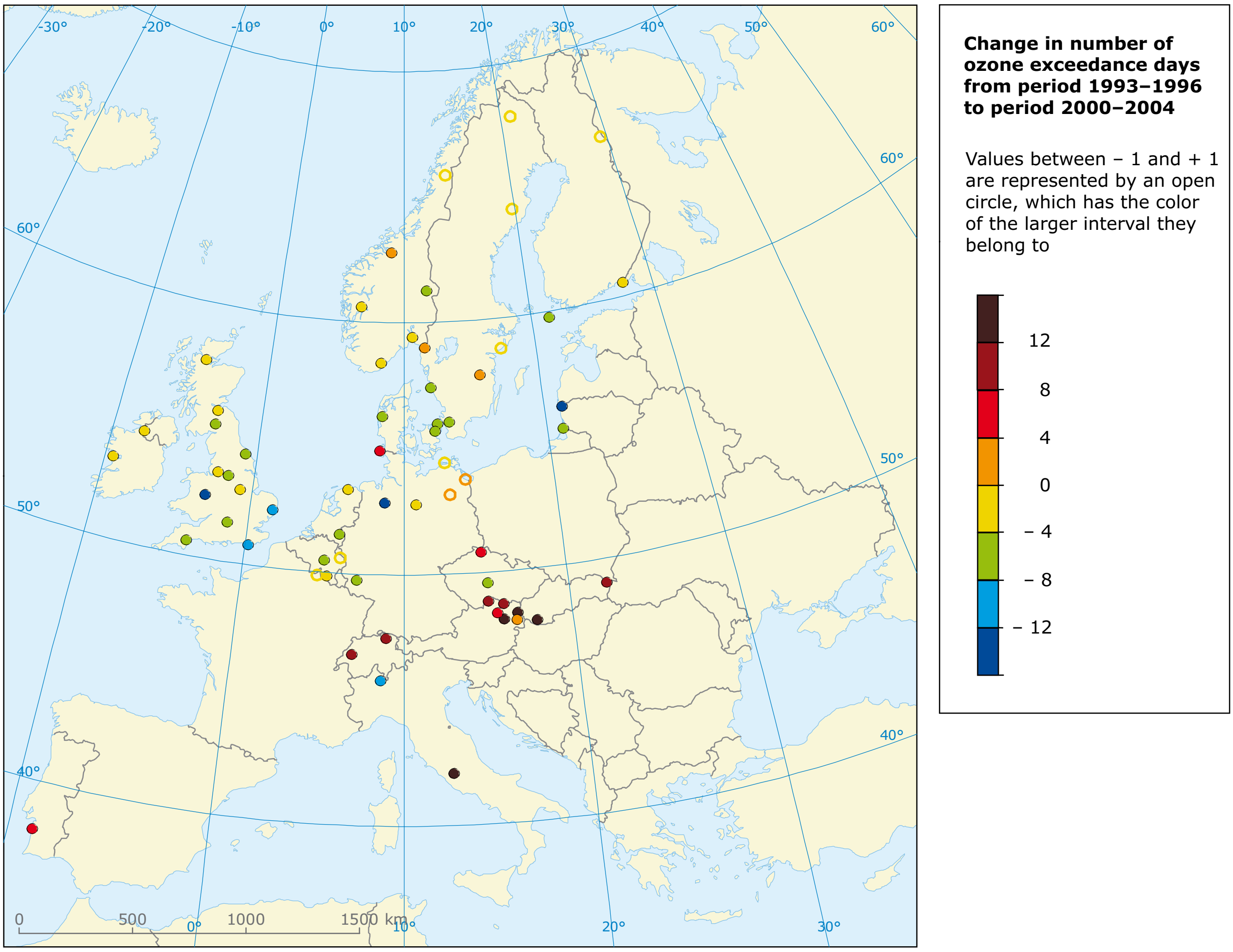
Past trends

A modelling study from 1958 to 2001 (Andersson *et al.*, 2007) shows that climate variability and change contributed to increased ozone concentrations during the period 1979–2001 over south-central and south-western Europe, and a decrease in north-eastern Europe (Map 5.12).

The reason for this is a combination of changes in temperature, wind patterns, cloud cover and stability. Further, temperature plays a role in various processes which directly affect the formation of ozone, like the emission of biogenic organic compounds (e.g. isoprene), and the photo-dissociation of NO_2.

A link between temperature and ozone concentration is also evident from observations. A statistical analysis of ozone and temperature measurements in Europe for 1993–2004 shows that in central-western Europe and the Mediterranean area, a change the increase in the daily maximum temperature in 2000–2004 compared with 1993–1996 contributed to extra ozone exceedences (Maps 5.13 and 5.14). In south and central Europe, the temperature trend was responsible for an average of 8 extra annual exceedence days of 120 µg/m³, i.e. 17 % of the total number of exceedences observed in that region.

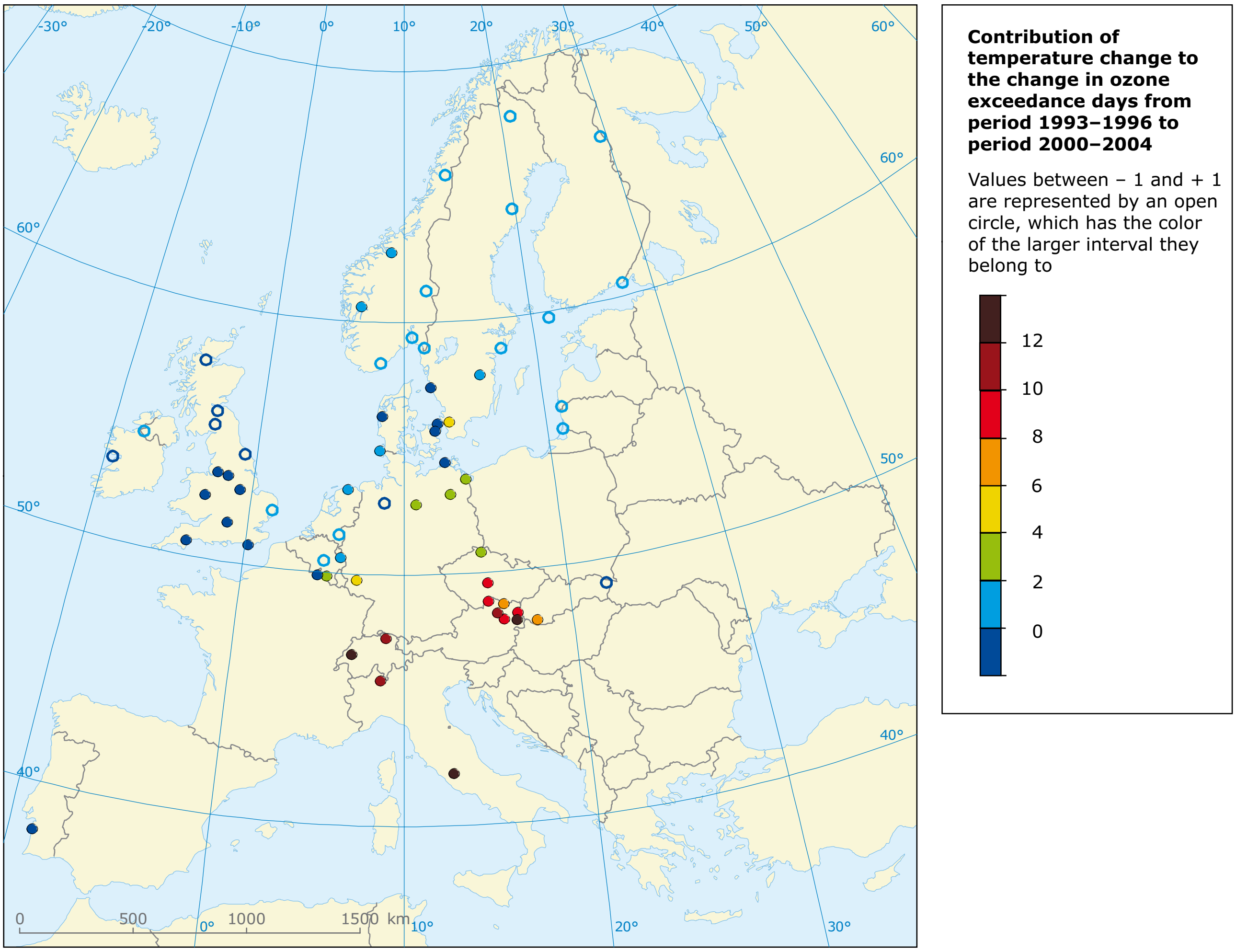
Map 5.13 Change in number of ozone exceedance days between 1993–1996 and 2000–2004



Note: Ozone exceedance days meaning days where the maximal 8 hr average ozone concentration exceeds 120 µg per m³ (year 2003 excluded).

Source: Van Dingenen *et al.*, 2008.

Map 5.14 Contribution of temperature increase to the change in ozone exceedance days between 1993–1996 and 2000–2004



Source: Van Dingenen *et al.*, 2008.

An analysis of trends over the past twelve years indicates that in the EU the average number of hours when ozone concentration exceeded the information threshold of 180 µg/m^3 was higher in summer 2003 than in all previous years (Fiala *et al.*, 2003).

Projections

The projected trends for ozone and other air pollutants are closely linked to projections for radiation, temperature, cloudiness, and precipitation. On a global scale, the effect of climate change alone on tropospheric ozone concentrations is expected to be small, because of a reduction in ozone lifetime as a consequence of higher humidity (Stevenson *et al.*, 2006). However, regional differences can be large. Regions where climate change is expected to result in an increased frequency of stable anticyclonic conditions with associated high temperatures, large solar inputs and little boundary layer ventilation may experience a deterioration of air quality (Hogrefe *et al.*, 2004; Sousounis *et al.*, 2002). A 30-year model study for the period 2071–2100, based on the IPCC A2 and B2 scenarios for CO_2 emissions (but with otherwise constant emissions of pollutants) shows that daily peak ozone amounts as well as average ozone concentrations will increase substantially during the summer in future climate conditions (Meleux *et al.*, 2007), in particular in central and western Europe, in line with observed trends from the past. The study also finds that summer ozone levels in future climate conditions are similar to those found during the exceptionally hot summer of 2003. The expected impact on human health may be exacerbated by the aging of the population, the elderly being more susceptible to air pollution than the average population (OECD, 2008).

5.3 Cryosphere

5.3.1 Introduction

The cryosphere is the frozen part of the world. It includes all permanent or seasonal snow and ice deposits on land, in the seas, rivers and lakes, and in the ground (permafrost). It is the second largest component of the climate system after the oceans with regard to mass and heat capacity. Snow and ice play a key role in the earth's energy budget by reflecting heat from the sun because of its light surfaces. As melting replaces white surfaces with darker ones, more heat is absorbed (the albedo effect). Two thirds of the world's freshwater resources are frozen. Snow and ice play a key role in the water cycle and are essential for storing fresh water for hotter and often dryer seasons.

The cryosphere is important for the exchange of gases between the ground and the atmosphere — these include several greenhouse gases, e.g. methane. Finally, ice and snow are defining components of ecosystems in the northern parts of the northern hemisphere and in high mountain areas. Many plants and animals have evolved to live under these conditions and can not live without. The cryosphere thus plays a major role in various dimensions of the climate system: it is affected if the climate changes, but its own changes in turn affect the climate system. Monitoring these changes therefore provides crucial knowledge about climate change.

Selection of indicators

The various components of the cryosphere play strong but different roles within the climate system.

- Because of their large volumes and areas, the continental *ice sheets* of Greenland and Antarctica actively influence the global climate over very long time-scales. Sea levels can however be affected more rapidly.
- *Snow* also covers a large area, but has relatively small volume. It is important for key global interactions and feedbacks like increased absorption of heat (albedo effect).
- *Sea ice* also covers a large area. It is important due to its albedo and its impacts on ocean circulation, which transports heat from the equator to the poles.
- Melting *permafrost* releases the strong greenhouse gas methane from frozen organic material. Together with seasonal snow, it influences the water content of the soil and the vegetation.
- *Glaciers, ice caps* and *seasonal lake ice*, with their smaller areas and volumes, react relatively quickly to changes in climate, influencing ecosystems and human activities on a local scale. They are good indicators of climate change.

The selected indicators cover strategic information from all these compartments of the cryosphere: glaciers and snow cover in Europe, the Greenland ice sheet, the Arctic sea ice and mountain permafrost in central Europe. Lake and river ice conditions are presented in the water chapter.

Indicators and vulnerability

The cryosphere is vulnerable to global warming. It is a very visible expression of climate change. It integrates climate variations over a wide range of time scales, from millennia to seasonal variations throughout the year. This can complicate interpretation of why changes happen.

In Europe, the most vulnerable areas are the high mountain areas and the Arctic. In both the Arctic and the European Alps, temperatures have increased at more than the global rate in the past few decades, in the Arctic as a whole, twice as much. The amount of ice and snow, especially in the northern hemisphere, has decreased substantially over the last few decades due to increased temperatures. European glaciers are shrinking, snow-covered areas are creeping higher up and further north, sea ice in the Arctic is melting and getting thinner, permafrost is starting to thaw, and the Greenland ice sheet shows increasing signs of disintegration and thawing at its borders. These trends will accelerate as climate change is projected to continue. However, there are large uncertainties in the fate of key components of the cryosphere: it is not yet possible to make reliable predictions of when the Arctic sea ice may melt completely in summer, neither is it yet possible to predict the future of the Greenland ice sheet with any confidence.

Data and info sources

Data on the components of the cryosphere vary significantly with regard to availability and quality. Long-term data on glaciers in all European glaciated areas are provided in good quality and quantity by the World Glacier Monitoring Service (WGMS) in Zürich. Data on snow cover and Arctic sea ice have been measured globally since satellite measurements started in the 1970s and are available for example at the Global Snow and Ice Data Centre (NSIDC) in Boulder/USA. However sensors in the satellites have gradually improved, allowing for new observations. Hence area-wide data on the Greenland ice-sheet are often available for not longer than 15 years. This is also the situation for data on mountain permafrost measured in boreholes which are drilled into frozen rock walls.

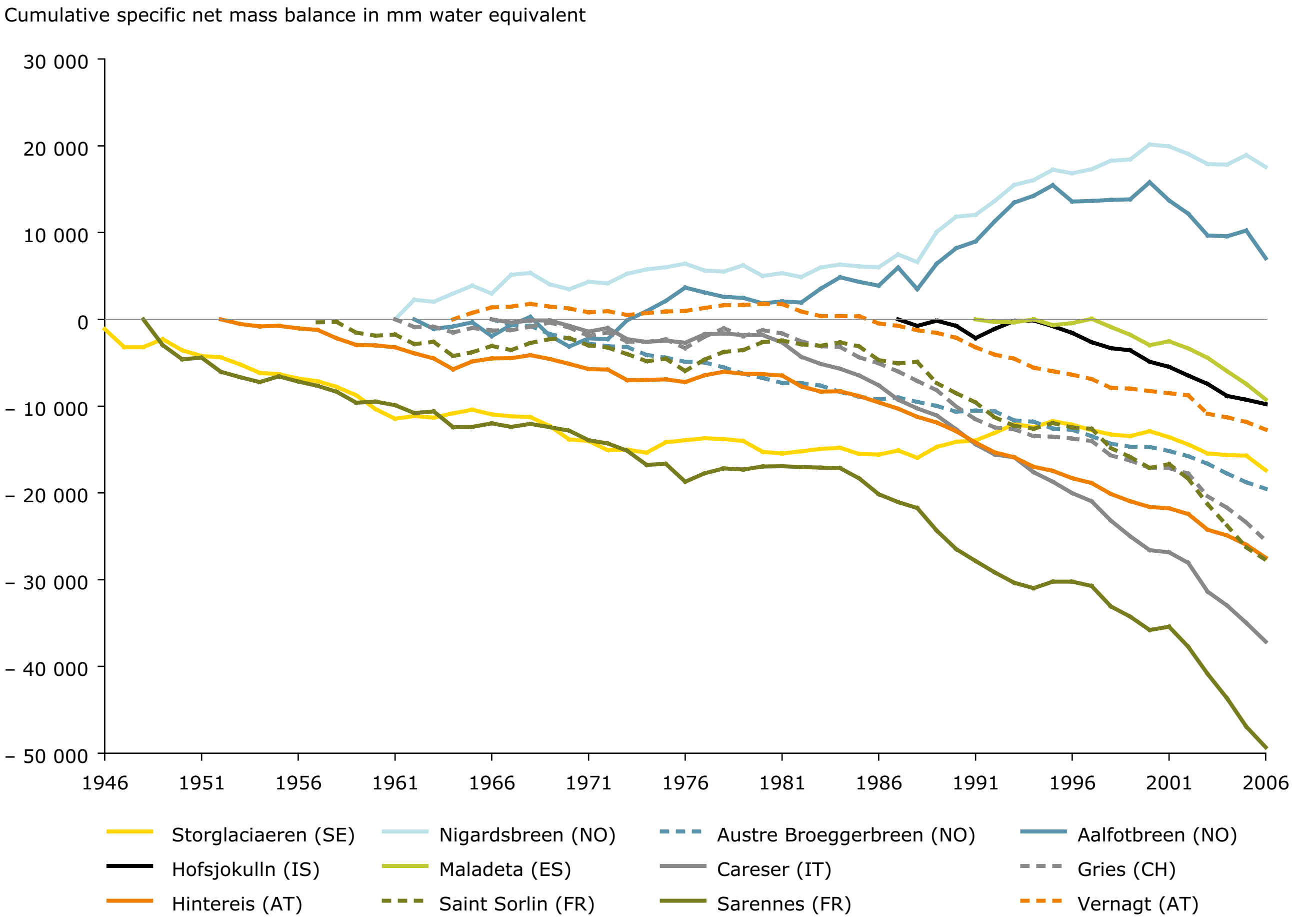
The gaps in the cryospheric data base are well recognised by the scientific community and many efforts are being made to improve the knowledge, e.g. during the International Polar Year (IPY) 2007–2008.

5.3.2 *Glaciers*

Key messages

- The vast majority of glaciers in the European glacial regions are in retreat.
- Since 1850, glaciers in the European Alps have lost approximately two thirds of their volume, with clear acceleration since the 1980s.
- Glacier retreat is projected to continue. A 3 °C increase in average summer air temperature could reduce the existing glacier cover of the European Alps by some 80 %. With continuing climate change nearly all the smaller glaciers and one third of the overall glacier area in Norway are projected to disappear by 2100.
- Glacier retreat has serious consequences for river flow. It affects freshwater supply, river navigation, irrigation and power generation. It could cause natural hazards and damage to infrastructure.

Figure 5.8 Cumulative specific net mass balance of glaciers from all European glaciated regions 1946–2006



Note: Positive values mean ice growth, negative values mean ice loss.

Source: Fluctuation of Glaciers Database (FoG), World Glacier Monitoring Service (www.wgms.ch), 2007.

Relevance

Glacier changes are among the most visible indications of the effects of climate change. Glaciers are particularly sensitive to changes in the global climate because their surface temperature is close to the freezing/melting point (Zemp *et al.*, 2006). Glacier fluctuations showed a strong relation to air temperature throughout the 20th century (Greene, 2005). Therefore the change in the mass balance of glaciers is considered to be an immediate signal of global warming trends. A negative mass balance indicates that the loss of ice, mainly from melting and calving in summer, is larger than the accumulation from snowfall in winter.

Glaciers are an important freshwater resource and act as 'water towers' for lower-lying regions. In the coming decades, we can first expect more melt water from the glaciers running into rivers. As the glaciers diminish, however, the annual melt water, and therefore their contribution to river flow and sea-level rise, will decrease. This will have serious consequences for freshwater supply, river navigation, ecosystems fed by water from rivers, irrigation facilities, and power generation. Furthermore, the solute release from melting rock-glaciers may affect the water quality of high mountain lakes adversely by the intrusion of heavy metals (Thies *et al.*, 2007).

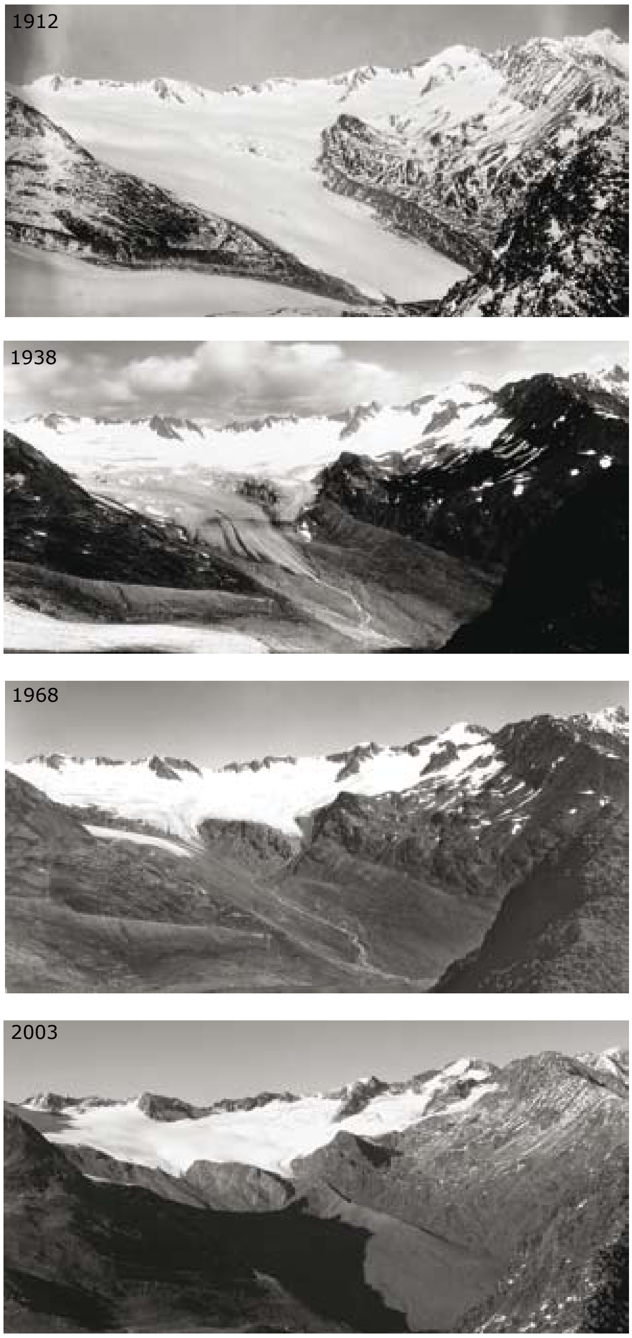
Strong retreat of glaciers can cause instabilities resulting in hazardous incidents such as glacier lake outbursts, rock-ice avalanches and landslides (Pralong and Funk, 2005; Huggel *et al.*, 2007). This may cause damage to infrastructure. Glacier retreat affects tourism and winter sports in the mountains (OECD, 2007) and changes the appearance of mountain landscapes.

Improved glacier monitoring, and adaptation options such as water management measures, draining of glacier-lakes and construction of protective walls can reduce some of the risks and negative consequences, but not all.

Past trends

According to the high-quality data records of the WGMS, a general loss of glacier mass has occurred in nearly all the European glacier regions (Figure 5.8). Glacier retreat in Europe started after the maximum glacier extent of the so-called 'Little Ice Age' in the middle of the nineteenth century. In the Alps, glaciers lost one third of their surface area and one half of their volume between 1850 and the end of the 1970s. Since 1985 an acceleration in glacial retreat has been observed, which led to a loss of 25 % of the remaining ice by 2000 (Zemp *et al.*, 2006). This was followed by a further loss of 5–10 % in the extraordinary hot and dry summer of 2003 (Zemp *et al.*, 2005), resulting in a total loss of about two thirds of the 1850 ice mass. This is illustrated by

Figure 5.9 Shrinking of the Vernagtferner glacier, Austria



Note: The glacier retreat is shown for the years 1912, 1938, 1968 and 2003.

Source: Commission of Glaciology, Bavarian Academy of Sciences; Munich, 2006 (www.glaziologie.de).

the shrinking of the Vernagtferner-glacier in Austria (Figure 5.9).

The Norwegian coastal glaciers, which were expanding and gaining mass due to increased snowfall in winter up to the end of the 1990s, are also now retreating, as a result of less winter precipitation and more summer melting (Nesje *et al.*, 2008; Andreassen *et al.*, 2005).

Glaciers in Svalbard are experiencing mass loss at lower elevations, and the fronts of nearly all glaciers there are retreating (Haeberli *et al.*, 2005, 2007; Nuth *et al.*, 2007). Some ice caps in north-eastern Svalbard seem to be increasing in thickness at higher elevations (Bamber *et al.*, 2004; Bevan *et al.*, 2007). However, estimates for Svalbard as a whole show that the total balance is negative (Hagen *et al.*, 2003), and there is a clear sign of accelerated melting, at least in western Svalbard (Kohler *et al.*, 2007).

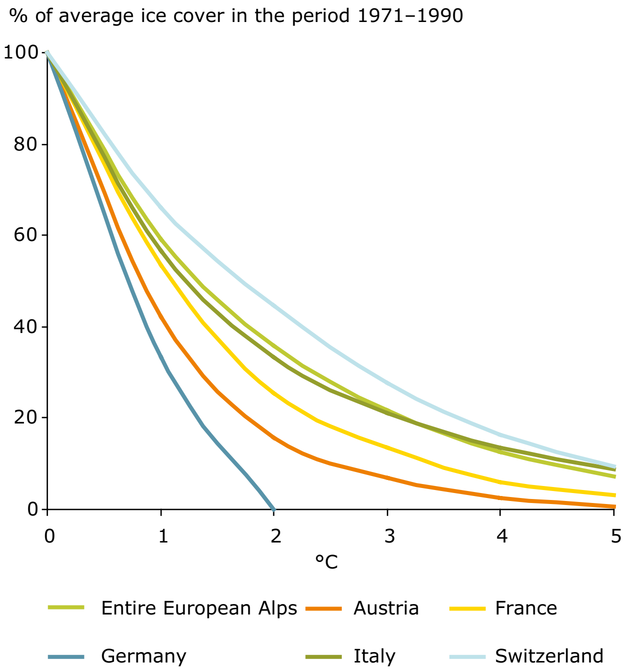
Very recent findings by the WGMS (UNEP, 2008) indicate a clearly increasing annual reduction of the global mean ice-thickness of glaciers since the turn of millennium (0.5 m) compared with the 1980–1999 period (0.3 m). Some of the most dramatic shrinking has been in Europe (Scandinavia, Alps, and Pyrenees).

The centennial retreat of European glaciers is attributed mainly to increased summer temperatures. However, changes in winter precipitation, the decreased glacier albedo due to the lack of summer snow-fall and various other feedback processes are altering the pattern on a regional and decadal scale. The recent strong warming has made disintegration and down-wasting increasingly dominant causes of glacier decline in the European Alps during the most recent past (Paul *et al.*, 2004).

Projections

According to a recently published sensitivity study (Zemp *et al.*, 2006), the European Alps could lose about 80 % of their average ice cover for the period 1971–1990 if summer air temperatures rose by 3 °C; a precipitation increase of 25 % for each 1 °C would be needed to offset the loss of cover. The modelled remains of Alpine glaciers as a consequence of warming are presented in Figure 5.10. Sugiyama *et al.* (2007) investigated the potential evolution of

Figure 5.10 Modelled remains of the glacier cover in the European Alps for an increase in average summer air temperature of 1 to 5 °C



Note: The total of 100 % refers to the average ice cover 1971–1990.

Source: Zemp *et al.*, 2006.

the Rhone Glacier, Switzerland, in the 21st century using a model which included more consideration of glacier flow dynamics. They found increasing mass loss as well as decreasing glacier cover, but at a gradually slower rate. However, neither modelling studies considered feedback processes such as the development of glacier lakes, which could accelerate glacier retreat dramatically.

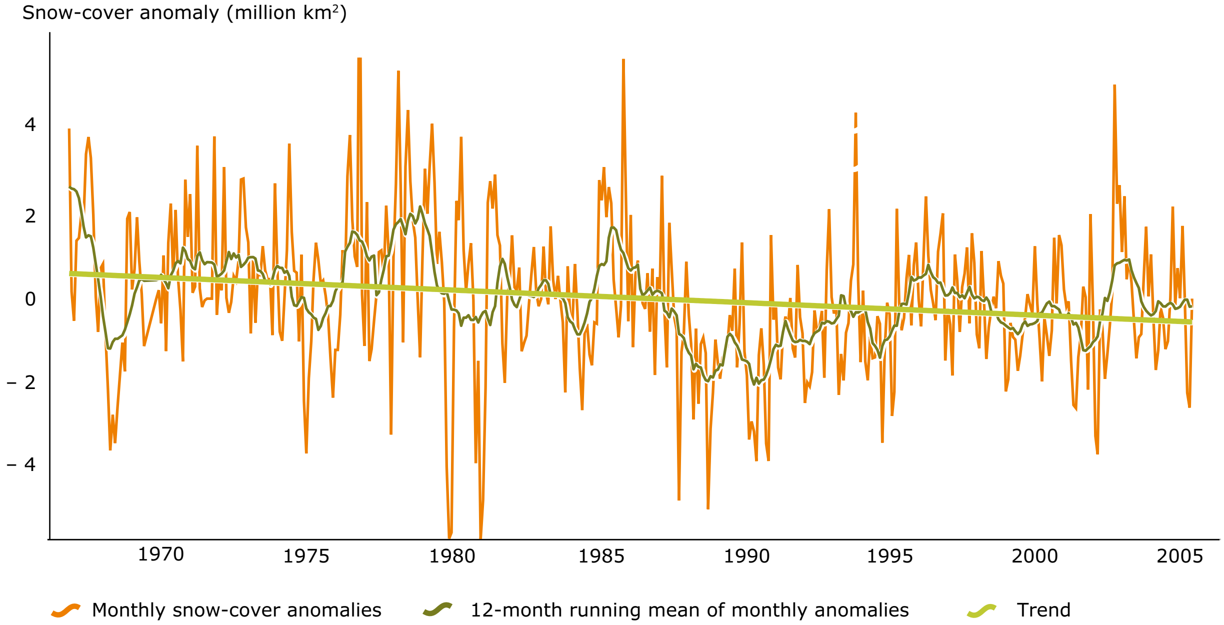
Recent climate scenarios for Norway, based on model calculations by the British Headley Centre and the German Max Planck Institute which follow the SRES B2 emission-scenario, indicate a rise in summer temperature of 2.3 °C and an increase in winter precipitation of 16 % in the period 2070–2100 compared with 1961–1990. As a result, nearly all the smaller Norwegian glaciers are likely to disappear and overall glacier area as well as volume may be reduced by about one third by 2100 (Nesje *et al.*, 2008).

5.3.3 *Snow cover*

Key messages

- Snow cover in the northern hemisphere has fallen by 1.3 % per decade during the past 40 years. The largest losses are during spring and summer.
- Model simulations project widespread reductions in the extent and duration of snow cover in Europe over the 21st century.
- Changes in snow cover affect the Earth's surface reflectivity, river discharge, vegetation, agriculture and animal husbandry, tourism, snow sports, transport and power generation.

Figure 5.11 Northern hemisphere snow-cover extent variation 1966–2005



Note: Snow-cover anomalies are expressed in deviations from monthly means.

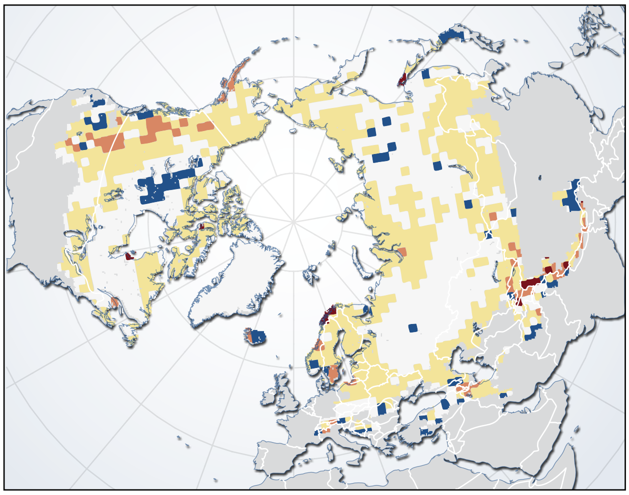
Source: Brodzik, 2006 (NOAA-data); UNEP, 2007. (http://maps.grida.no/go/graphic/northern-hemisphere-snow-cover-extent-anomalies-1966-2005).

Relevance

Snow covers more than 33 % of the land surface north of the equator from November to April. It reaches a maximum of about 45.2 million km^2 in January, and a minimum of about 1.9 million km^2 in August (Clark *et al.*, 1999).

Snow cover is an important feedback mechanism of the climate system. The extent of snow cover depends on the climate, for example on temperature and precipitation, and on solar radiation. But it also influences the climate and climate-related systems because of its high reflectivity, insulating properties, effects on water resources and ecosystems, and cooling of the atmosphere. Thus a decrease in snow cover reduces the reflection of solar radiation, contributing to accelerated climate change. Changes in the extent, duration, thickness and properties of snow cover can affect water availability for domestic use, navigation and power generation. Changes in snow cover affect human well-being through influences on agriculture, infrastructure, the livelihoods of indigenous Arctic people, environmental hazards and winter recreation. Snow-cover retreat can reduce problems of winter road and rail maintenance, affecting the exploitation and

Map 5.15 Observed change in spring snow-cover duration 1970–2004



Observed change in spring snow-cover duration 1970–2004 (days/year)

– 4 to – 2 | – 2 to – 1 | – 1 to – 0.25 | – 0.25 to 0.25 | 0.25 to 3

Note: Data are in days/year. Negative values (brown/yellow) indicate reduced duration of snow cover/positive values (blue) indicate extended duration of snow cover.

Source: R. Brown, Environment Canada; data from D. Robinson, Rutgers University. (http://maps.grida.no/go/graphic/trends-in-spring-snow-cover-duration-for-the-northern-hemisphere-1970-2004).

transport of oil and gas in cold regions (UNEP, 2007; ACIA, 2004).

Shallow snow cover at low elevations in temperate regions is the most sensitive to temperature fluctuations and hence most likely to decline with increasing temperature (IPCC, 2007a, b).

For several of these impacts, adaptation can reduce the negative effects of snow-cover change. Some adaptation options, such as artificial snowmaking in the Alps to maintain tourism as a main source of income, have to be balanced against their negative implications for mitigation, due to increased energy use and greenhouse gas emissions.

Past trends

Data from satellite monitoring (NESDIS-database at NOAA) from 1966 to 2005 show that monthly snow-cover extent in the northern hemisphere is decreasing by 1.3 % per decade (Figure 5.11), with the strongest retreat in spring and summer (UNEP, 2007). Snow cover fell in all months except November and December, with the most significant decrease during May to August (Brodzik *et al.*, 2006). This was accompanied by lower springtime water content, earlier disappearance of continuous snow cover in spring (Map 5.15) by almost two weeks in the 1972–2000 period (Dye, 2002), less frequent frost days (days with minimum temperature below 0 °C) and shorter frost seasons (period of consecutive frost days).

The trends in duration and depth of northern hemispheric snow cover at higher latitudes differ between regions. In contrast to a reduced duration of snow cover over North America, a long-term increase in depth and duration has been observed over most of northern Eurasia (Kitaev *et al.*, 2005).

Snow-cover trends in the mountain regions of Europe vary considerably with region and altitude. Recent declines in snow cover have been documented in the mountains of Switzerland (e.g. Scherrer *et al.*, 2004), Slovakia (Vojtek *et al.*, 2003), and in the Spanish ski-resorts in the Sierra Nevada and the Pyrenees (Rodriguez *et al.*, 2005), but no change was observed in Bulgaria over the period 1931–2000 (Petkova *et al.*, 2004). Declines, when observed, were largest at lower elevations, and Scherrer *et al.* (2004) statistically attributed the declines in the Swiss Alps to warming. Lowland areas of central Europe are characterised by recent reductions in annual snow-cover duration of about 1 day/year (Falarz, 2002). At Abisko in sub-Arctic Sweden, increases in snow depth have been recorded since 1913 (Kohler *et al.*, 2006), and trends towards greater maximum snow depth but shorter snow season have been noted in Finland (Hyvärinen, 2003).

Photo: © M. Zebisch, 2004

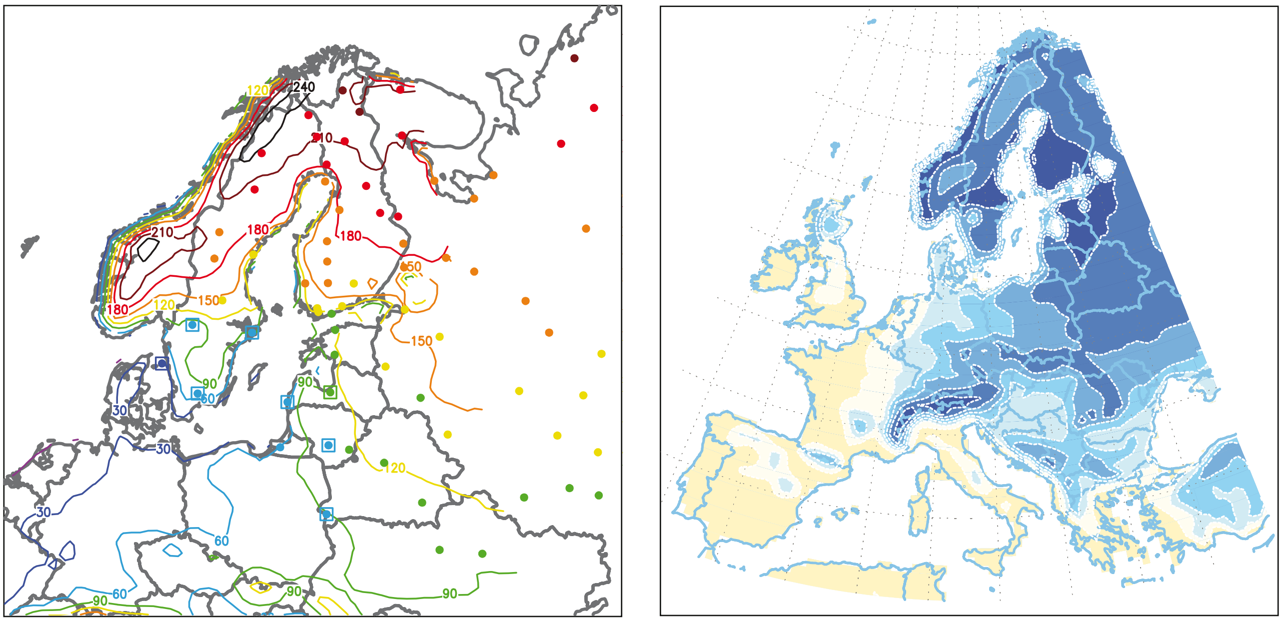
Projections

Model simulations project widespread reductions in snow cover over the 21st century (IPCC, 2007a). Decreases of between 9 and 17 % in the annual mean northern hemisphere snow cover by the end of 21st century are projected by individual models (ACIA, 2004). Although winter precipitation is projected to increase in northern and central Europe (Christensen and Christensen, 2007), less frequent frost occurrences associated with higher temperatures are projected to reduce the number of days with snow cover (Map 5.16). Decreases of more than 60 snow-cover days are projected to occur (for the period 2071–2100 compared with 1961–1990) around the northern Baltic Sea, on the west slopes of the Scandinavian mountains and in the Alps (Jylhä *et al.*, 2007). The beginning of the snow accumulation season is projected to be later and the end earlier, and snow coverage during the snow season is projected to decrease (Hosaka *et al.*, 2005).

For every 1 °C increase in average winter temperature, the snowline in the European Alps rises by about 150 metres (Beniston, 2003). Regional climate model runs, following the SRES emission scenarios A1B, B1 and A2, project milder winters with more precipitation in this region, increasingly falling as rain (Jacob *et al.*, 2007). A recently-published study on the sensitivity of the Alpine snow cover to temperature by Hantel and Hirtl-Wielke (2007) reported a distinctive and strong variation of snow-cover sensitivity to temperature change with altitude. The study estimated that a 1 °C increase in temperature over central Europe (5–25°E and 42.5–52.5°N) would result in a reduction of about 30 days in snow duration (snow cover of at least 5 cm) in winter at the height of maximum sensitivity (about 700 m).

Snowfall in lower mountain areas is likely to become increasingly unpredictable and unreliable over the coming decades (Elsasser and Bürki, 2002), with consequences for natural snow reliability and therefore difficulties in attracting tourists and winter sports enthusiasts (OECD, 2007).

Map 5.16 Annual number of days with snow cover over European land areas 1961–1990 and projected change for 2071–2100



Annual number of days with snow cover

Observed means in nothern Europe, 1961–1990 (coloured dots) and modelled means for Europe, 1961–1990

5 30 60 90 120 150 180 210 240

Projected change of annual number of days with snow cover

Projected multi-model mean changes for the period 2071–2100, relative to 1961–1990

– 60 – 50 – 40 – 30 – 20 –10

Note: Results are based on seven regional climate-model simulations.

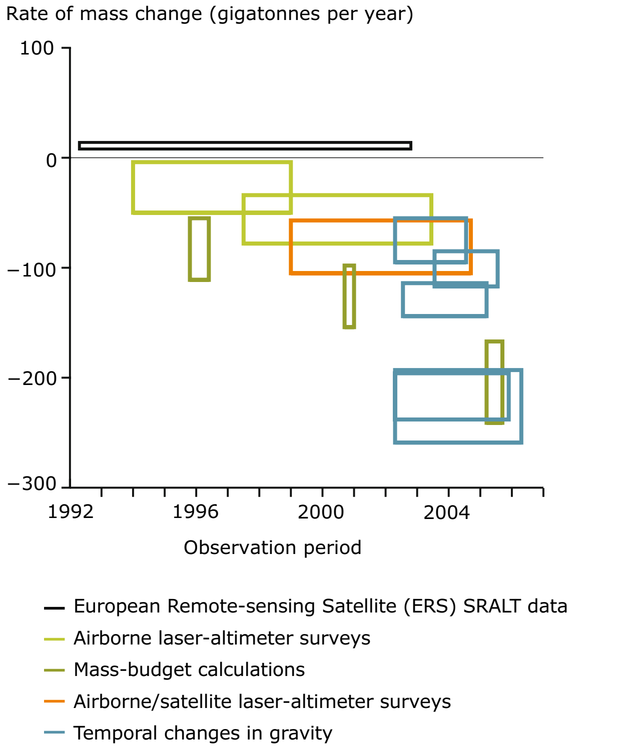
Source: Jylhä *et al.*, 2007.

5.3.4 *Greenland ice sheet*

Key messages

- The Greenland ice sheet changed in the 1990s from being in near mass balance to losing about 100 billion tonnes of ice per year. Ice losses may have doubled again by 2005. Accelerated flow of outlet glaciers to the sea accounts for more of the ice loss than melting.
- The contribution of ice loss from the Greenland ice sheet to global sea-level rise is estimated at 0.14–0.28 mm/year for the period 1993–2003 and has since increased. In the long term, melting ice sheets have the largest potential to increase sea level.
- No reliable predictions of the future of the ice sheets can yet be made; the processes causing the faster movement of the glaciers are poorly understood and there is a lack of long-term observations.

Figure 5.12 Estimated changes of the ice mass in Greenland 1992–2006



Note: The rectangles depict the time period of the observations (horizontal) and the upper and lower estimates of mass balance for that period (vertical), calculated by different techniques as marked with colour codes. The uncertainty in assessing the trend is largest in periods when the vertical parts of rectangles from different estimates do not overlap. The main factors determining whether the Greenland ice sheet gains or loses ice (mass balance) are: (1) Surface mass balance = the difference between net snow accumulation and loss from melting (meltwater runoff and evaporation) and (2) Dynamic ice loss from the movements of glaciers, leading to ice berg calving.

Source: Thomas *et al.*, 2008.

Relevance

The ice sheets of Greenland and Antarctica contain 98–99 % of the freshwater ice on earth's surface. To illustrate their sizes, the volumes of the Antarctic and Greenlandic ice sheets are equivalent to a 57 and 7 m layer, respectively, of water on top of the world's oceans. When setting their upper estimate of a projected 59 cm sea-level rise by the end of this century, the IPCC did not take into account increased discharges into the ocean from the moving outlet glaciers of the ice sheets. The uncertainty about their future is therefore a main reason for uncertainties in projections of sea-level rise. The Greenland ice sheet is the most susceptible to warming because of its closeness to the Atlantic Ocean and other continents. But the more isolated Antarctica now also seems to be experiencing a net loss of ice, which may be accelerating (UNEP, 2007) (See indicator on sea-level rise (Section 5.4.2)).

The speed of ice loss is important as well as its magnitude because a faster rise in sea level reduces the time available to take appropriate adaptation measures.

The melt water from Greenland will contribute to reducing the salinity of the surrounding ocean. An upper layer of fresher water may reduce the formation of dense deep water, one of the mechanisms driving global ocean circulation.

Past trends

The Greenland ice sheet is a huge inland glacier with several glacier tongues calving into the sea. It covers roughly 80 % of Greenland. The average ice thickness is 1 600 m, with the highest summit reaching

3 200 m above sea level. It has a volume of about 3 million km^3.

Until recent improvements in remote sensing, it was hard to measure whether the polar ice sheets were growing or shrinking. Most time-series remain short. There is however a general consensus from different approaches that ice loss from the Greenland ice sheet has accelerated. From a near balance in the early 1990s, about 100 billion tonnes were being lost annually at the end of the century. This may have doubled again by 2005 (UNEP, 2007). However, there is still considerable discrepancy between different estimates of ice loss rates (Figure 5.12).

The IPCC estimated the Greenland ice sheet contribution to sea-level rise during 1993–2003 to be 0.14–0.28 mm/year, based on an annual ice loss in that period of 50 to 100 billion tonnes (IPCC, 2007a). A study estimating an ice loss of 224 billion tonnes/year in 2005, found a corresponding contribution to sea-level rise of 0.57 mm/year (Rignot and Kanagaratnam, 2006). This is one of the upper estimates in Figure 5.12 and illustrates the effects that different rates of ice loss can have on sea level.

The ice in the interior of the Greenland ice sheet at high elevations has thickened since it has received more snowfall — on average about 4 cm/year since 2000 (UNEP, 2007). This gain has been more than offset by the loss in lower-lying regions from melting and increased calving of ice bergs. Air temperatures in summers have increased significantly along the coast since the early 1990s, whereas little change or slight cooling has been observed in the high interior (Steffen, 2007 unpubl.).

Ice loss can partly be caused by surface melting. On the low-lying edge of the ice sheet, the surface melts each summer causing evaporation and meltwater runoff from the glacier. If this exceeds the net snow accumulation in winter, the glacier has a negative surface mass balance. Areas with melting can be measured from satellites, and from 1979 to 2007, the cumulative melt area increased by approximately 50 % (Figure 5.13). Melting has reached higher elevations, and the melting season is lasting longer. However, both snowfall and surface melting has increased. The resulting trend in surface mass balance for the whole Greenland ice sheet between 1958 and 2006 has been modelled to be insignificantly negative (Hanna *et al.*, 2007). Data from recent years extending to 2007 suggest a strong increase in the net loss of surface mass balance (Steffen, 2007 unpubl.).

Melt water forms rivers at the glacier surfaces

Photo: © John McConnico

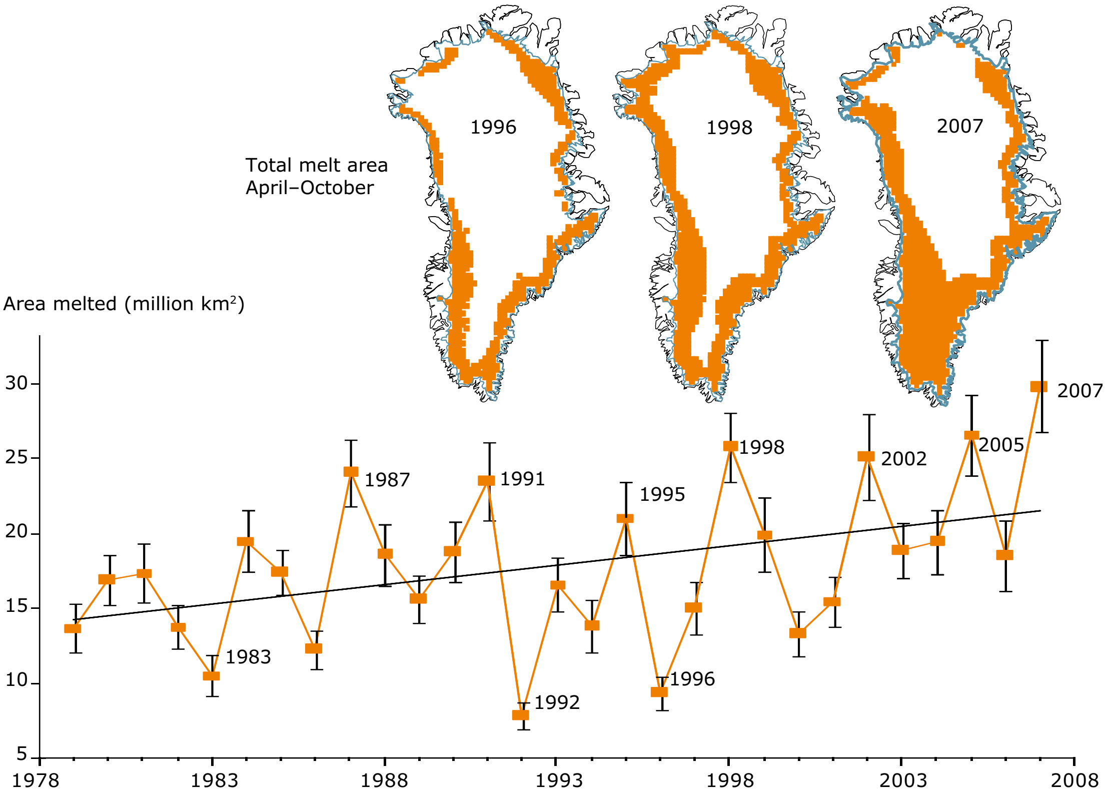
The other mechanism behind the ice loss since the 1990s is accelerated flow of outlet glaciers towards the sea. Large amounts of meltwater form rivers and melting ponds at the glacier surface and penetrate through crevasses to the bottom. This water probably lubricates the bedrock/ice interface, making the glaciers move faster. Another explanation is that the glacier fronts may be affected by increasing ocean temperatures, reducing their buttress effect. The outlet glaciers are also influenced by the topography of the fjords. Outlet glaciers act as 'bathtub drains' for the inland ice: ice is being transported into the melting zone, and calving into the ocean increases. The speed of the fastest-flowing glacier, Jakobshavn isbræ on the west coast, has nearly doubled, to about 14 km a year (UNEP, 2007). Some glaciers are however reported to be slowing down from the maximum speeds measured, possibly around a new equilibrium position. Acceleration is widespread mostly on the southeast coast and has moved northwards to about 70°N. It is associated with large retreats and thinning of the ice sheet. Near the outlets, glacier surface elevation can subside by tens of metres.

The ice losses caused by accelerated flow of the outlet glaciers (ice dynamics) have exceeded the losses from melting processes (negative surface mass balance) several times during the recent few warmest years. For 2005, it has been estimated that two thirds of the ice loss was caused by ice dynamics (Rignot and Kanagaratnam, 2006).

Projections

It is currently not possible to predict the future development of the Greenland ice sheet with confidence. Glacier models account mostly for accumulation of snow during winter and melting in summer (surface mass balance). The accelerated ice flow has been observed for a rather short period of time. Scientists are now trying to understand the

Figure 5.13 Area of Greenland ice sheet melting 1979–2007



Note: The area of the Greenland ice sheet where there is at least one day of surface melting in summer increased to a new record extent in 2007. Melting passed the 2 500 m elevation and probably led to a record ice loss that year.

Source: Updated from Steffen *et al.*, 2004; Witze, 2008.

processes driving this phenomenon. That should in turn allow better ice models to be developed. But for models to predict the future well, they must be validated by data from long-term measurements describing key processes. Until science comes closer to this, our ability to predict the sensitivity of the Greenland ice sheet to global warming will remain limited.

Further temperature increases can accelerate the ice loss because of positive feed-back mechanisms, like thinning of the ice sheet that exposes larger areas to melting. It is hard to say how strong these mechanisms are, how rapidly the ice sheet will react to them and whether ice loss will be irreversible.

Throughout the earth's history, the ice sheets have shrunk in response to warming and grown in response to cooling. Deep ice core drillings reveal past climates and can give some indications of how they have changed. The Eemian era was an interglacial period 120 000 years ago when temperatures over Greenland were about 5 °C warmer than today. But the Greenland ice sheet did not melt completely. Sea level rose to about 5 m above today's level, with melting Greenland ice contributing 1–2 m (Dahl Jensen, pers. com.). Because global warming is amplified near the poles, a future temperature rise of 5 °C in Greenland may be reached when global average temperature rises by around half of this, which is within the range of IPCC projections for this century.

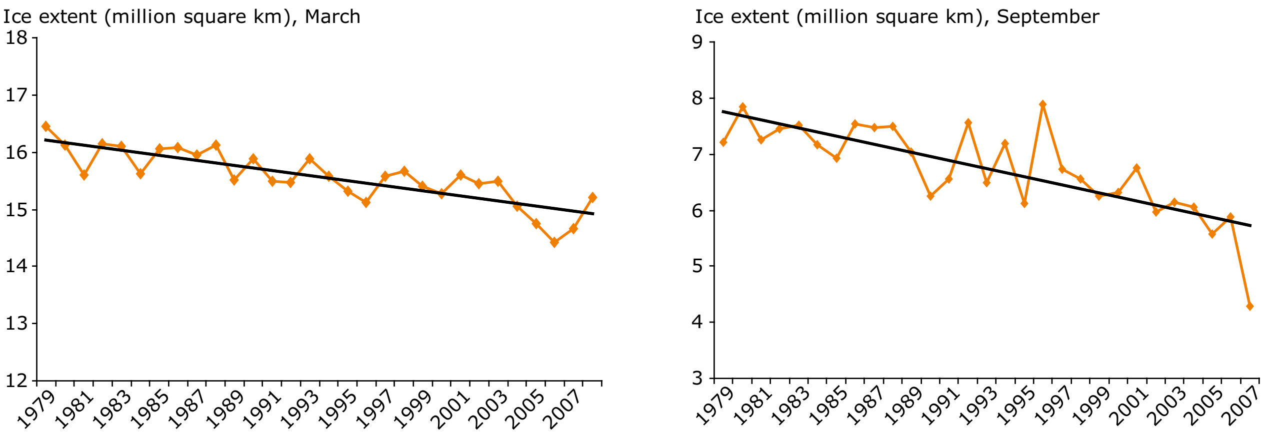
The ice sheets of Greenland and Antarctica have previously been associated with slow climate responses over thousands of years. But the acceleration of ice movement has caused a rethinking of how rapidly they respond to warming. Paleodata show periods of rapid melting of the large continental ice sheets after the last ice age, resulting in an average rise of sea level of 1 cm/year and peak rates up to 4 cm/year (UNEP, 2007). Shrinkage seems to be a faster process than growth, probably because accelerated ice flow plays an important role in retreat. A better understanding of these processes is of vital importance for assessing how much we can expect the flow of meltwater from the Greenland ice sheet to increase.

5.3.5 *Arctic sea ice*

Key messages

- The extent of the sea ice in the Arctic has declined at an accelerating rate, especially in summer. The record low ice cover in September 2007 was roughly half the size of the normal minimum extent in the 1950s.
- The summer ice is projected to continue to shrink and may even disappear at the height of the summer melt season in the coming decades. There will still be substantial ice in winter.
- Reduced polar ice will speed up global warming and is expected to affect ocean circulation and weather patterns. Species specialised for life in the ice are threatened.
- Less ice will ease access to the Arctic's resources. Oil and gas exploration, shipping, tourism and fisheries will offer new economic opportunities, but also increase pressures and risks to the Arctic environment.

Figure 5.14 Average extent of arctic sea ice in March and September 1979–2007



Note: Arctic sea ice grows to its greatest yearly size in March and melts to its lowest size in September. The figure shows the average ice extents for these two months after 1979. The linear trend for March indicates that the Arctic is losing an average of 44 000 km^2 of ice per year in winter. The corresponding value for September and summer is 72 000 km^2.

Source: National Snow and Ice Data Centre, Boulder (http://nsidc.org/data/seaice_index/).

Relevance

Reduction in Arctic sea ice has several feedbacks to the climate system. Snow-covered ice reflects 85 % of the sunlight (high albedo), whereas open water reflects only 7 % (low albedo). Less ice and snow will therefore accelerate both sea-ice decline and global warming. Reduced ice formation will also reduce the formation of dense deep water which contributes to driving ocean circulation. As the ice cover influences air temperature and the circulation of air masses, changes in weather patterns such as storm tracks and precipitation can be expected even at mid-latitudes (Serreze *et al.*, 2007). Warming over the Arctic Ocean can also penetrate into the surrounding continents, raising concern about thawing of the permafrost with release of additional greenhouse gasses (Lawrence *et al.*, 2008).

The sea ice is an ecosystem filled with life uniquely adapted to these conditions, from micro-organisms in channels and pores within the ice, rich algal communities underneath, to fish, seals, whales and polar bears. The diversity of life in the ice usually grows 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. Indigenous Arctic peoples adapted to fishing and hunting will face large economic, social and cultural changes.

Less summer ice will ease access to the Arctic Ocean's resources, though remaining ice will still

Map 5.17 The 2007 minimum sea-ice extent

Average sea-ice extent for September 2007

Sea ice

Median September monthly sea-ice extent 1979–2000

Note: The extent of the summer sea ice in September 2007 reached a historical minimum, 39 % below the climatic average for the first two decades of satellite observations (red line). The weather conditions that summer were dominated by clear skies. Continuous warm winds blew the ice towards the coast of Canada-Greenland and out into the north-east Atlantic, where it melted.

Source: National Snow and Ice Data Centre, Boulder (http://nsidc.org/news/press/2007_seaiceminimum/20070810_index.html).

pose a major challenge for operations most of the year. Expectations of large undiscovered oil and gas resources are already driving the focus of the petroleum industry and governments northwards. As marine species move northwards with warmer sea and less ice, so will the fishing fleet. It is however hard to tell 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 are likely to increase, although drift ice, short sailing seasons and lack of infrastructure will impede a rapid development of transcontinental shipping of goods; it is more likely that traffic linked to extraction of Arctic resources on the fringes of the Arctic sea routes will grow first. These activities offer new economic opportunities. At the same time they represent new pressures and risks to an ocean that has so far been closed to most economic activities by the ice. This should be met by better international regulations of these activities.

High interest in getting access to the resources in the Arctic may create tensions and security problems. However most borders in the Arctic Ocean have been drawn, thereby clearly defining who has the ownership to the resources and right to manage them. In the remaining unresolved issues of delimitation of the Exclusive Economic Zones and extended continental shelves, all the coastal states of the Arctic Ocean follow the procedures of the UN Convention of the Law of the Seas.

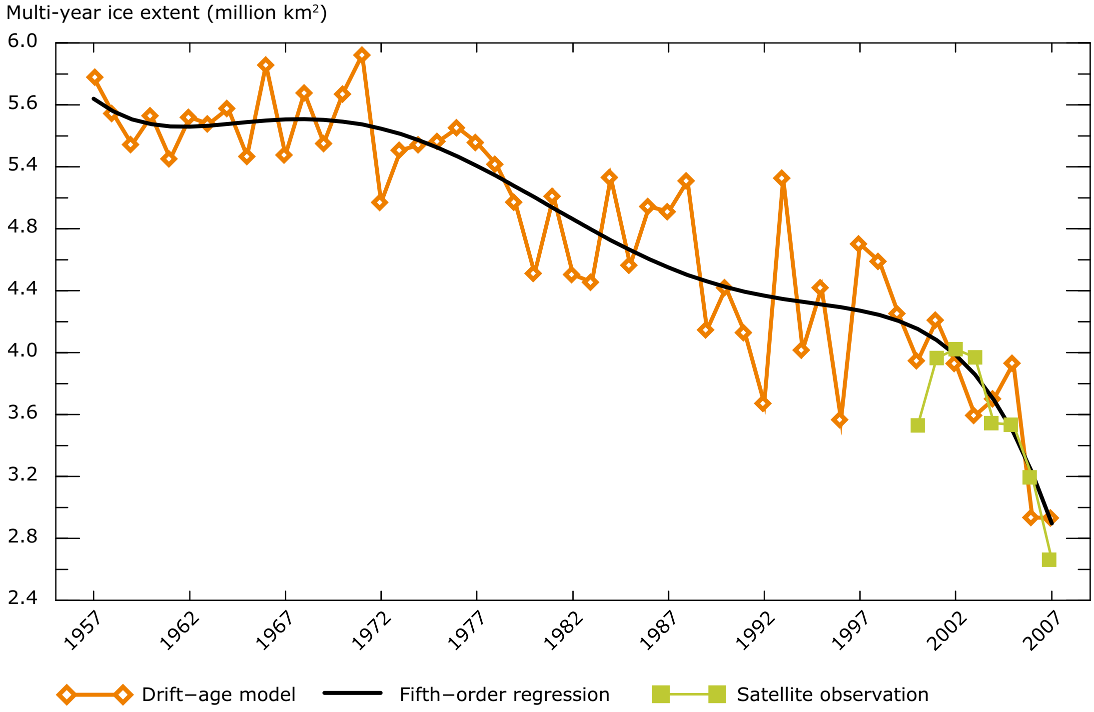
Past trends

The extent of the minimum ice cover at the end of the melt season in September 2007 broke all previously observed records. If older ship and aircraft observations are taken into account, sea ice coverage may have halved since the 1950s (NSIDC, 2007; Meier, 2007). Since the more reliable satellite observations started in 1979, summer ice has shrunk by 10.2 % per decade (Comiso *et al.*, 2008; NSIDC, 2007). This strong negative trend

The polar cod is a key species in the sea ice ecosystem; here in ice with ice algae at the surfaces

Photo: © Bjørn Gulliksen; www.UWPhoto.no

Figure 5.15 Area of multi-year Arctic sea ice in March 1957–2007



Note: The area of thick, multi-year sea ice in the Arctic Ocean is decreasing. The figure is based on a combination of modelling and satellite observations.

Source: Nghiem *et al.*, 2007.

was further reinforced when the second lowest minimum extent was recorded summer 2008. The reduction in maximum winter extent is smaller, with a decrease of 2.9 % per decade (Figure 5.14) (Stroeve *et al.*, 2007). Both summer and winter declines have accelerated (Comiso *et al.*, 2008).

The Arctic sea ice is also getting thinner and younger since less ice survives the summer to grow into thicker multi-year floes. There has been a remarkable shift in its composition towards less multi-year ice and larger areas covered with first-year ice (Figure 5.15). The first-year ice is weaker and melts easier in summer.

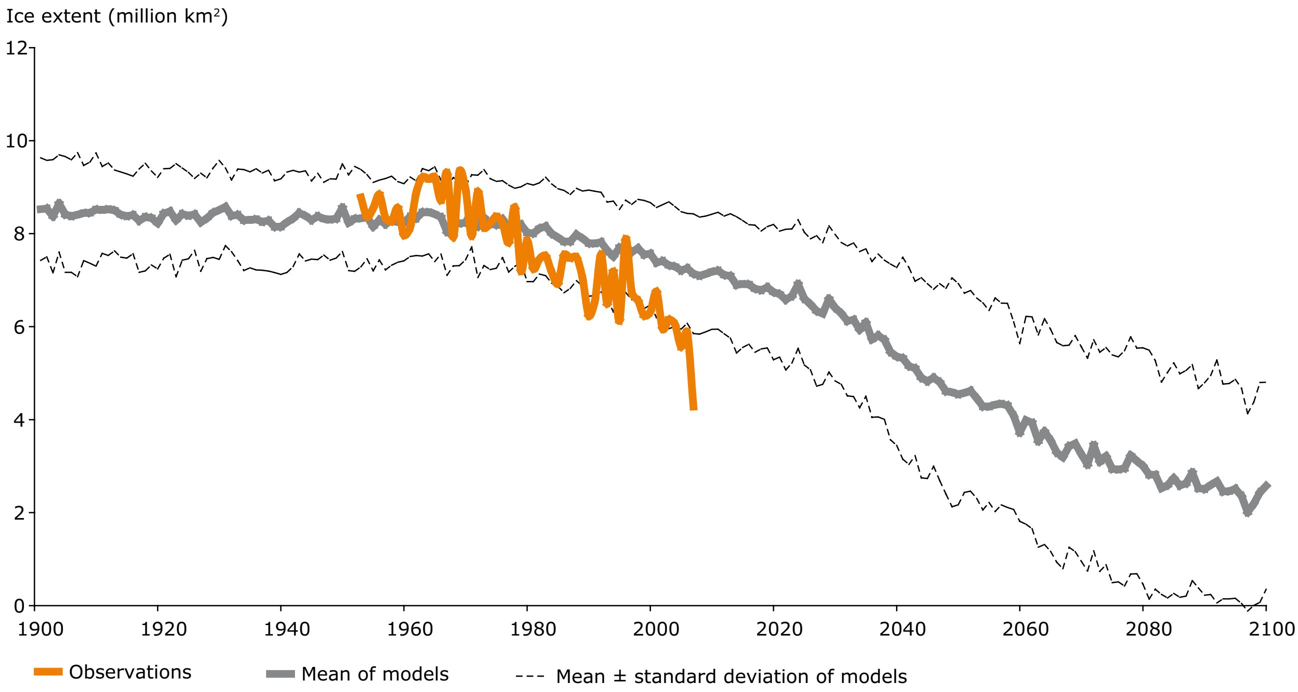
Observations of thickness are more scattered, and it is hard to calculate trends for the whole ice cover. Submarine data have been considered to be most representative and have demonstrated a decrease of 40 % from an average of 3.1 m in 1956–1978 to 1.8 m in the 1990s (UNEP 2007). British submarine data from 2007 show continued thinning (Wadham, pers. com.). German observations from the area around the North Pole and towards northeast Greenland indicate that ice thickness there decreased by 44 % from 2001 to 2007. This was due mainly to a fundamental regime shift from multi-year ice to first-year ice. But there has also been a general thinning of the ice (Nghiem *et al.*, 2007; Haas *et al., 2008*) These results are in stark contrast with observations between Ellesmere Island and 86°N, where ice thickness was still above 4 m in 2006 (Haas *et al.*, 2006).

Arctic sea ice reacts very sensitively to changes in air and ocean temperatures as well as winds, waves and ocean currents (both thermodynamic and dynamic forcing). There are strong imprints of natural variability in the observed changes, e.g. due to regular shifts in the circulation patterns of the polar atmosphere. However, the changes that can be attributed to increases in greenhouse gases seem to be increasing over time (Stroeve *et al.*, 2007).

Projections

The summer ice is very likely to continue to shrink in extent and thickness, leaving larger areas of open water for an extended period. It is also very likely

Figure 5.16 Observed and projected Arctic September sea-ice extent 1900–2100



Note: The retreat of the sea ice has been faster than predicted: Arctic September sea-ice extent from observations (thick orange line) together with the mean value (solid grey line) from 13 IPCC AR4 climate models and the variance (dotted black line) of models runs.

Source: Updated from Stroeve *et al.*, 2007.

that conditions for freezing in winter will persist so that winter sea ice will still cover large areas.

The speed of change is however uncertain. Several international assessments until recently concluded that mostly ice-free late-summers may occur by the end of this century (ACIA, 2004; IPCC, 2007a; UNEP, 2007). But the actual melting has been faster than the average trends simulated by the climate models used for these assessments (Figure 5.16). New model studies suggest that ice-free summers may occur in a much nearer future. (Winton, 2006; Holland *et al.*, 2006; Stroeve *et al.*, 2007). Exactly when is impossible to predict with confidence, due both to the limited understanding of the processes involved and the large variability of the system.

Photo: © John McConnico

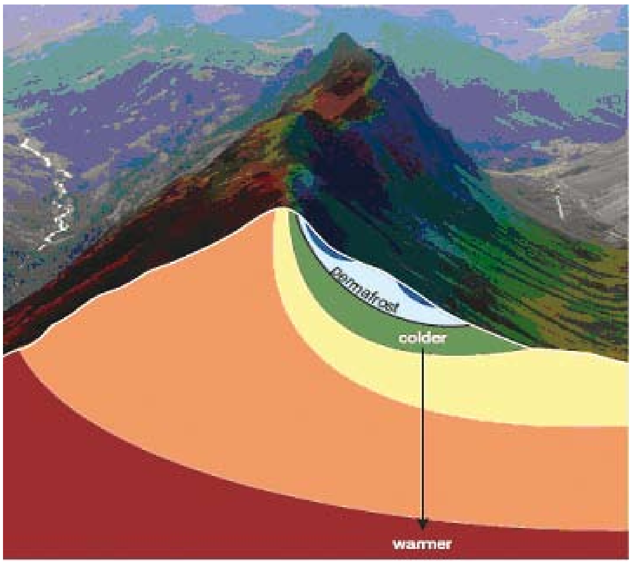
Most studies emphasise that it is very likely that thinner and more vulnerable ice will break up more easily so more heat from the sun will be absorbed in the open water. This can lead to abrupt melting and a high susceptibility to dynamic stress like strong winds when weather conditions are favourable, as in the summer of 2007. An increased influx of warm Atlantic water can also be an important mechanism for further weakening of the sea ice. Unless followed by consecutive years of cold winters, such events will produce a thinner, younger and even more vulnerable ice cover that can melt more easily the next summer, and be more easily transported out of the Polar Ocean.

5.3.6 *Mountain permafrost*

Key messages

- A warming of mountain permafrost in Europe of 0.5–1.0 °C was observed during the past 10–20 years.
- Present and projected atmospheric warming will likely lead to wide-spread thaw of mountain permafrost.
- Warming and melting of permafrost is expected to contribute to increasing the destabilisation of mountain rock-walls, the frequency of rock falls, debris flow activity and geotechnical and maintenance problems in high-mountain infrastructure.

Figure 5.17 Temperature distribution within a mountain range containing permafrost



Note: Permafrost is present in the blue area bordered by a black line.

Source: Gruber and Haeberli, 2007. http://maps.grida.no/go/graphic/mountain-permafrost-patterns-and-temperature-gradients.

Relevance

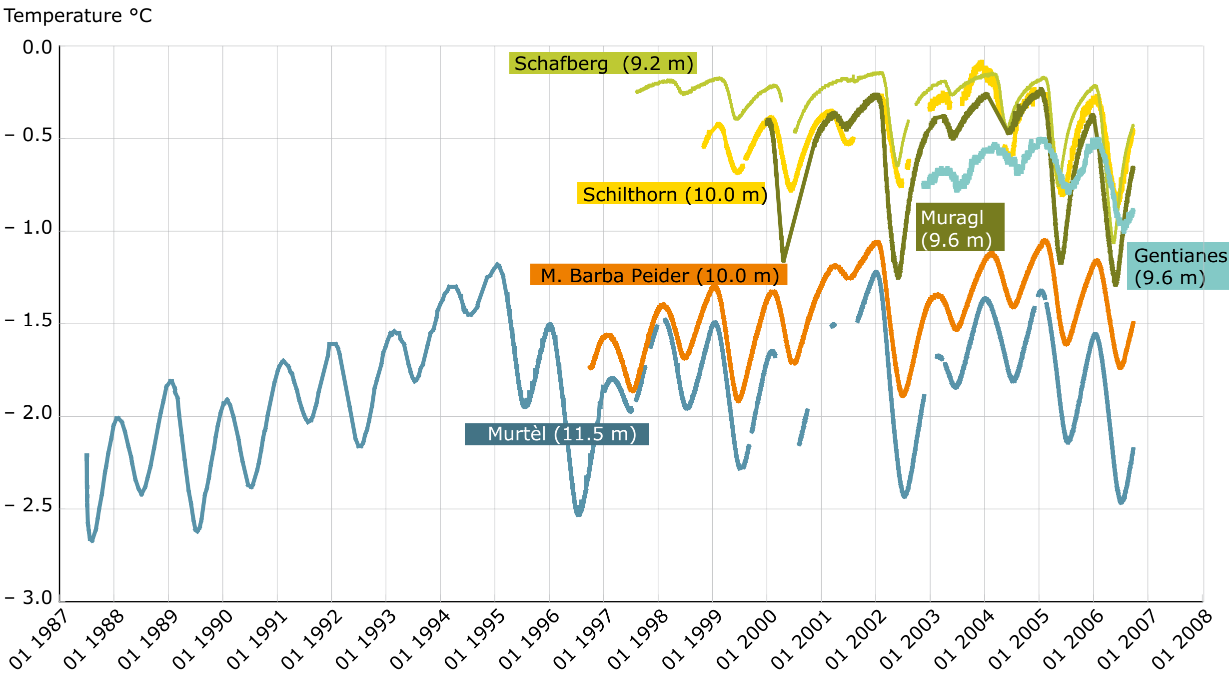
Permafrost is permanently frozen ground and consists of rock or soil that has remained at or below 0 °C continuously for more than two years. Mountain permafrost is the dominating permafrost in Europe, because Arctic permafrost is found in Europe only in the northernmost parts of Scandinavia. Permafrost is abundant at high elevations in mid-latitude mountains, where the annual mean temperature is below – 3 °C. It contains variable amounts of ice and exists in different forms: in steep bedrock, in rock glaciers, in debris deposited by glaciers and in vegetated soil. Because vegetation and circulating groundwater in mountain permafrost areas are mostly absent, the temperature in the deeper rock material is largely determined by the temperature history at its surface. Mountain permafrost therefore contains valuable information on climate change. Temperature profiles from alpine boreholes are difficult to interpret in terms of past trends due to the effects of the complex topography (Figure 5.17) and the availability of insulating snow-cover (Gruber *et al.*, 2004a). Nevertheless, monitoring of temperature change at depth provides valuable data on the thermal response of permafrost to climate change.

Permafrost influences the evolution of mountain landscapes and affects human infrastructure and safety. Permafrost warming or thaw affects the potential for natural hazards, such as rock falls (e.g. at the Matterhorn in summer 2003) and debris flows (Noetzli *et al.*, 2003; Gruber and Haeberli, 2007). At least four large events involving rock volumes of more than 1 million m^3 have occurred in the Alps during the past decade. Their effects on infrastructure have motivated the development of technical solutions to improve design lifetime and safety (Philips *et al.*, 2007).

Past trends

Data from a north-south transect of boreholes, 100 m or more deep, extending from Svalbard to the Alps (European PACE-project) indicate a long-term regional warming of permafrost of 0.5–1.0 °C during the recent decade (Harris *et al.*, 2003). In Scandinavia and Svalbard, monitoring over 5–7 years shows warming down to 60 m depth and current warming rates at the permafrost surface of 0.04–0.07 °C/year (Isaksen *et al.*, 2007). In Switzerland, a warming trend and increased active-layer depths were observed in 2003, but results varied strongly between borehole locations due to variations in snow cover and ground properties (PERMOS, 2007). At the Murtel-Corvatsch (rock-glacier) borehole in the Swiss Alps, the only long-term data record (20 years), permafrost temperatures

Figure 5.18 Temperature measured in different boreholes in mountain permafrost in Switzerland 1987–2007



Note: Measured at ca. 10 m depth in rock-glaciers and frozen rock-walls.

Source: PERMOS, 2007.

in 2001, 2003 and 2004 were only slightly below – 1 °C (Figure. 5.18) and were, apart from 1993 and 1994, the highest since measurements began in 1987 (Vonder Mühll *et al.*, 2007). Such data measured at rock-glaciers are difficult to interpret because the sub-surface thermodynamics in ice-rich frozen debris is rather complex. Complementary and clearer signals on thawing permafrost are expected from boreholes drilled directly into bedrock

Rock glacier Murtel-Corvatsch

Photo: © M. Phillips, SLF

(e.g. Schilthorn, M. Barba Peider; Figure 5.18). Corresponding monitoring programmes, such as PACE and PERMOS, however, only started less than a decade ago.

Projections

No specific projections on the behaviour of mountain permafrost are yet available, but changes in mountain permafrost are likely to continue in the near future and the majority of permafrost bodies will experience warming and/or melting. According to recent model calculations based on the regional climate model REMO and following the IPCC SRES-Scenarios A1B, A2 and B1, a warming of up to 4 °C by 2100 is projected for the Alpine region (Jacob *et al.*, 2007). Further rises in temperature and melting permafrost could increasingly destabilise mountain walls and increase the frequency of rock falls, posing problems to mountain infrastructure and communities (Gruber *et al.*, 2004a). The warming and thaw of bedrock permafrost can sometimes be rapid and failure along ice-filled joints can occur even at temperatures below 0 °C (Davies *et al.*, 2001). Water flowing along linear structures and the advection of heat along joint systems will further accelerate destabilisation (Gruber and Haeberli, 2007).

5.4 Marine biodiversity and ecosystems

5.4.1 Introduction

The oceans play a key role in regulating climate by transporting heat northward and transferring energy from the atmosphere into the deep parts of the ocean. The Gulf Stream and its extensions, the North Atlantic current and drift, influence European weather patterns and storm tracks. The heat transported northward by the oceanic circulation affects precipitation and wind regimes over Europe. The oceans themselves are also affected by climatic conditions and the resulting changes in physical conditions affect marine ecosystems.

This chapter discusses changes in sea level and sea surface temperature resulting from climate change, and gives examples of the chemical (acidification of the ocean) and biological (changes in physiology, distribution, phenology and genetic composition) consequences of these changes and the associated impacts on marine life in European seas.

Climate change impacts are observed in all European seas (e.g. Halpern *et al.*, 2008), although the extent to which these have been documented in time and space varies. The examples chosen to demonstrate changes in the marine food-web in this report are all well accepted by the scientific community as examples of a climatic impact on the marine environment. In general, changes related to the physical marine environment are better documented than chemical or biological changes simply because observations have been made for longer. For example, systematic observations of both sea level and sea surface temperature were started around 1880 and are today complemented by observations from space with high temporal resolution and geographic coverage. The longest-available records of plankton are from the Continuous Plankton Recorder (CPR), a sampler towed behind many different merchant vessels, along fixed shipping routes. Sampling with the CPR was started in the North Sea in the 1950s and a network covering the entire North Atlantic has been established. No other plankton time-series of equivalent length and geographic coverage exist for the European regional seas.

The primary physical impact of climate change on European regional seas is increased sea surface temperature. However, because of different geographical constraints, climate change is expected to affect physical conditions differently in different seas, and consequently biological impacts also vary depending on the region, as shown in the following examples:

North-east Atlantic: projections indicate that warming will extend throughout the water column during the course of the 21st century (Meehl *et al.*, 2007). Sea surface temperature changes have already resulted in an increased duration of the marine growing season and a northward movement of marine zooplankton. Some fish species are shifting their distributions northward in response to increased temperatures.

Baltic Sea: climate models project a mean increase of 2–4 °C in the sea-surface temperature in the 21st century, and increasing run-off and decreasing frequency of Atlantic inflows, both of which will decrease the salinity of the sea. Consequently, the extent of sea-ice is expected to decrease by 50–80 % over the same period (Meier *et al.*, 2006a) and stratification is expected to become stronger, increasing the probability of a deficiency of oxygen (hypoxia) that kills a lot of marine life in the region. Changes in stratification are expected to affect commercially important regional cod fisheries because stratification appears to be an important parameter for the reproductive success of cod in the Baltic Sea.

Mediterranean Sea: temperature is projected to increase and run-off to decrease. In contrast to the Baltic Sea, the combination of these two effects is not expected to change stratification conditions greatly because of the compensating effects of increasing temperature and increasing salinity on the density of sea water. The invasion and survival of alien species in the Mediterranean is correlated with the general sea surface temperature increase, resulting in the replacement of local fauna with new species. Such changes affect not only local ecosystems, but also the activities of the international fishing fleet when commercial species are affected (Marine Board Position Paper, 2007).

Box 5.5 Ocean acidification

In addition to increasing atmospheric temperature, greenhouse gases (specifically CO_2) affect marine systems more directly. The global ocean is the primary storage medium for carbon dioxide and the amount stored in the ocean depends on its concentration in the atmosphere. CO_2 is soluble in the ocean where carbon dioxide reacts with water to form carbonic acid, which then dissociates into hydrogen ions (H^+), bicarbonate ions (HCO_3^-) and, to a lesser extent, carbonate ions (CO_3^{2-}). The higher the concentration of CO_2 in the atmosphere, the more CO_2 will be dissolved in the ocean and thus increase the concentration of H^+ ions. This will cause a drop in the pH of sea water, i.e. the ocean will become more acidic (less alkaline). Ocean pH has already fallen by 0.1 units since the industrial revolution and simulations for the next century project a further reduction of 0.3 to 0.5 units, depending on which IPCC scenario is adopted in the calculation (Orr *et al.*, 2005; Caldeira and Wickett, 2005). The increased concentration of dissolved CO_2 will lower the saturation levels of carbonate minerals such as calcite, aragonite, and high-magnesium calcite, which will decrease the availability of materials used to form the supporting skeletal structures of many major groups of marine organisms. The decrease in ocean pH is seen as particularly severe because it has been relatively stable for the past 300 million years (Caldeira and Wickett, 2003), it will take a very long time to reverse the trend, and it could fundamentally alter the lowest levels of the marine food-web with unpredictable consequences for higher trophic levels.

Implications for European seas

In European seas, the largest effects are expected in the Arctic where an analysis of the consequences of doubling the atmospheric CO_2 concentration suggests the possibility of a complete undersaturation of aragonite by 2100, which experimental evidence has shown to damage the shells of pteropods (a form of zooplankton), which are key organisms at the bottom of the marine food-web in Arctic and Antarctic waters. By 2150–2200, undersaturation of calcite is expected. (Orr *et al.*, 2005). This will cause other key marine organisms such as coccolithophores (a diatom), echinoderms (sea urchins), and cold-water corals along the northwestern European continental margin to have difficulties in building and maintaining their external structure (Orr *et al.*, 2005). These changes at the bottom of the food web may have serious knock-on effects on all European marine ecosystems (Pearson *et al.*, 1999).

Table 5.1 Average ocean surface pH values

Time	pH	pH change	Source
Pre-industrial	8.2	0	Model (Houghton *et al.*, 1995)
Present day (1994)	8.1	– 0.1	Model (GLODAP reference year, Key *et al.*, 2004)
2050	8.0	– 0.2	Model (Orr *et al.*, 2005)
2100 (based on IPCC scenario IS92a, SRES scenarios)	7.7 to 7.9	– 0.3 to – 0.5	Models (Orr *et al.*, 2005; Caldeira and Wickett, 2005)

Source: Houghton *et al.*, 1995; Key *et al.*, 2004; Orr *et al.*, 2005; and Caldeira and Wickett, 2005.

5.4.2 *Sea-level rise*

Key messages

- Global average sea level rose by around 0.17 m (1.7 mm/year) during the 20th century. In Europe rates of sea-level rise (SLR) ranged from – 0.3 mm/year to 2.8 mm/year. Recent results from satellites and tide gauges indicate a higher average rate of global SLR in the past 15 years of about 3.1 mm/year.
- Projections by the IPCC for the end of the 21st century suggest an additional SLR of 0.18 to 0.59 m above the average 1980–2000 level. Based on the latest observations, recent projections indicate a future SLR that may exceed the IPCC upper limit.
- SLR can cause flooding, coastal erosion and the loss of flat and low-lying coastal regions. It increases the likelihood of storm surges, enforces landward intrusion of salt water and endangers coastal ecosystems and wetlands. An additional 1.6 million people living in Europe's coastal zones could experience coastal flooding by 2080.

Map 5.18 Sea-level change at different European tide-gauge stations 1896–2004

Tide gauge with observation record of at least

- 100 years (reference station)
- 50 years
- 50 years (reference station)

Note: Data (mm/year) corrected with regard to postglacial land movement and gravity-field variation.

Source: Novotny and Groh, 2007.

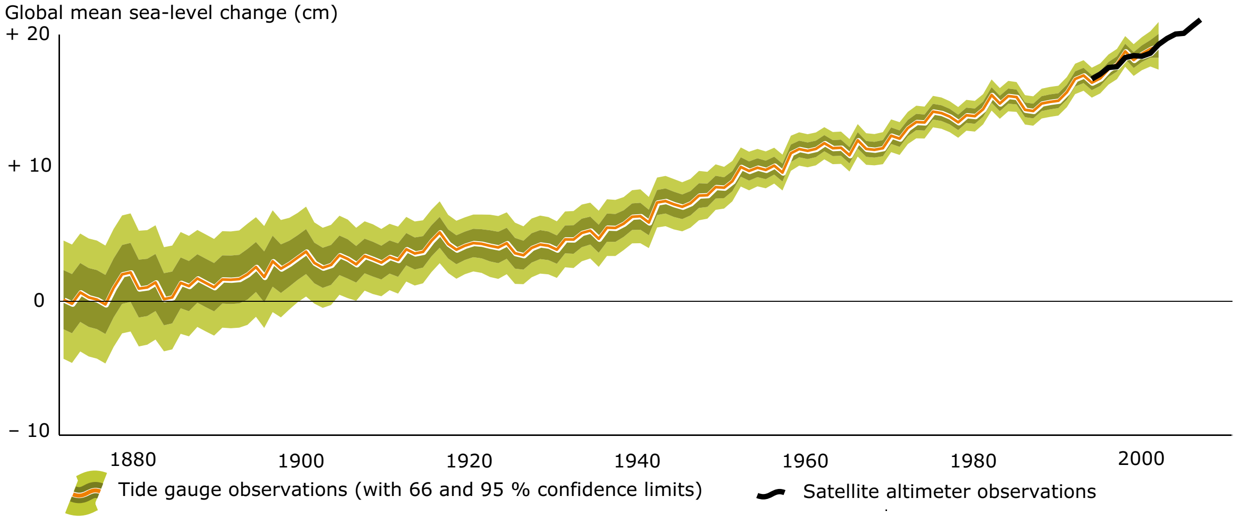
Relevance

Sea-level rise (SLR) results from thermal expansion of the oceans (the increase in volume due to rising ocean water temperature) and increased inflow of melt-water from glaciers and ice-sheets (in particular the Greenland and west Antarctic ice sheets). Thus it is an important indicator of climate change, with great relevance in Europe for flooding, coastal erosion and the loss of flat coastal regions. Rising sea levels increase the likelihood of storm surges, enforce landward intrusion of salt water and endanger coastal ecosystems and wetlands. Coastal areas in Europe often contain important natural ecosystems, productive economic sectors, and major urban centres.
A higher flood risk increases the threat of loss of life and property as well as damage to sea-dikes and infrastructure, and could lead to an increased loss of tourism, recreation and transportation functions (Nicholls and Tol, 2006; Nicholls *et al.*, 2007; Devoy, 2008). Low-lying coastlines with high population densities and small tidal ranges will be most vulnerable to SLR (Kundzewicz, 2001). Thus coastal flooding related to SLR could affect a large population (Arnell, 2004; Nicholls, 2004). Because of the slow reaction of the climate system, climate change mitigation will not reduce these risks over the coming decades to any significant degree, but various options for adaptation exist.

Past trends

Tide gauge-based data e.g. from the Permanent Service for Mean Sea Level (PSMSL), show that the long-term average sea level on European coasts changed, depending on the region, at a rate between – 0.3 mm/year and 2.8 mm/year

Figure 5.19 Changes in global sea level 1870–2006



Source: Church and White, 2006 (http://maps.grida.no/go/graphic/trends-in-sea-level-1870-2006).

during the 20th century (Map 5.18). In this period, global sea level rose by an average of 1.7 mm/year (Church and White, 2006). Recent satellite data-sets indicate an accelerated global trend in sea-level rise to about 3.1 mm/year (Figure 5.19) in the past 15 years which is almost backed by tide-gauge data from this period (Nerem *et al.*, 2006; Church and White, 2006; Rahmstorf *et al.*, 2007). It is very likely that the observed trend in sea-level rise over the past 100 years is attributable mainly 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 (Table 5.3). Several recently-published papers underline the relatively small, but significantly increasing contribution of ice-sheets, e.g. from Greenland (Cazenave, 2006; Chen *et al.*, 2006; Rignot and Kangaratnam, 2006), see Section 5.3.4.

Satellite observations indicate a large spatial variability of SLR trends in the European seas (Map 5.19; Table 5.2). For instance in the Mediterranean and the Levantine Sea positive trends are observed while negative trends are observed in the northern Ionian Sea. These local variations could 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 (e.g. gyres) (Demirov and Pinardi, 2002).

Projections

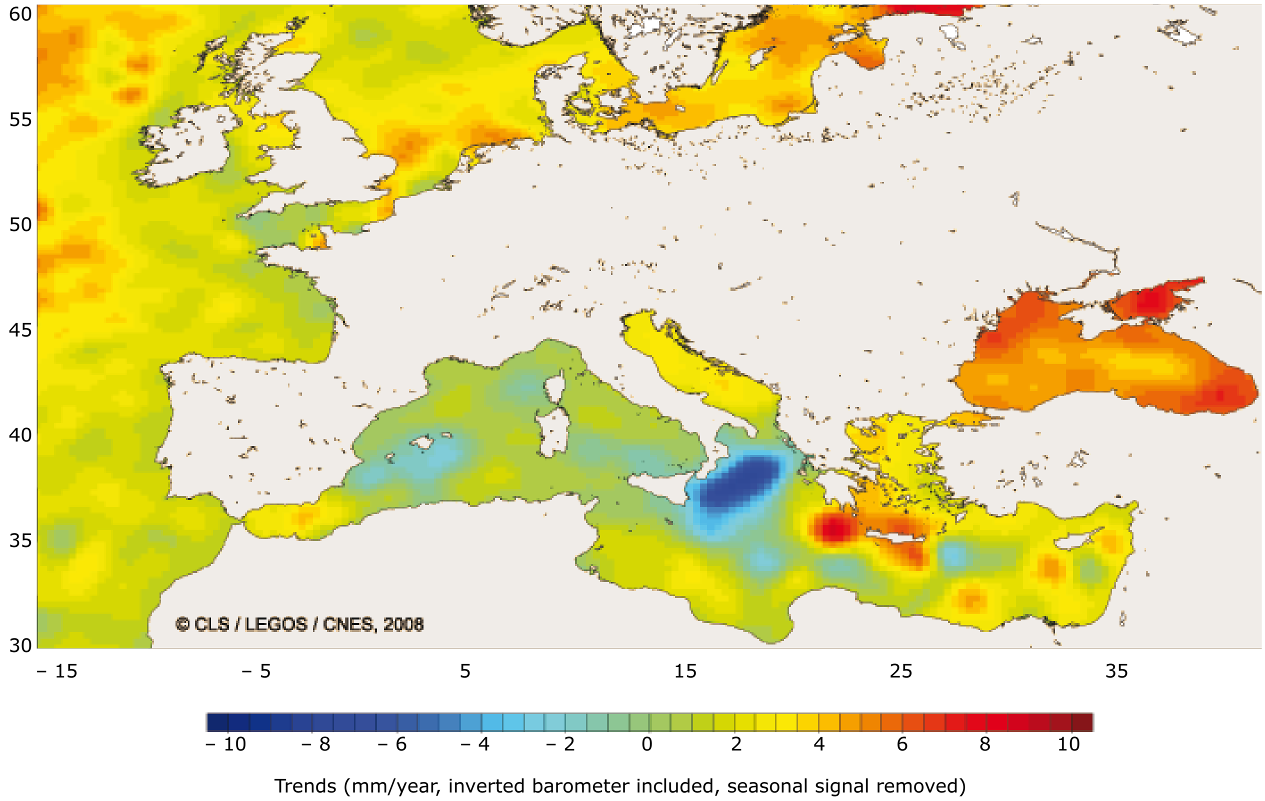
Sea-level rise by the end of this century (2090–2099) is projected, under the SRES-scenarios, to be 0.18–0.59 m above the present (1980–1999) level,

Table 5.2 Contribution of different processes to global sea-level rise (1993–2006)

Process	Contribution to global sea-level rise (mm/year)
Ocean thermal expansion	1.6 ± 0.5
Melting of glaciers and ice caps	0.8 ± 0.2
Melting of the Greenland ice sheet	0.2 ± 0.1
Melting of the west Antarctic ice sheet	0.2 ± 0.4
Unaccounted for	0.3
Total global sea-level rise	3.1 ± 0.7

Source: IPCC, 2007a.

Map 5.19 Sea-level changes in Europe October 1992–May 2007



Note: Map based on satellite altimeter data.

Source: Guinehut and Larnicol, 2008.

with a maximum rate of rise three times that in the past decade (Figure 5.20). Thermal expansion is the largest component, contributing 70–75 % of the central estimate of these projections for all scenarios. Glaciers, ice caps and the Greenland ice sheet are also projected to contribute to sea-level rise (IPCC, 2007a).

Sea-level rise during the 21st century is projected to have substantial geographic variability (IPCC, 2007a). In Europe, regional influences in the Arctic Ocean and the northern North Atlantic may result in SLR being up to 50 % higher than these global estimates (Woodworth *et al.*, 2005). The impact of the NAO on winter sea levels adds an uncertainty of 0.1–0.2 m to these estimates (Hulme *et al.*, 2002; Tsimplis *et al.*, 2004). A slowing of the Atlantic Meridional Overturning Circulation (MOC), also known as great conveyor belt, in the North Atlantic would result in a further rise in relative sea level at European coasts (IPCC, 2007b).

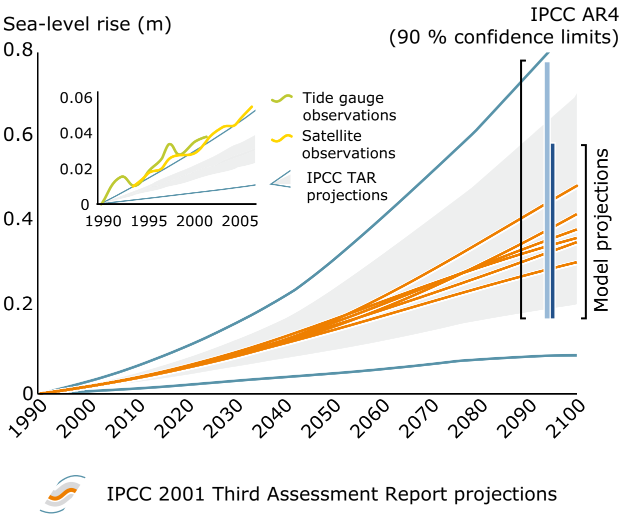
SLR projections for the Baltic and Arctic coasts based on SRES scenarios indicate an increased risk of flooding and coastal erosion after 2050 but always lower than the risk in the North Sea and the Mediterranean (Johansson *et al.*, 2004; Meier *et al.*, 2004, 2006b; Nicholls, 2004). The A1F1-scenario,

Table 5.3 Average sea-level rise in some European seas (satellite observations) October 1992–May 2007)

European seas	Sea-level rise (mm/year)
North Atlantic (50°N to 70°N)	3.4
Central North Atlantic (30°N to 50°N)	1.15
Mediterranean Sea	1.5
Black Sea	7.5

Source: Guinehut and Larnicol, 2008.

Figure 5.20 Projected global average sea-level rise 1990–2100



Note: Six SRES scenarios are shown. The graph displays model projections, including ice sheet dynamic processes.

Source: UNEP, 2007; IPCC, 2001.

which assumes very high greenhouse gas emission from fossil-fuel combustion, would lead to a greater impact of SLR in the northern Mediterranean, as well as in northern and western Europe. While it was highly unlikely that the populations in these coastal areas would experience flooding in 1990, up to 1.6 million people might experience coastal flooding each year by 2080 (Nicholls, 2004).

Various adaptation measures are available to reduce these risks. But there are limits to adaptation: due to the thermal inertia of the oceans, sea-level rise would not stop by 2100 even if greenhouse gas concentrations were stabilised. Over a period of centuries and millennia, a very large SLR could result from the melting of the world's major ice sheets in Greenland and on the West Antarctic ice shelf, which have an SLR potential of about 7 and 5–6 m respectively, should they melt completely (IPCC, 2007a).

Photo: © Pavel Šťastný

Box 5.6 Long-term sea-level rise: insights since IPCC AR4

Observed sea-level rise from 1990 onwards is close to the 'upper limit' line of the range projected in the Third and Fourth Assessment Report of the IPCC (Figure 5.20) (Rahmstorf *et al.*, 2007). This indicates that one or more drivers of SLR were underestimated (UNEP, 2007). As noted by the IPCC, a further acceleration in ice flow of the kind recently observed in some Greenland outlet glaciers and west Antarctic ice streams could substantially increase the contribution from the ice sheets to SLR (IPCC, 2007a). To allow a margin for these ice sheet uncertainties, the IPCC AR4 increased the upper limit of the projected SLR by 10–20 cm, but stated that understanding of these effects was too limited to assess their likelihood or give a best estimate (IPCC, 2007a).

In a recently-published paper Rahmstorf estimated a possible global SLR of 0.5–1.4 m above the 1990 level by 2100, basing on a semi-empirical approach (Rahmstorf, 2007). Using a different method, Katsman projected a range of SLR rise of up to 0.8 m in the northeast Atlantic Ocean for the same time period (Katsman *et al.*, 2007). This difference already shows one of the uncertainties. While the appreciable contributions from thermal water expansion and melting glaciers and ice-caps are fairly well understood and thus predictable, to a certain extent, the complexity of the (inadequately understood) internal dynamics of ice sheets makes it extremely challenging to project sea-level change accurately at present day. In addition to the uncertainty about the behaviour of the world's major ice sheets, ocean dynamics, e.g. a further rise of the relative sea level under a slowing MOC (Meridional Overturning Circulation), and the effect of gravity changes induced by the melting of land-based ice-masses (e.g. the Greenland ice-sheet) can also have a noticeable effect, particularly on regional SLR (Katsman *et al.*, 2007).

Due to the complexity of the problem and the possible overlap of natural processes and those induced by anthropogenic climate change, both of which could contribute to SLR, long-term projections remain rather uncertain.

5.4.3 *Sea surface temperature*

Key messages

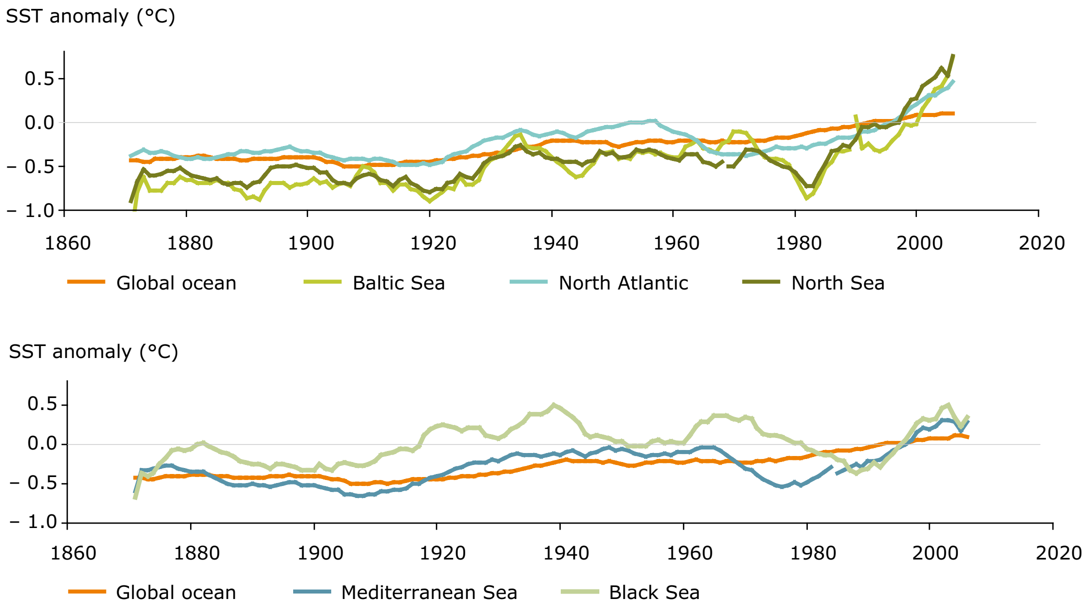
- Sea surface temperature (SST) in European seas is increasing more rapidly than in the global oceans. The rate of increase is higher in the northern European seas and lower in the Mediterranean Sea.
- The rate of increase in sea surface temperature in all European seas during the past 25 years has been about 10 times faster than the average rate of increase during more than the past century.
- The rate of increase observed in the past 25 years is the largest ever measured in any previous 25 year period.

Table 5.4 Summary of sea surface temperature changes in the global ocean and the four European regional seas

Sea	1871–2006 annual rate °C/year (past 136 years)	1982–2006 annual rate °C/year (past 25 years)
Global ocean	0.004	0.01
North Atlantic Ocean	0.002	0.03
Baltic Sea	0.006	0.06
North Sea	0.004	0.05
Mediterranean Sea	0.004	0.03
Black Sea	0.003	0.03

Source: SST datasets from the Hadley Centre (HADISST1 (global)), MOON (Mediterranean Sea), and Bundesamt für Seeschifffahrt und Hydrographie (Baltic and North Seas).

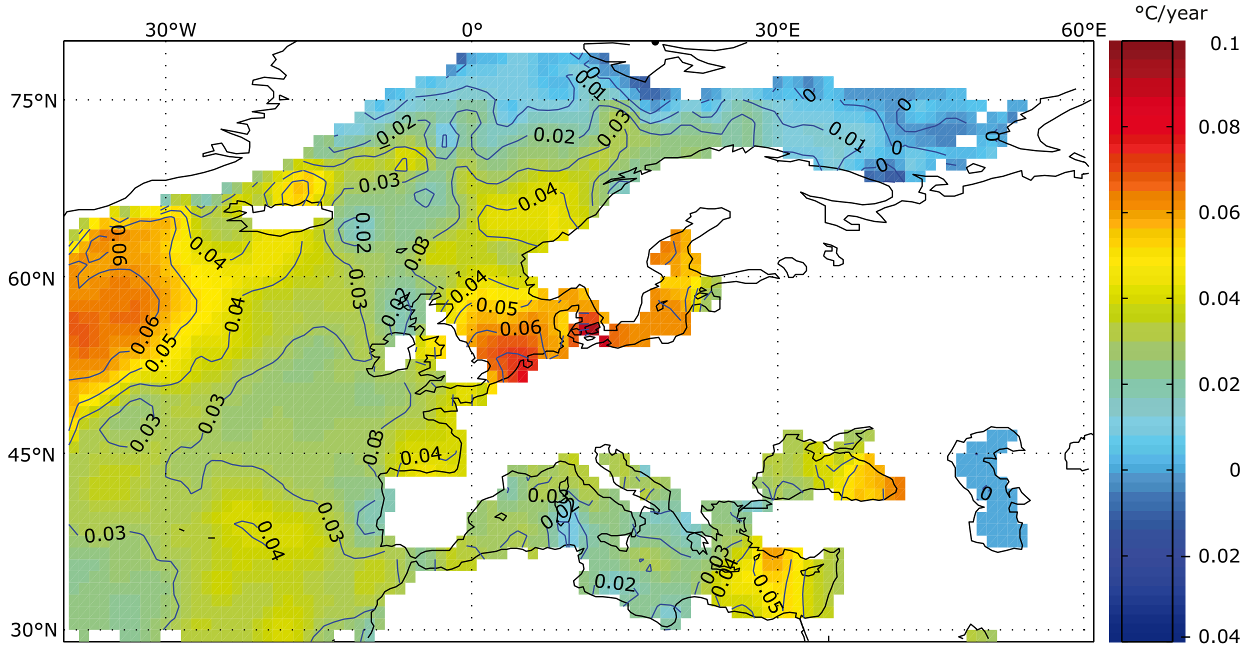
Figure 5.21 Sea surface temperature anomaly for period 1870–2006



Note: Data (°C) show the difference between annual average temperatures and the period 1982–2006 mean in different European seas. Data sources are: SST datasets from the Hadley Centre (HADISST1 (global)), MOON (Mediterranean Sea), and Bundesamt für Seeschifffahrt und Hydrographie (Baltic and North Seas).

Source: Coppini *et al.*, 2007.

Map 5.20 Sea surface temperature changes for the European seas 1982–2006



Note: Calculated from HADISST1 dataset, the unit of numbers is in °C/year.

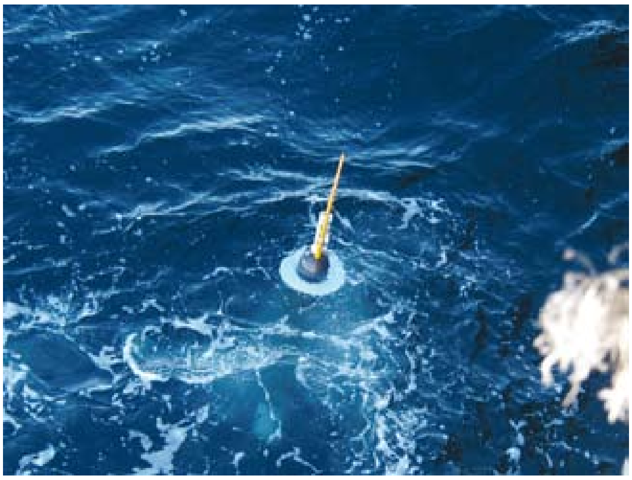
Source: Coppini and Pinardi, 2007.

Relevance

Sea surface temperature (SST) is closely linked to one of the strongest drivers of climate in western Europe: the ocean circulation known as the Atlantic Meridional Overturning Circulation (MOC). This circulation (also known as the great conveyor belt) carries warm upper waters north in the Gulf Stream and returns cold deep waters south. It is widely accepted that the MOC is an important driver of low frequency variations in sea surface temperature on the time scale of several decades (Griffies *et al.*, 1997). It is also widely accepted that the NAO index (a proxy of atmospheric variability, see Section 5.2) plays a key role in forcing variations in MOC as well as the northward extent of the Gulf Stream (Frankignoul and Kestenare, 2005; De Coetlogon *et al.*, 2006). At present, changes in sea surface temperatures of the global ocean and the regional seas of Europe are consistent with the changes in atmospheric temperature (Levitus *et al.*, 2000; Rayner *et al.*, 2006).

The sensitivity of the MOC to greenhouse warming, however, remains a subject of much scientific debate. Observations indicate that there has indeed been a freshening of the North Atlantic since 1965 due to increased freshwater inputs from rivers, precipitation and melting glaciers (Curry and Mauritzen, 2005), and thus possibly a weakening of the Atlantic MOC. The freshening calculated by these authors occurred mainly before 1970 and does not yet appear to have substantially altered the MOC and its northward heat transport. Uncertainties regarding the rates of future climate warming and glacial melting limit the predictability of the impact on ocean circulation, but do not exclude the possibility of a weakening of the MOC. Recent observations, have, however, shown that the variability of the MOC is large. The year-long average MOC is 18.7 ± 5.6 Sverdrup ([3]), but with large variability ranging from 4.4 to 35.3 Sverdrup (Cunningham *et al.*, 2007). A recent study has shown that the variability of the MOC may be predictable on decadal time scales, and the study predicts that North Atlantic and European sea surface temperatures will fall slightly in the next decade as natural climate variability off-sets the projected anthropogenic warming (Keenlyside *et al.*, 2008). The plausibility of the Keenlyside *et al.*, 2008 projections are, however, also subject to intense debate in the scientific community (see e.g. http://www.realclimate.org).

([3]) 1 Sverdrup = 10^6 m^3s^{-1}.



An Argo PROVOR float measuring sea surface temperature

Photo: © Sabrina Speich and www.argo.ucsd.edu

One of the most visible ramifications of increased temperature of the ocean is the reduced area of sea ice coverage in the Arctic polar region (see also Section 5.3) and there is an accumulating body of evidence suggesting that many marine ecosystems are responding both physically and biologically to changes in regional climate caused predominantly by the warming of air and SST, as shown in the following sections.

Past trends

The SST changes in the European regional seas are stronger than in the global oceans (Table 5.4). The strongest trend in the last 25 years is in the Baltic Sea and the North Sea, while the rates are lower in the Black Sea and Mediterranean Sea. The regional seas experienced warming rates that are up to six times larger than those in the global oceans in the past 25 years. These changes have not been observed in any other 25-year period since systematic observations started more than a century ago (Figure 5.21).

The spatial distribution of trend over the European seas is shown in Map 5.20. It shows that the positive temperature trend is more pronounced in the North Sea, Baltic Sea, the area south of the Denmark Strait, the eastern part of the Mediterranean, and the Black Sea. Absolute maxima are located in the North Atlantic around 50°N, in the North Sea and Baltic Sea, with values over 0.06–0.07 °C/year. Negative trends are detected in the Greenland Sea. Here, the estimates also depend on the extent of the ice.

Projections

IPCC (2007a) reports global-scale SST patterns for the SRES-A1B scenario for 2011–2030, 2046–2065, and 2080–2099. In these scenarios, ocean warming evolves more slowly than the warming of the atmosphere. Initially ocean warming will be greatest in the upper 100 m of the ocean (in the surface mixed layer), but later in the 21st-century temperatures will also increase in the deep ocean (IPCC, 2007a; Watterson, 2003; Stouffer, 2004).

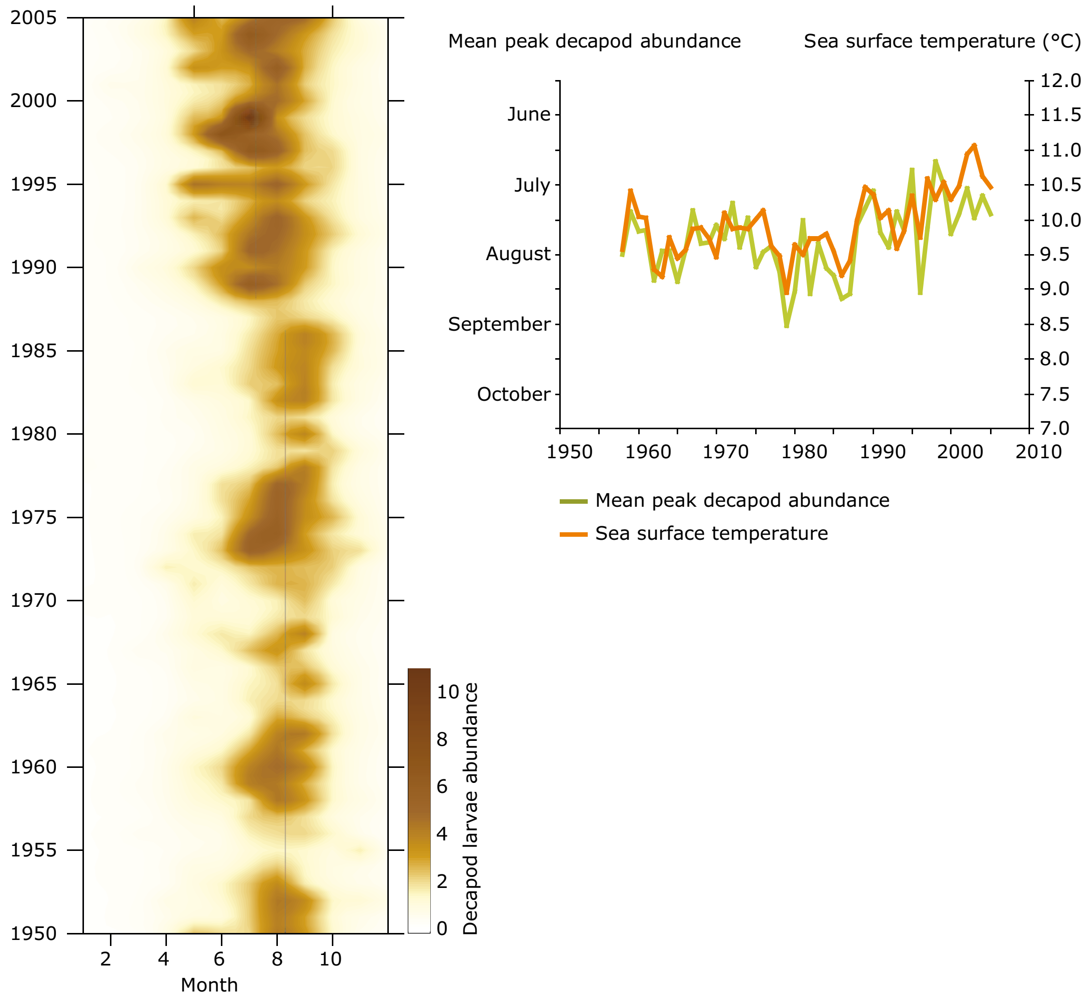
The scenario projects ocean warming to be relatively large in the Arctic and along the equator in the eastern Pacific, with less warming over the North Atlantic and in the Southern Ocean (e.g. Xu *et al.*, 2005). Enhanced oceanic warming along the equator is also evident, and can be associated with oceanic heat flux changes (Watterson, 2003) and temperature changes in the atmosphere (Liu *et al.*, 2005). It is not possible to project changes in SST for the different geographic regions across Europe because the spatial resolution of the coupled ocean-climate models is not high enough to evaluate trends on the scale of individual European regional seas.

5.4.4 *Marine phenology*

Key messages

- Temperature increases in the ocean have caused many marine organisms in European seas to appear earlier in their seasonal cycles than in the past. For example, some species have moved forward in their seasonal cycle by 4–6 weeks.
- Changes in the timing of seasonal cycles have important consequences for the way organisms within an ecosystem interact and ultimately for the structure of marine food-webs at all trophic levels. The consequences include:
  - increased vulnerability of North Sea cod stocks to over-fishing;
  - decline in seabird populations.
- Marine species may be able to adapt genetically to changed conditions. However, with the current pace of climate warming this may be hampered because genetic changes require several reproductive cycles to occur.

Figure 5.22 Decapod abundance in the central North Sea 1950–2005



Note: Left: year vs. month plot is highlighting the mean seasonal peak in the decapod abundance. Right: the month of seasonal peak of decapod larvae for each year 1958–2005 (green line) shown together with sea surface temperature (orange line).

Sources: Edwards and Richardson, 2004 (left and right); Hadley Centre (http://hadobs.metoffice.com/hadisst/data/download.html) (right).

Relevance

Phenology is the study of annually recurring life-cycle events such as the timing of migrations and flowering of plants. In the marine environment such phenology indicators would include the timing of the spring phytoplankton bloom and the peak in the abundance of other marine organisms such as the earlier appearance of dinoflagellates associated with summer stratified conditions. Change in phenology is one of the key indicators of the impacts of climate change on biological populations. Because marine species have different sensitivities to changes in temperature, these changes may lead to large shifts in the marine food web that can ultimately affect the food available to fish, birds or marine mammals.

In the North Sea, many species are appearing earlier in their normal seasonal cycles while others are not. This has led to a decoupling of species relationships and changes in food-web structures (Edwards and Richardson, 2004). Such changes in plankton have been strongly implicated in worsening the decline in North Sea cod stocks, caused initially by over-fishing (Beaugrand *et al.*, 2003), and have contributed to changing other fish populations (sand-eels) that are an essential food source for seabirds (Frederiksen *et al.*, 2006).

The southern North Sea has been identified as being particular vulnerable to phenology changes (Edwards, Woo and Richardson, in prep.). Phenology changes have been related to the degree and speed of regional climate change. For example, the southern North Sea is warming faster than other regions in the North East Atlantic and is where phenological movement has been much more pronounced.

The 'Continuous Plankton Recorder'

Photo: © SAHFOS, 2003

Past trends

In the North Sea, work on pelagic phenology has shown that plankton communities, including fish larvae, are very sensitive to regional climate warming with the response to warming varying between trophic levels and functional groups. However the ability and speed at which fish and planktonic communities adapt to climate warming is not yet known. In other European regional areas, long-term data on marine phenology changes are quite sparse. According to some preliminary studies, there has also been some phenological movement in certain copepod species in the Mediterranean Sea over the past decade (Juan-Carlos Molinero, pers. com.).

Due to the sensitivity of their physiological development to temperature, decapod larvae were selected as representative of phenological changes in shelf-sea environments (Lindley, 1987). The zooplankton growing season indicator shows the annual timing of peak seasonal abundance of decapod larvae from 1958–2005 in the central North Sea (Figure 5.22 left). A shift towards an earlier seasonal peak is clearly visible. In particular, since 1988, the seasonal development of decapod larvae has occurred much earlier than the long-term average (baseline mean: 1958–2005) — in the 1990s up to 4–5 weeks earlier than the long-term average This trend towards an earlier seasonal appearance of decapod larvae during the 1990s is highly correlated with sea surface temperature (Figure 5.22 right).

Projections

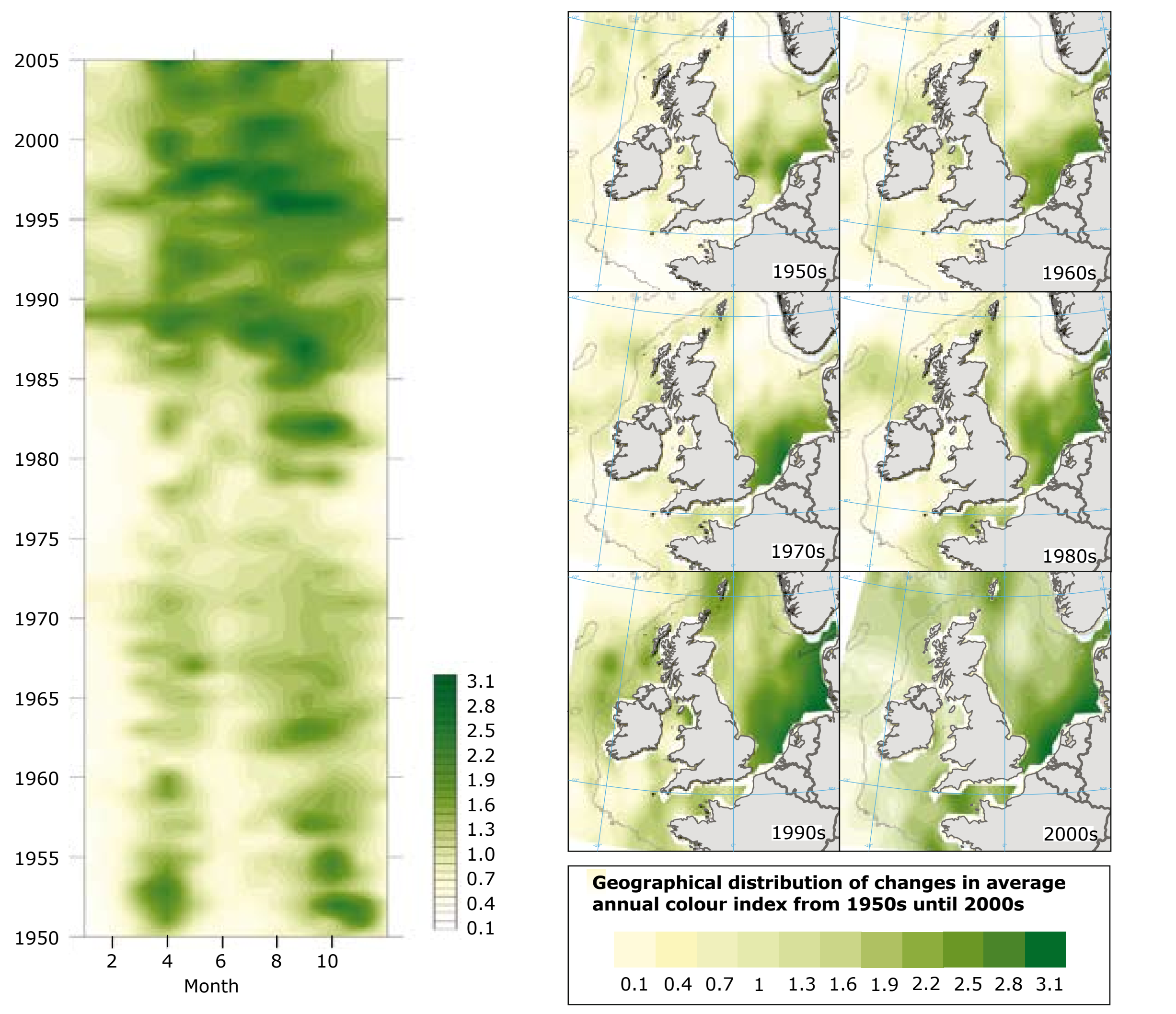
Projections of how individual species react to future climate change have not yet been made, but the empirical evidence suggests that it is very likely that phenological changes will continue to occur as climate warming continues to accelerate. It is currently much less certain to what degree genetic adaptations within species populations can cope with these changes and whether the current pace of climate warming is too fast for genetic adaptations to take place.

Box 5.7 Phytoplankton biomass and growing season

The oceans are thought to absorb one third (approximately 2 Gt C y^{-1}) of anthropogenic emissions of CO_2 because phytoplankton use CO_2 for their photosynthesis. These microscopic algae are responsible for removing carbon dioxide from the atmosphere through photosynthesis and transferring the carbon to other trophic levels. Phytoplankton are also the lowest trophic level of the marine food-web and thus any change has consequences for all other trophic levels (e.g. zoo-plankton, fish, seabirds) through bottom-up control. Increased sea surface temperature has been linked to extending growing seasons in the North Sea (see example below) but because phytoplankton growth is also regulated by nutrient and light availability, it is an area of active research to identify exactly how climate change will impact phytoplankton growth in other parts of Europe.

Over the past fifteen years, considerable increase in phytoplankton biomass and an extension of its growing season has occurred in the North Sea and eastern North Atlantic (Figure 5.23). This change is closely related to changes in sea surface temperature and the NAO index (see Section 5.2). In particular, an increase in biomass was observed after the mid-1980s in the North Sea and west of Ireland (Reid *et al.*, 1998; Edwards *et al.*, 2001). In contrast, a decrease in phytoplankton biomass was detected in the area north-west of the European Shelf. The mechanisms for this change remains poorly understood but the different regional responses can be partly explained by variations in the NAO index and sea surface temperature. The NAO index has positive correlations with SST and phytoplankton biomass in the North Sea and to the west of Ireland, and negative correlations north-west of the European Shelf (Edwards *et al.*, 2001).

Figure 5.23 Change in colour index in southern North Sea from the 1950s until 2000s



Note: Data are from the Continuous Plankton Recorder. Left: year vs. month plot of colour-index change in the southern North Sea.

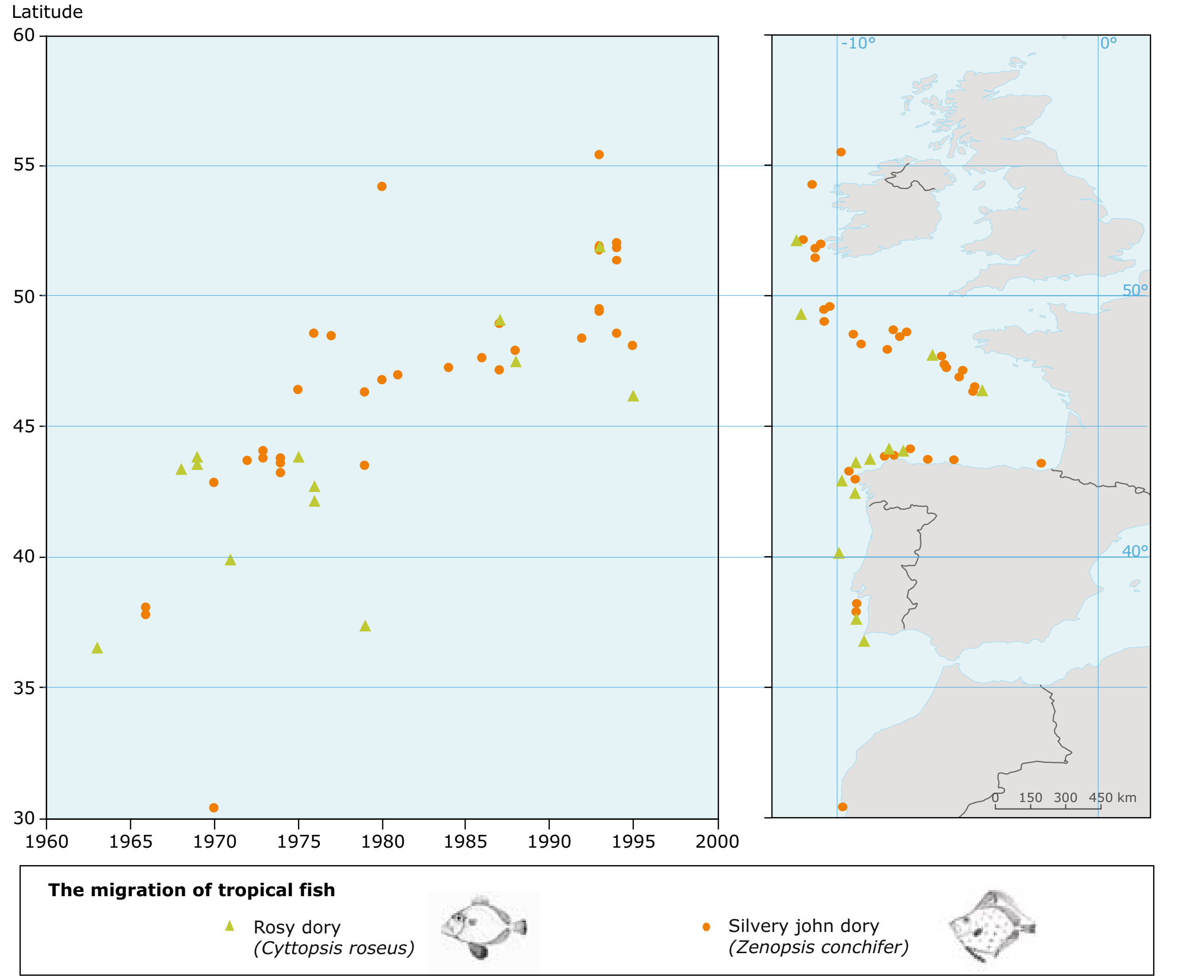
Source: Updated from Reid *et al.*, 1998 and Edwards *et al.*, 2001.

5.4.5 *Northward movement of marine species*

Key messages

- Increases in regional sea temperatures have triggered a major northward movement of warmer-water plankton in the north-east Atlantic and a similar retreat of colder-water plankton to the north. This northerly movement is about 10° latitude (1 100 km) over the past 40 years, and it seems to have accelerated since 2000. This will have an impact on the distribution of fish in the region.
- Many species of fish and plankton have shifted their distributions northward. Sub-tropical species are occurring with increasing frequency in European waters and sub-Arctic species are receding northwards. The rate of northward movement of a particular species, the silvery john dory, has been estimated at about 50 km/year.
- Changes in the geographic distribution of some species of fish have been observed and may affect the management of fisheries. Fisheries regulations in the EU include allocations of quotas based on historic catch patterns, and these may need to be revised.

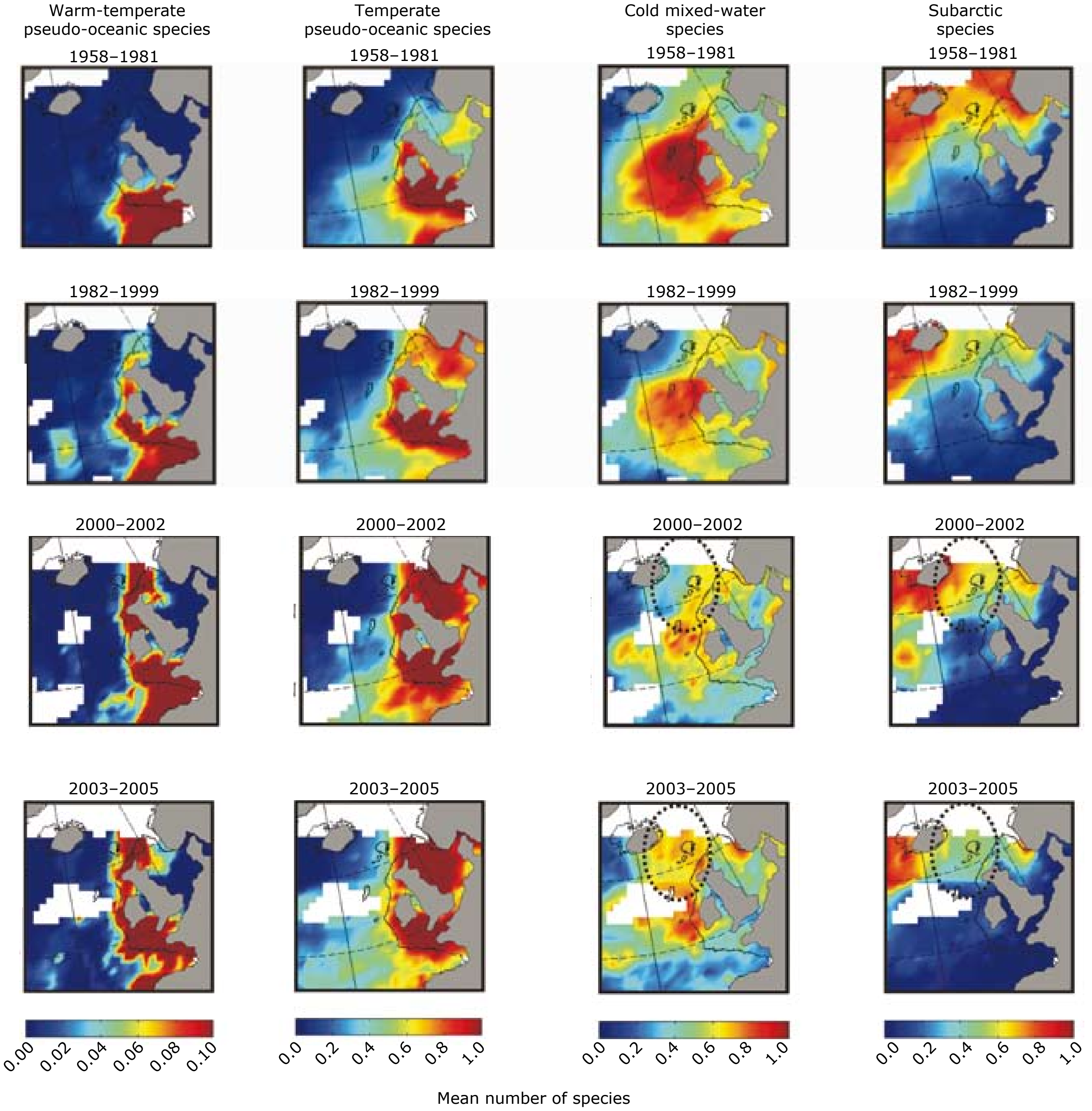
Figure 5.24 Recordings of two tropical fish 1963–1996



Note: Recordings of the migration of the tropical species silvery john dory (*Zenopsis conchifer*) and rosy dory (*Cyttopsis roseus*) 1963–1996. The left panel shows the distribution according to latitude and years. The right panel shows the geographical distribution of catches.

Source: Quero *et al.*, 1998.

Map 5.21 Northward movement of zooplankton between 1958–2005



Note: The northward movement of zoo-plankton spanning five decades. The warm-water species (warm-temperate pseudo oceanic species) are moving north and cold-water species (sub-arctic species) are moving north, and have greatly decreased their presence in the North Sea. In the past 45 years, a rapid (approximately 1 100 km) northward movement along the continental shelf edge has been observed. Data are based on observations from the Continuous Plankton Recorder.

Source: Update of Beaugrand *et al.*, 2002.

Relevance

Many species of plankton and fish have shifted their distribution northward and sub-tropical species are occurring with increasing frequency in European waters, changing the composition of local and regional marine ecosystems in a major way (Brander *et al.*, 2003; Beare *et al.*, 2004; Beare *et al.*, 2005; Perry *et al.*, 2005; Stebbing *et al.*, 2002). Recent studies have shown that the northward movement of southerly species has caused species richness in the North Sea to increase (Hiddink and Hofstede, 2008). This may have negative ecological and socio-economic effects: the three large species that have decreased their range the most in the North Sea are all commercially relevant, while only one of the five most increasing species and less than half of the all the species that expanded their range are of commercial value. A climate change-induced shift from large to smaller species is thus likely to reduce the value of North Sea fisheries (Hiddink and Hofstede, 2008).

The kinds of fish which are available for human consumption are not necessarily affected by the distribution changes shown above, because fish are often transported long distances from where they are caught to where they are marketed, but the prices of fish may change if certain species that are common today become less common. People eating locally-caught fish may notice changes in the species they catch or buy. Changes in distribution may affect the management of fisheries. Fisheries regulations in the EU include allocations of quotas based on historic catch patterns, and these may need to be revised.

In a few situations, e.g. early retreat of sea ice in Arctic areas, the effect of climate change may be to increase fish catches (ACIA, 2004), but in general it is not possible to predict whether northward shifts in distribution will have a positive or a negative effect on total fisheries production (Brander, 2007).

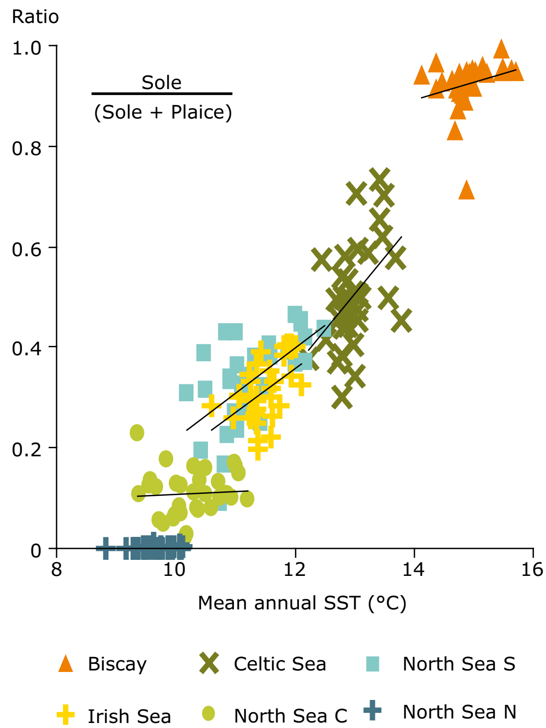
Past trends

The increase in regional sea temperatures has triggered a major re-organisation of zooplankton species composition and biodiversity over the entire North Atlantic basin (Beaugrand *et al.*, 2003), shown in Map 5.21. During the past 40 years there has been a northerly movement of warmer-water plankton by 10° latitude (1 100 km) in the north-east Atlantic and a similar retreat of colder-water plankton to the north. This northerly movement has continued over the past few years and appears to have accelerated since 2000.

Common sole (*Solea solea*)

Photo: © Biopix.dk; JC Schou

Figure 5.25 Relative abundance of warm-water to cold-water flatfish species



Note: Data are shown for four different seas and three sections of the North Sea, depending on mean annual SST. The index is calculated from annual catches of sole and plaice in these areas and is the ratio sole/(sole+plaice). In all seas SST is correlated with the SST anomaly in the North Sea shown in Figure 5.21, i.e. there has been a steadily increasing trend in the past 25 years.

Source: Brander *et al.*, 2003.

Marine species generally have a large potential to spread. Ocean currents are able to spread plankton and larvae rapidly over large distances and many species of fish have migration patterns that exceed 100 km each year. Their movement is particularly pronounced along the European continental shelf edge and has been associated with the Shelf Edge Current running north. Consequently the rate of northward movement is faster in the ocean than on land, partly because the marine environment has fewer barriers to dispersal than terrestrial systems; many terrestrial species, for example, are not able to cross water.

Some clear, well-documented examples of fish species shifts are shown in Figure 5.24. The silvery

Box 5.8 Climate-change-induced impacts on fish distribution and abundance in the Baltic Sea

The changes in marine species observed in the Baltic Sea do not fit into the general pattern of northward shift due to increasing temperature. In this sea, salinity is one of the predominant factors that influence species presence. Salinity ranges from high (close to oceanic values) at the boundary of the North Sea to almost fresh water in the Bothnian Bay (northernmost part between Sweden and Finland). In general, the Baltic aquatic ecosystems are species-poor, but with predominantly marine species in the western parts near the North Sea boundary, and predominantly brackish and freshwater species in the central parts. Quite a small change in salinity can change the distribution of species. Changes in salinity are driven by climate-induced changes in precipitation and salt-water inflow from the North Sea. It appears that changes have already been large enough to affect the composition of the Baltic Sea biota.

Salinity in the Baltic has decreased steadily since the mid 1980s due to increased freshwater input (precipitation) and a reduction in the frequency of inflow events from the North Sea, which bring in more saline, oxygenated water. Of the three major fished species, cod (*Gadus morhua*), herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), cod is particularly sensitive to reduced salinity — at levels below 11 psu the eggs lose their buoyancy and the sperm become inactive. The major zooplankton prey species for cod larvae *Pseudocalanus acuspes* also decline when salinity is low.

Projections for the future climate of the Baltic are for continuing increases precipitation and decreases in inflows from the North Sea, therefore the distribution and abundance of cod and other marine species is likely to continue to diminish. Their position in the ecosystem may be taken over by more brackish and freshwater species, such as whitefish, pikeperch and perch (MacKenzie *et al.*, 2007).

john dory (*Zenopsis conchifer*) was first recorded in European waters off the coast of Portugal at 38°N in 1966 and has since been recorded progressively further north, to north of 55°N by the early 1990s (Quero *et al.*, 1998). It is probably transported northward in the continental slope current and the rate of northward shift in distribution of this species is more than 50 km per year. Other species which have become much more common further north, such as sea bass (*Dicentrarchus labrax*), red mullet (*Mullus surmulletus*) and European anchovy (*Engraulis encrasicolus*), are probably now able to overwinter and establish breeding populations there (Brander *et al.*, 2003).

The ratio of catches of two common flatfish species — European plaice (*Pleuronectes platessa*) and Common sole (*Solea solea*) can be used as an index of the increase in the relative abundance of a warm-water vs. a cold-water species of flatfish (Figure 5.25). This change is linked to a steadily increasing temperature trend in the past 25 years, which has caused the sole to plaice ratio to change, particularly in the southern North Sea, the Irish Sea and the northern North Sea. This change is a change in their distribution, as sole and other warm-water species have become relatively more abundant in northerly areas, while plaice and other cold-water species have become rare in southerly areas (Brander *et al.*, 2003). Recently it has been shown that a further temperature increase may lead sole to spawn earlier in the season and thus increase the duration of their growing season whereas plaice does not seem to be affected (Teal *et al.*, 2008). Climate is only one of many factors which affect distribution and abundance, but the consistency of the response of this particular index to temperature, both within particular areas (i.e. time trend) and across all areas (i.e. geographic trend) suggest that the causal relationship is quite strong. In addition, an index based on ratios of catches minimises the influence of fishing when fishing acts on both species in a similar way, as is the case with these flatfish, which are caught in the same kinds of gear and often in the same fishing operations.

Other factors affecting abundance and distribution include fishing pressure, biological interactions, salinity, oxygen, the North Atlantic Oscillation, and pollution. In some cases changes in distribution are probably due to geographic patterns of fishing and not to climate effects.

Projections

Scenario projections of future movements of marine species have not yet been made. Uncertainty in making projections of fish distribution changes over the next 20–50 years arise from both the uncertainties in projections of ocean climate and uncertainties of fish community responses to those changes.

5.5 Water quantity, river floods and droughts

5.5.1 Introduction

Water is essential to life and is an indispensable resource for nearly all human activity. It is intricately linked with climate through a large number of connections and feedback cycles, so that any alteration in the climate system will induce changes in the hydrological cycle. Global warming not only results in widespread melting of snow and ice, but also augments the water-holding capacity of the air and amplifies evaporation. This leads to larger amounts of moisture in the air, an increased intensity of water cycling, and changes in the distribution, frequency and intensity of precipitation (see also Sections 5.2.3 and 5.2.5). Consequently, the distribution in time and space of freshwater resources, as well as any socio-economic activity depending thereon, is affected by climate variability and climate change.

There is growing evidence for changes in the global hydrological cycle over the past 50 years that may be linked to changes in climate, such as an increasing continental runoff, a wetter northern Europe and a drier Mediterranean, an increase in the intensity of extreme precipitation events over many land regions, and changes in the seasonality of river flows where winter precipitation dominantly falls as snow (see also Section 5.3).

Long-term trends in hydrological variables, however, are often masked by the significant inter-annual to decadal variability. Compared with historic data availability about meteorological variables, hydrometric records are more sparse and limited in time because of the lack of dense observation networks for long-term hydrological variables. Also, confounding factors such as land-use change, water management practices or extensive water withdrawals have considerably changed the natural flows of water, making it more difficult to detect climate change-induced trends in hydrological variables. It may therefore require substantially more time before statistically significant changes can be observed, especially in the frequency of extreme events such as floods and droughts, because of their infrequency and the random nature of their occurrence.

For the coming decades, global warming is projected to further intensify the hydrological cycle, with impacts that will probably be more severe than those so far observed. Climate change is projected to lead to major changes in yearly and seasonal water availability across Europe. Water availability generally is projected to increase in northern regions, although summer flows may decrease. Southern and south-eastern regions, which already suffer most from water stress, will be particularly exposed to reductions in water resources and will see an increase in the frequency and intensity of droughts. On the other hand, an increase in extreme high river flows is projected for large parts of Europe due to the increase in heavy rain events, even in regions that will become drier on average. Quantitative projections of changes in precipitation and river flows at the river basin scale remain, however, highly uncertain, due to the limitations of climate models, as well as scaling issues between climate and hydrological models.

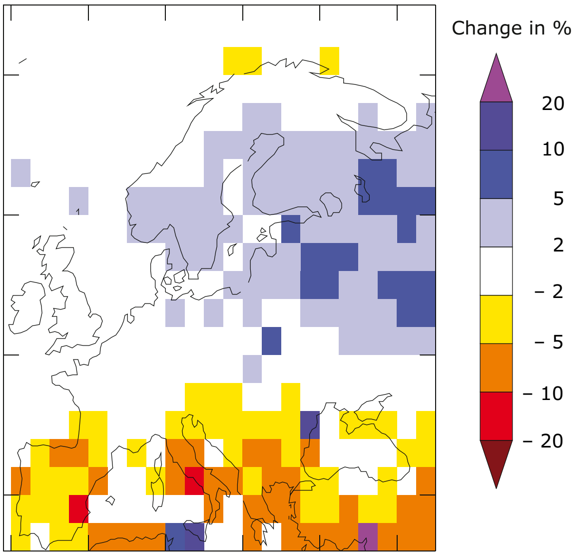
The projected climate-induced changes will aggravate the impact of other stresses (such as land-use, demographic and socio-economic changes) on water availability, freshwater ecosystems, energy production, navigation, irrigation, tourism, as well as on several other sectors. In the face of these uncertain changes, adaptation procedures need to be designed that can be altered or that are robust to change. Such measures include, for example, stimulating awareness, improving water efficiency and encouraging water conservation to mitigate water stress, directing spatial planning and watershed management to enhance retention and reduce flood risk, as well as effective monitoring, detection and early warning of hazards or changes in water availability.

5.5.2 *River flow*

Key messages

- Over the 20th century, annual river flows showed an increasing trend in northern parts of Europe, with increases mainly in winter, and a slightly decreasing trend in southern parts of Europe. These changes are linked to observed changes in precipitation patterns and temperature.
- Annual river flow is projected to decrease in southern and south-eastern Europe and increase in northern Europe, but absolute changes remain uncertain.
- Climate change is projected to result in strong changes in the seasonality of river flows across Europe. Summer flows are projected to decrease in most of Europe, also in regions where annual flows will increase.
- Regions in southern Europe which already suffer most from water stress are projected to be particularly vulnerable to reductions in water resources due to climate change. This will result in increased competition for available resources.

Map 5.22 Modelled change in annual river flow between 1971–1998 and 1900–1970



Note: The map is based on an ensemble of 12 climate models and validated against observed river flows.

Source: Milly *et al.*, 2005.

Relevance

Water is an indispensable resource for human health, ecosystems and socio-economic activity. From a resource perspective, river flow is a measure of sustainable fresh water availability in a basin. Variations in river flow are determined mainly by the seasonality of precipitation and temperature, as well as by catchment characteristics such as geology, soils and land cover. River flow can be used as an indicator because changes in temperature and precipitation patterns due to global warming modify the distribution of water at the land surface, and consequently the annual water budget of river basins as well as the timing and seasonality of river flows. The consequent changes in water availability may adversely affect ecosystems and several socio-economic sectors such as water management, energy production, navigation, irrigation and tourism.

In view of projected global warming and the associated changes in water availability, it will become increasingly important to balance competing societal, industrial, agricultural and environmental demands. Sustainable options for mitigating the effects of changes in water availability include improved water efficiency, the re-use of water, and metering and water pricing to stimulate awareness and encourage water conservation.

Past trends

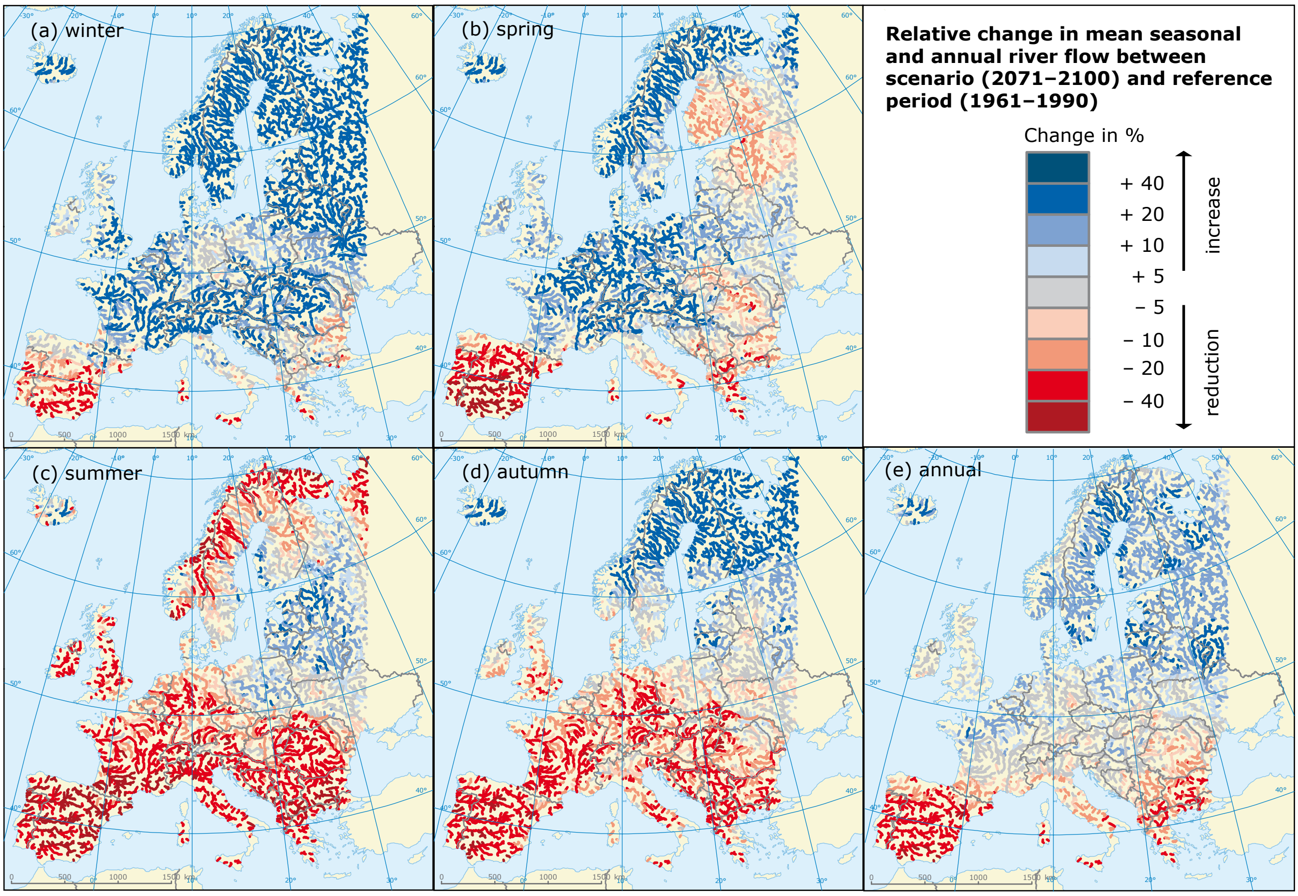
In accordance with the observed changes in precipitation and temperature (see Sections 5.2.2 and 5.2.3), there is some evidence for climate-induced changes in annual river flow, as well as in the seasonality of flow, in Europe during the 20th century. However, anthropogenic interventions in the catchment, such as groundwater abstraction, irrigation, river regulation, land-use changes and urbanisation, have considerably altered river flow regimes in large parts of Europe, confounding climate change detection studies.

In northern parts of Europe, mean annual river flow has in general increased (Lindström and

Bergström, 2004; Milly *et al.*, 2005). Increases occurred mainly in winter and spring (Hisdal *et al.*, 2007), probably caused by a general temperature increase during recent decades (see Section 5.2.2) in combination with increased winter precipitation (see Section 5.2.3) in the northern regions. Significant increases in river flow have also been observed in Scotland at one third of the river gauging stations in the past three decades (Werritty, 2002), as well as in winter and autumn in western Britain, consistent with recent increases in winter rainfall and a positive North Atlantic Oscillation index (see Section 5.2) (Dixon *et al.*, 2006). However, some of these changes could be part of natural variability (Wade *et al.*, 2005). In western and central Europe, annual and monthly mean river flow series appear to have been stationary over the 20th century (Wang *et al.*, 2005). In mountainous regions of central Europe, however, the main identified trends are an increase in annual river flow due to increases in winter, spring and autumn river flow. In summer, both upward and downward trends have been detected (Birsan *et al.*, 2005). In southern parts of Europe, a

Photo: © European Environment Agency

Map 5.23 Projected change in mean seasonal and annual river flow between 2071–2100 and the reference period 1961–1990



Note: Simulations with LISFLOOD driven by HIRHAM — HadAM3H/HadCM3 based on IPCC SRES scenario A2.

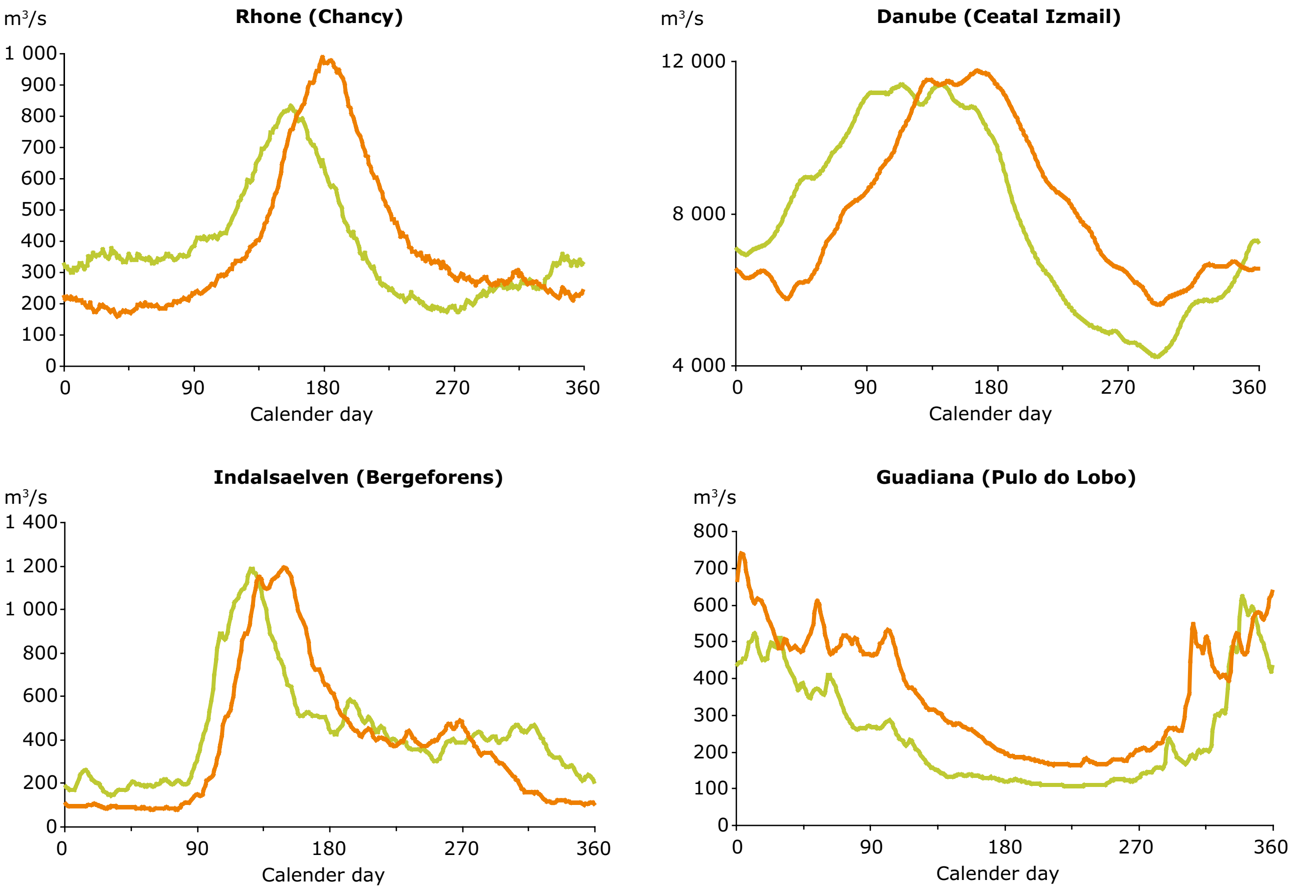
Source: Dankers and Feyen, 2008a.

slightly decreasing trend in annual river flow has been observed (Milly *et al.*, 2005).

Projections

Annual river flow is projected to decrease in southern and south-eastern Europe and increase in northern and north-eastern Europe (Arnell, 2004; Milly *et al.*, 2005; Alcamo *et al.*, 2007). Strong changes are also projected in the seasonality of river flows, with large differences across Europe. Winter and spring river flows are projected to increase in most parts of Europe, except for the most southern and south-eastern regions. In summer and autumn, river flows are projected to decrease in most of Europe, except for northern and north-eastern regions where autumn flows are projected to increase (Dankers and Feyen, 2008a). In snow-dominated regions, such as the Alps, Scandinavia and the Baltic, the fall in winter retention as snow, earlier snowmelt and reduced summer precipitation will reduce river flows in summer (Andréasson, *et al.*, 2004; Jasper *et al.*, 2004; Barnett *et al.*, 2005), when demand is typically highest.

Figure 5.26 Projected change in daily average river flow between 2071–2100 and the reference period 1961–1990



Note: Projected river flow 2071–2100 (green line) and the observed river flow 1961–1990 (orange line). Simulations with LISFLOOD driven by HIRHAM — HadAM3H/HadCM3 based on IPCC SRES scenario A2.

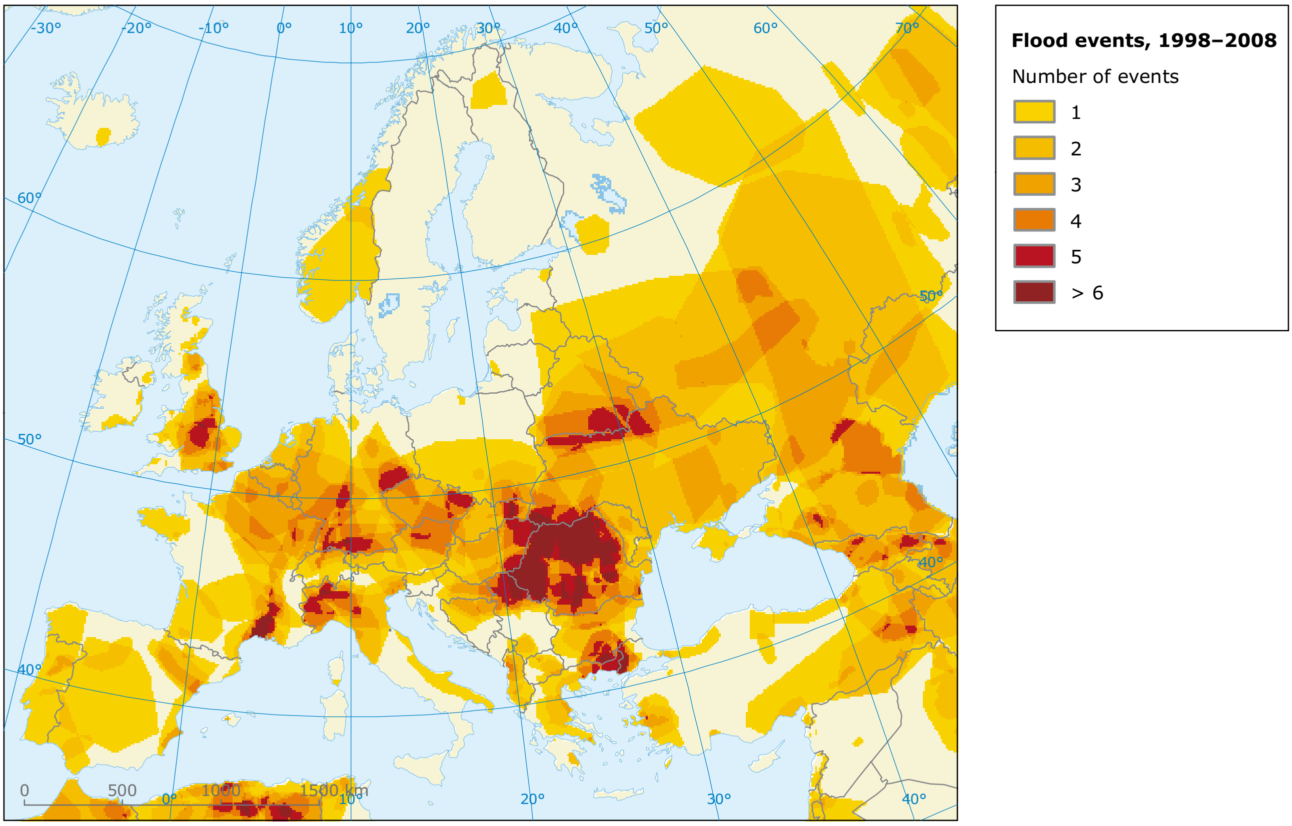
Source: Dankers and Feyen, 2008a.

5.5.3 *River floods*

Key messages

- Although a significant trend in extreme river flows has not yet been observed, twice as many river flow maxima occurred in Europe between 1981 and 2000 than between 1961 and 1980.
- Since 1990, 259 major river floods have been reported in Europe, of which 165 have been reported since 2000. The rise in the reported number of flood events over recent decades results mainly from better reporting and land-use changes.
- Nevertheless, global warming is projected to intensify the hydrological cycle and increase the occurrence and frequency of flood events in large parts of Europe, although estimates of changes in flood frequency and magnitude remain highly uncertain.
- Projections suggest that warming will result in less snow accumulation during winter and therefore a lower risk of early spring flooding.

Map 5.24 Occurrence of flood events in Europe 1998–2008



Source: Based on data from Dartmouth Flood Observatory (http://www.dartmouth.edu/~floods/).

Relevance

There are different types of floods, such as large-scale river floods, flash floods, ice-jam and snowmelt-induced floods, and coastal floods due to sea-level rise (see Section 5.4.2). Inland river floods are linked mainly to prolonged or heavy precipitation events or snowmelt, hence are suitable indicators of climate change.

River floods are the most common natural disaster in Europe. They can result in huge economic losses due to damage to infrastructure, property and agricultural land, and indirect losses in or beyond the flooded areas, such as production losses caused by damaged stock or roads, or the interruption of power generation and navigation. They can lead to loss of life, especially in the case of flash floods, and displacement of people, and can have adverse effects on human health and the environment.

Procedures for designing flood-control infrastructures will have to be revised if they are to cope with the projected changes in extreme precipitation and river flows. Flood management policy will have to shift from defensive action towards the management of risk and enhancing the ability of societies to live with floods. This can be achieved by the use of non-structural flood protection measures such as spatial planning, early warning, relief and post-flood recovery systems, as well as flood insurance (Kundzewicz *et al.*, 2002).

Past trends

Despite the considerable rise in the number of reported major flood events and economic losses caused by floods in Europe over recent decades (see Section 7.3), no significant general climate-related trend in extreme high river flows that induce floods has yet been detected (Becker and Grunewald, 2003; Glaser and Stangl, 2003; Mudelsee *et al.*, 2003; Kundzewicz *et al.*, 2005; Pinter *et al.*, 2006; Hisdal *et al.*, 2007; Macklin and Rumsby, 2007).

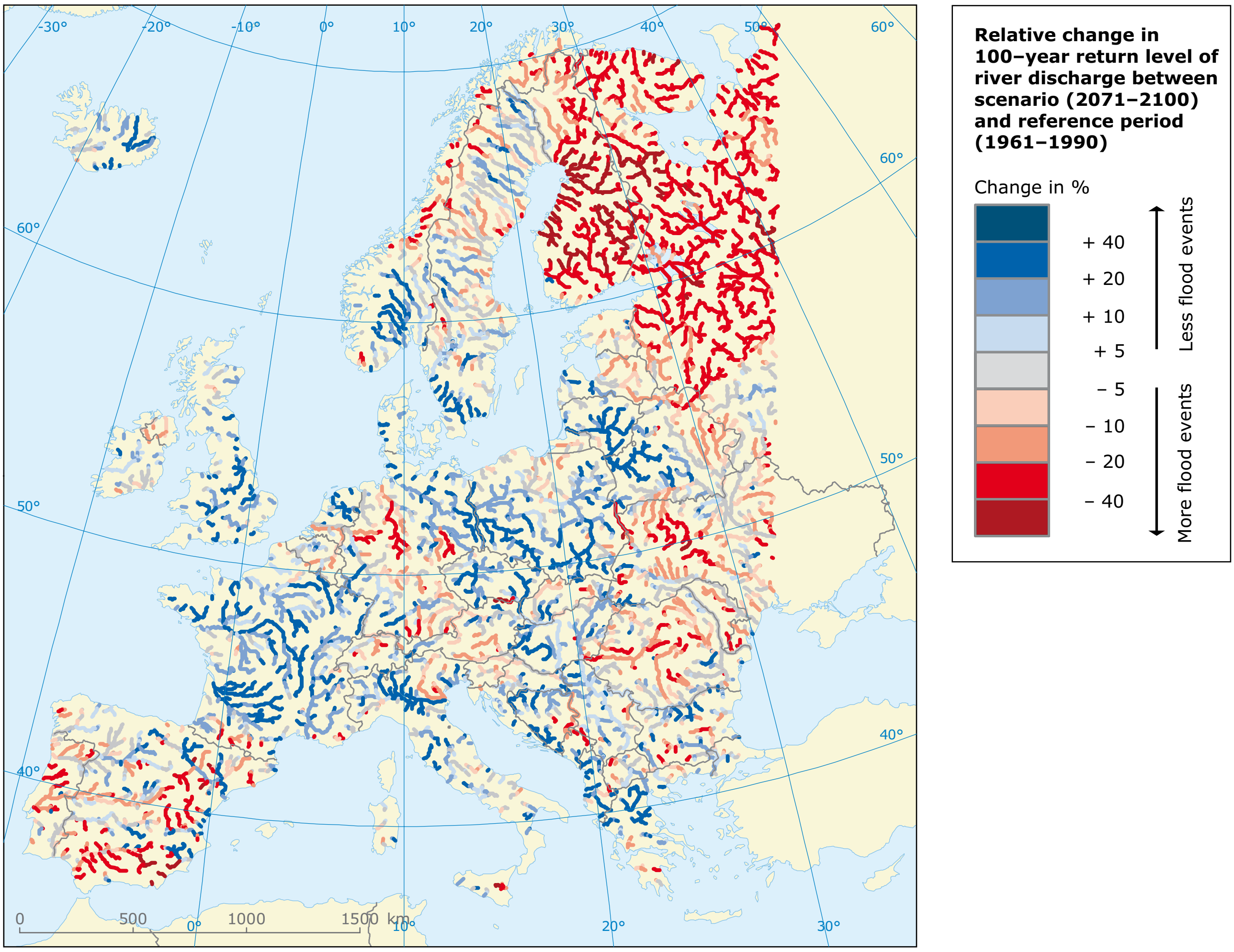
Some changes, however, have been reported that may be linked to climate change. For example, in Europe twice as many river flow maxima occurred between 1981 and 2000 than between 1961 and 1980 (Kundzewicz *et al.*, 2005), whereas globally there has probably been an increase in the frequency of extreme flood events in very large catchments (Milly *et al.*, 2002). On the other hand, the frequency and severity of snowmelt and ice-jam floods in central Europe has decreased over recent decades because of the warming of European winters combined with less abundant snow cover (e.g. Mudelsee *et al.*, 2003; Brázdil *et al.*, 2006; Cyberski *et al.*, 2006). In the Nordic countries, snowmelt floods have occurred earlier because of warmer winters (Hisdal *et al.*, 2007). In Portugal, changed precipitation patterns have resulted in larger and more frequent floods during autumn but a decline in the number of floods in winter and spring (Ramos and Reis, 2002). In the United Kingdom, positive trends in high flows have been observed over the past 30–50 years (Robson, 2002; Dixon *et al.*, 2006), some of which are consistent with observed changes in the North Atlantic Oscillation. Comparisons of historic climate variability with flood records suggest, however, that many of the changes observed in recent decades could have resulted from natural climatic variation. Changes in the terrestrial system, such as urbanisation, deforestation, loss of natural floodplain storage, as well as river and flood management have also strongly affected flood occurrence (Barnolas and Llasat, 2007).

Photo: © Pavel Šťastný

Projections

Although there is as yet no proof that the extreme flood events of recent years are a direct consequence of climate change, they may give an indication of what can be expected: the frequency and intensity of floods in large parts of Europe is projected to increase (Lehner *et al.*, 2006; Dankers and Feyen, 2008b). In particular, flash and urban floods, triggered by local intense precipitation events, are likely to be more frequent throughout Europe (Christensen and Christensen, 2003; Kundzewicz *et al.*, 2006). Flood hazard will also probably increase during wetter and warmer winters, with more frequent rain and less frequent snow (Palmer and Räisänen, 2002). Even in regions where mean river flows will drop significantly, as in the Iberian Peninsula, the projected increase in precipitation intensity and variability may cause more floods. In snow-dominated regions such as the Alps, the Carpathian Mountains and northern parts of Europe, spring snowmelt floods are projected to decrease due to a shorter snow season and less snow accumulation in warmer winters (Kay *et al.*, 2006; Dankers and Feyen, 2008b).

Map 5.25 **Projected change in 100-year return level of river discharge between 2071–2100 and the reference period 1961–1990**



Note: Simulations with LISFLOOD driven by HIRHAM — HadAM3H/HadCM3 based on IPCC SRES scenario A2.

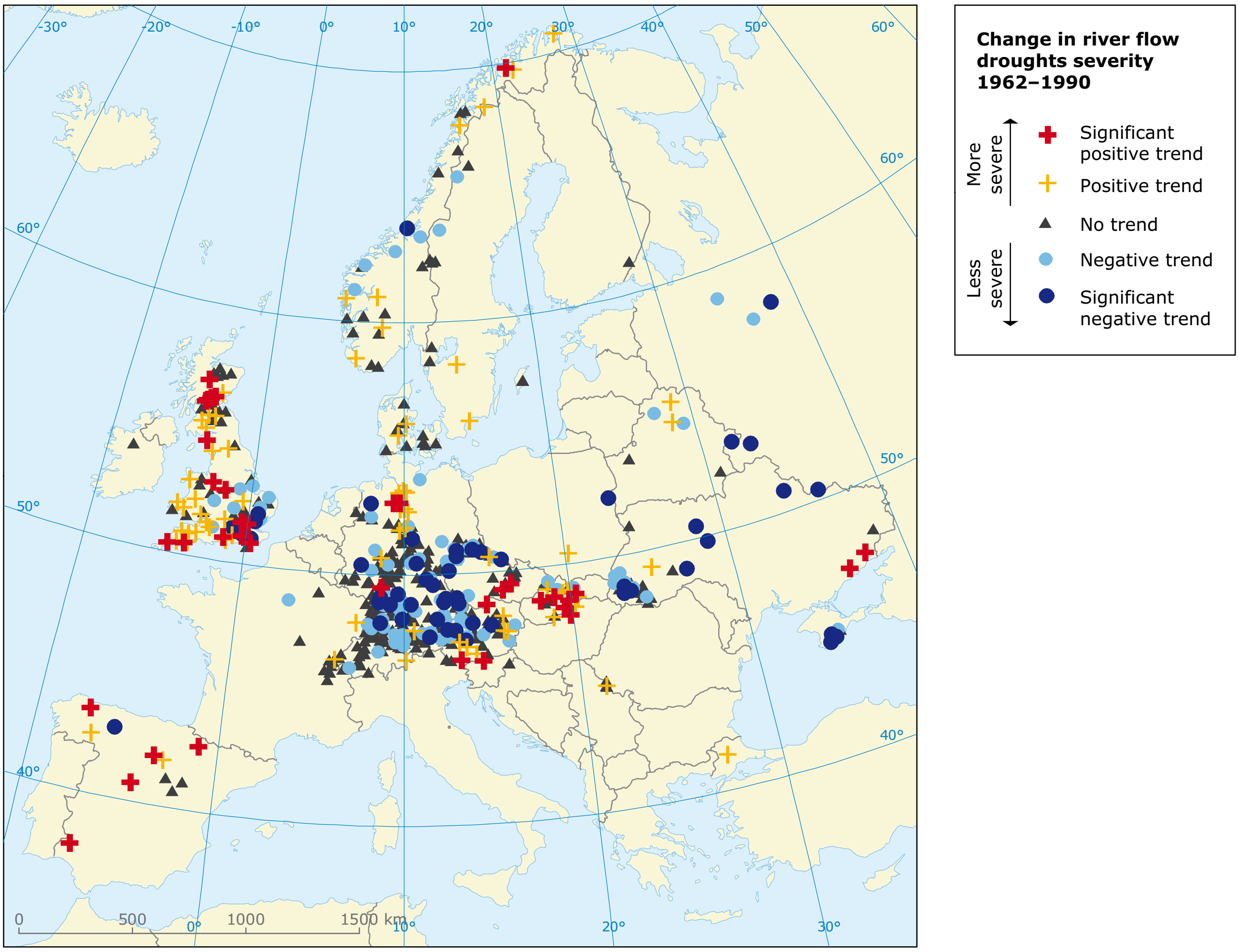
Source: Dankers and Feyen, 2008b.

5.5.4 *River flow drought*

Key messages

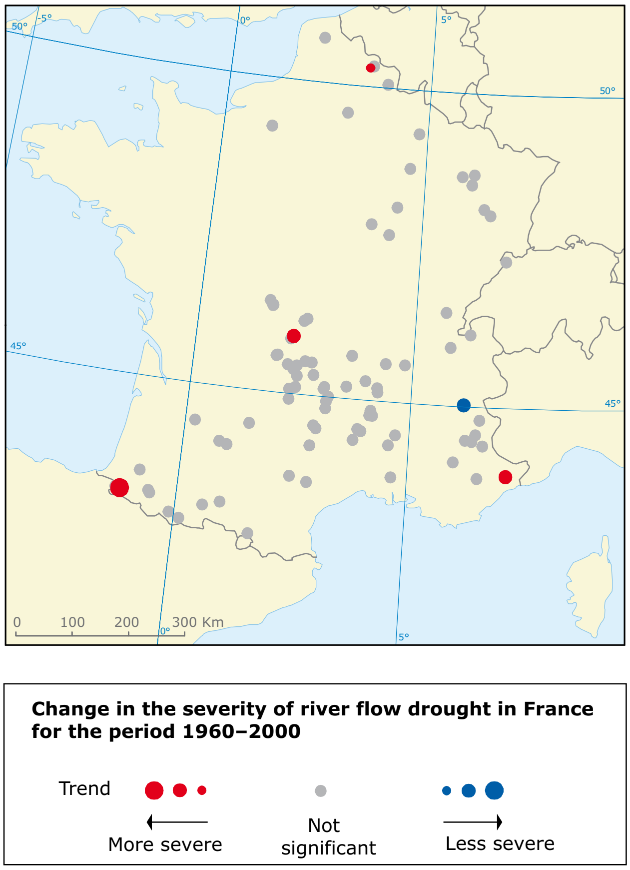
- Europe has been affected by several major droughts in recent decades, such as the catastrophic drought associated with the summer 2003 heatwave in central parts of the continent and the 2005 drought in the Iberian Peninsula.
- Despite the absence of an overall trend in Europe as a whole, climate change has probably increased the frequency and/or severity of droughts in some regions.
- Climate change is projected to increase the frequency and intensity of droughts in many regions of Europe as a result of higher temperatures, decreased summer precipitation, and more and longer dry spells.
- The regions most prone to an increase in drought hazard are southern and south-eastern Europe, but minimum river flows will also decrease significantly in many other parts of the continent, especially in summer.

Map 5.26 Change in the severity of river flow droughts in Europe 1962–1990



Source: Hisdal *et al.*, 2001.

Map 5.27 Change in the severity of river flow droughts in France 1960–2000



Source: Lang *et al.*, 2006.

Relevance

Drought may refer to meteorological drought (precipitation well below average, Section 5.2.3), hydrological drought (low river flows, lake and groundwater levels), agricultural drought (soil moisture deficit, Sections 5.8 and 5.9), environmental drought (impact on ecosystems) or socio-economic drought (impact on economic goods and services). The focus here is on hydrological drought, more specifically on river flow drought, as river flow is a measure of sustainable fresh water availability in a basin and is affected by climate change. River flow data are also more available than other hydrometric information such as groundwater recharge, surface water storage and soil moisture. Climate-induced trends in extreme low river flows are however often masked by land-use change, water management practices and extensive water withdrawals.

Prolonged droughts have considerable economic, societal and environmental impacts. They affect several sectors, such as energy production, both in terms of water availability for hydropower and cooling water for electricity generation, river navigation, agriculture, and public water supply.

Adverse effects of droughts and low river flow conditions can be mitigated on the supply side through the combined use of surface and groundwater, desalination of sea water, and water storage and transfer. Demand-side measures include improving water efficiency, metering, and water pricing. Shortages of water can be anticipated through effective monitoring and forecasting of future river flows and storage in reservoirs.

Past trends

Over the past 30 years, Europe has been affected by a number of major droughts, most notably in 1976, 1989, 1991, and more recently, the prolonged drought over large parts of the continent associated with the 2003 summer heatwave. The most serious drought in the Iberian Peninsula in 60 years occurred in 2005, reducing overall EU cereal yields by an estimated 10 %. The drought also triggered forest fires, killing 15 people and destroying 180 000 ha of forest and farmland in Portugal alone (UNEP, 2006). However, there is no evidence that river flow droughts have become more severe or frequent over Europe in general in recent decades (Hisdal *et al.*, 2001), nor is there conclusive proof of a general increase in summer dryness in Europe over the past 50 years due to reduced summer moisture availability (van der Schrier *et al.*, 2006).

Despite the absence of a general trend in Europe, there have been distinct regional differences. In particular, more severe river flow droughts have been observed in Spain, the eastern part of eastern Europe and large parts of the United Kingdom (Hisdal *et al.*, 2001). However, in the United Kingdom there is no evidence of a significant increase in the frequency of occurrence of low river flows (Hanneford and Marsh, 2006). In large parts of central Europe and in the western parts of eastern Europe droughts have become less severe (Hisdal *et al.*, 2001). In France, a majority of stations showed a decreasing trend in the annual minima of 30-day mean river flows over the past 40 years, but no such trend was found for drought severity or duration (Lang *et al.*, 2006). In southern and eastern Norway there has been a tendency towards more severe summer droughts (Hisdal *et al.*, 2001). On the other hand, several stations in Europe have shown trends towards less severe low flows over the 20th century, consistent with an increasing number of reservoirs becoming operational in the catchments

Box 5.9 Groundwater

The main pressures on the groundwater system due to climate change are sea-level rise, shrinking land ice and permafrost areas, declining groundwater recharge, especially in southern European countries, more extreme peak flows and more prolonged low flows of rivers, and increased groundwater abstraction. Regions with higher precipitation may experience rising groundwater levels that may affect houses and infrastructures.

The resulting effects on groundwater quantity are shrinking of fresh groundwater resources, especially in coastal areas and in southern European countries, while brackish and salt groundwater bodies will expand. In addition, the fresh groundwater bodies will become more vulnerable to pollution through reduced turnover times and accelerated groundwater flow.

Saline intrusion in coastal aquifers, making the water unsuitable for drinking, may be exacerbated by future sea-level rise Other effects on groundwater quality are more difficult to predict as they depend strongly on changes in land-use. Nevertheless, it is already clear that groundwater temperature has increased on average by 1 °C since the 1970s (Stuyfzand *et al.*, 2007). Further increases will raise the salinity of groundwater due to increased evapotranspiration losses, increased soil CO_2 pressures and increased water — rock interaction.

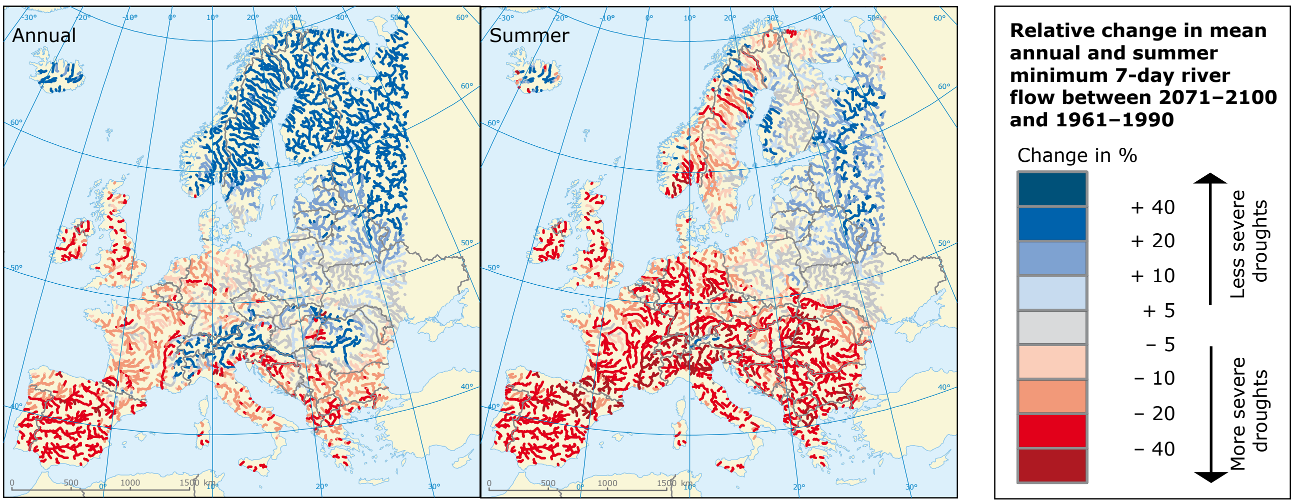
over the period for which there are records (Svensson *et al.*, 2005).

Projections

River flow droughts are projected to increase in frequency and severity in southern and south-eastern Europe, the United Kingdom, France, Benelux, and western parts of Germany over the coming decades. In snow-dominated regions, where droughts typically occur in winter, river flow droughts are projected to become less severe because a lower fraction of precipitation will fall as snow in warmer winters.

In most of Europe, the projected decrease in summer precipitation, accompanied by rising temperatures which enhances evaporative demand, may lead to more frequent and intense summer droughts (Douville *et al.*, 2002; Lehner *et al.*, 2006; Feyen and Dankers, 2008). As a result of both climate change and increasing water withdrawals, more river basins will be affected by severe water stress, resulting in increased competition for water resources. The regions most prone to an increase in drought risk are the Mediterranean and south-eastern parts of Europe, which already suffer most from water stress (Alcamo *et al.*, 2003; Schröter *et al.*, 2005).

Map 5.28 Projected change in mean annual and summer minimum 7-day river flow between 2071–2100 and the reference period 1961–1990



Note: Red indicates more severe droughts, blue less severe droughts. Simulations with LISFLOOD driven by HIRHAM — HadAM3H/HadCM3 based on IPCC SRES scenario A2.

Source: Feyen and Dankers, 2008.

5.6 Freshwater quality and biodiversity

5.6.1 Introduction

Climate change can result in significant changes in the variables that affect the quality of water. These include:

- *physical changes* such as water temperature (see indicator on water temperature), river and lake ice-cover (see Section 5.6.3), stratification of water masses in lakes, and water discharge including water level and retention time;
- *chemical changes*, in particular oxygen content, nutrient loading and water colour;
- *biological changes* affecting the structure and functioning of freshwater ecosystems.

Changes in these variables lead to impacts on all the socio-economic and environmental goods and services that depend on these systems directly or indirectly.

A rise in water temperature will affect the rate of biogeochemical and ecological processes that determine water quality. This may result in:

- *Reduced oxygen content*. Increases in water temperature in streams and lakes reduce oxygen content and increase biological respiration rates and may therefore result in lower dissolved oxygen concentrations, particularly in summer low-flow periods and in the bottom layers of lakes. Higher temperature and lower oxygen concentrations will cause stress and may reduce the habitats of cold-water species such as salmonid fish in lakes and rivers.
- *Less ice cover,* Earlier ice break-up and longer ice-free period in rivers and lakes (see Section 5.6.3).
- *More stable vertical stratification and less mixing of water of deep-water lakes*, which in turn affect deep-water oxygen conditions, nutrient cycling and plankton communities.
- *Eutrophication.* A warmer climate will generally enhance the pollution load of nutrients in surface and groundwater. Higher temperatures will increase mineralisation and releases of nitrogen, phosphorus and carbon from soil organic matter and increase run-off and erosion, which will result in increased pollution transport. Also release of phosphorus from bottom sediments in stratified lakes is expected to increase, due to declining oxygen concentrations in the bottom waters.
- *Change in timing of algal blooms and increase of harmful algal blooms* (see Section 5.6.4).
- *Alterations to habitats and distribution of aquatic organisms*. The geographic distribution of aquatic organisms is partly controlled by temperature. Higher water temperatures lead to changes in distribution (more northwards in Europe and to higher elevations) and may even lead to the extinction of some aquatic species (see Section 5.6.4).

Climate change factors other than temperature can also affect water quality. In areas where river flow and groundwater recharge will decrease, water quality may also decrease due to less dilution of pollutants. Higher intensity and frequency of floods and more frequent extreme precipitation events are expected to increase the load of pollutants (organic matter, nutrients, and hazardous substances) washed from soils and overflows of sewage systems to water bodies.

Many of the diverse aspects of climate change (e.g. temperature increase, variations in rainfall and runoff) affect the distribution and mobility of hazardous substances in freshwater systems. Loading of hazardous substances may increase due to sewage overflow, as well as higher pesticide use and run-off due to heavy rains, while higher temperatures increase the degradation rate of some pesticides and organic pollutants, which may reduce their concentrations in rivers and lakes. Thus the net effect of climate change on hazardous substances is uncertain. However, higher air and water temperatures may change the migration and biological uptake of atmospherically-transported toxic organic pollutants including those already banned (Grimalt *et al.*, 2001).

European freshwaters are already being affected by many human activities, resulting in changes in land-use, pollution with nutrients and hazardous substances, and acid deposition. Because of difficulties in disentangling the effects of climatic factors from other pressures, there is limited empirical evidence to demonstrate unequivocally the impact of climate change on water quality and freshwater ecology.
On the other hand, there are many indications that freshwaters that are already under stress from human activities are highly susceptible to climate change impacts and that climate change may significantly hinder attempts to restore some water bodies to good ecological status.

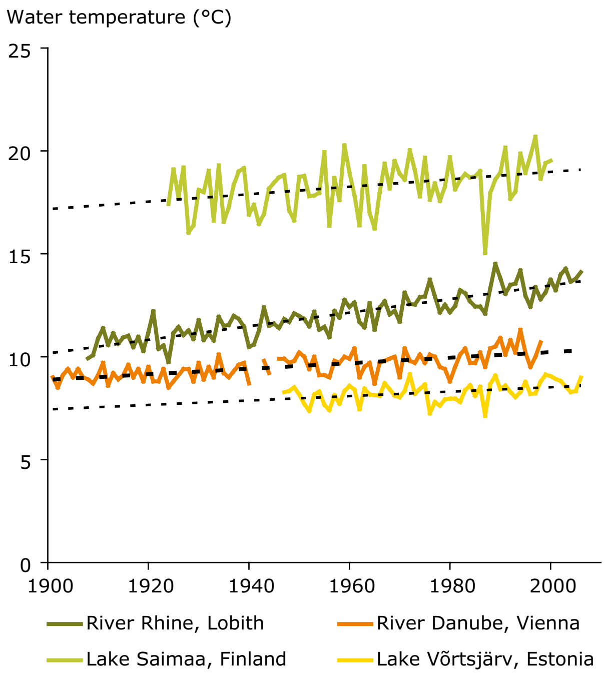
Currently many national and European research activities are producing relevant and valuable results on climate change impacts on Europe's freshwater; see for example, Euro-limpacs (http://www.eurolimpacs.ucl.ac.uk/index.php) and CLIME: Climate and Lake Impacts in Europe (http://clime.tkk.fi/). IPCC (2008) published a report on climate change and water summarising the different water sections in the 2007 fourth assessments reports.

5.6.2 *Water temperature*

Key messages

- During the last century the water temperature of some European rivers and lakes increased by 1–3 °C, mainly as a result of air temperature increase, but also locally due to increased inputs of heated cooling water from power plants.
- In line with the projected increases in air temperature, lake surface water temperatures may be around 2 °C higher by 2070.

Figure 5.27 Water temperatures in four selected European rivers and lakes in the 20th century



Note: Annual average water temperature in River Rhine (1909–2006), River Danube (1901–1998), Lake Võrtsjärv (1947–2006), and average water temperature in August in Lake Saimaa, Finland (1924–2000).

Source: River Rhine: Rijkswaterstaat; River Danube: Hohensinner *et al.*, 2006; Lake Saimaa: Korhonen (pers. com.), and Lake Võrtsjärv: Estonian Meteorological and Hydrological Institute.

Relevance

Since water temperature is mainly determined by heat exchange with the atmosphere, higher air temperatures lead to higher water temperatures. Higher water temperatures, particularly in standing waters and low-flow situations in rivers, will bring about changes in the physico-chemical condition of water bodies with subsequent impacts on biological conditions. This may have severe consequences for ecosystem structure and function as well as for water use and ecosystem services.

Impacts of increased water temperatures may also include more stable vertical stratification of deep lakes and increased oxygen depletion in lake bottoms (stratification in other lakes may become less stable), more frequent harmful algal blooms, reduced habitats for cold-water aquatic species, and increased incidence of temperature-dependent diseases (see also Section 5.6.4).

Human intervention can only help freshwater ecosystems to adapt to increasing water temperature in a limited way, for example by reducing the pressures from other human activities such as pollution by nutrients and hazardous substances and pressure from hydromorphological modifications. Such actions may make the waterbodies less vulnerable to stress resulting from higher water temperature. Additional pollution load reduction measures may be needed in river basin management plans to obtain good ecological status, as required by the Water Framework Directive.

Past trends

Long time-series, covering the past 100 years, show that the surface water temperatures of some of the major rivers in Europe have increased by 1–3 °C over the last century (Figure 5.27). The temperature of the river Rhine increased by 3 °C between 1910 and 2006. Two-thirds of this is estimated to be due to the increased use of cooling water in Germany and one-third to the increase in temperature as a result of climate change (MNP, 2006). In the river Danube the annual average temperature increased by around by 1 °C during the last century. A similar temperature increase was found in some large lakes: Lake Võrtsjärv in Estonia had a 0.7 °C increase between 1947 and 2006 and the summer (August) water temperature of Lake Saimaa, Finland increased more than 1 °C over the last century.

There are many shorter time-series of water temperature covering the past 30–50 years and the general trend has been for temperatures in European freshwater systems to increase, generally by from 0.05 to 0.8 °C decade^{-1}.

George and Hurley (2004) found that the temperature of Lake Windermere (England) and Lough Feeagh (Ireland) increased by 0.7–1.4 °C between 1960 and 2000. The water temperature of Lake Veluwe (the Netherlands) has increased by more than 1 °C since 1960 (MNP, 2006).

Marked increases in water temperature were found in eight Lithuanian lakes (Pernaravičiūtė, 2004) and six Polish lakes (Dabrowski *et al.*, 2004). Since 1950, water temperatures in rivers and lake surface waters in Switzerland have in some cases increased by more than 2 °C (BUWAL, 2004; Hari *et al.*, 2006). In the large lakes in the Alps the water temperature has generally increased by 0.1–0.3 °C per decade: Lake Maggiore and other large Italian lakes (Ambrosetti and Barbanti, 1999), Lake Zürich (Livingstone, 2003), Lake Constance and Lake Geneva (Anneville *et al.*, 2005).

Dokulil *et al.* (2006) studied the trend in hypolimnion (bottom water) temperature in 12 deep European lakes and found generally a temperature increase of 0.1–0.2 °C per decade. This may have significant effects on thermal stratification and mixing of water in lakes, which in turn affects deep water oxygen conditions and nutrient cycling.

Photo: © European Environment Agency

Projections

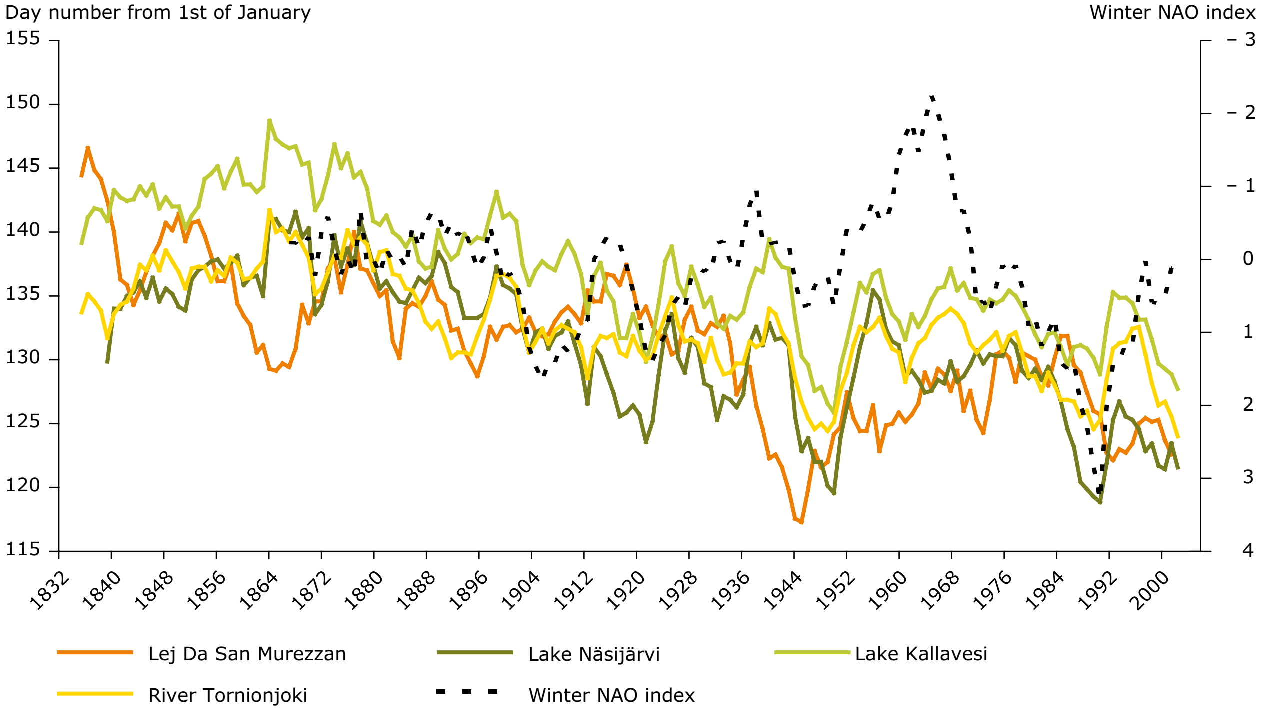
As water temperature is closely linked to change in air temperature, the predicted increase in air temperature due to climate change will be reflected in increased surface water temperature. This is in addition to temperature changes caused by other factors, such as changes in cooling water releases. Projected increases in surface water temperatures are often 50 to 70 % of the projected increases in air temperature. In line with the projected increases in air temperature (see Section 5.2.2), lake surface water temperatures may be around 2 °C higher by 2070, but with a clear seasonal dependency and depending on lake properties (Malmaeus *et al.*, 2006; George *et al.*, 2007).

5.6.3 *Lake and river ice cover*

Key messages

- The duration of ice cover in the northern hemisphere has shortened at a mean rate of 12 days per century, resulting from an average 5.7 days later ice cover and 6.3 days earlier ice break-up.
- The strongest trends in northern Europe are in the timing of ice break-up which is consistent with the fastest warming in winter and spring.
- The ice cover of lakes with mean winter temperature close to zero is much more dependent on temperature change than lakes in colder regions such as northern Scandinavia.

Figure 5.28 Ice break-up dates from selected European lakes and rivers (1835–2006) and the North Atlantic Oscillation (NAO) index for winter 1864–2006



Note: Data smoothed with a 7-year moving average. See Box 5.1 'Atmospheric circulation patterns in Europe'.

Source: Benson and Magnuson 2000 (Updated to 2006 by J. Korhonen, Finnish Environment Institute (SYKE) and D. Livingstone, Water Resources Department, Swiss Federal Institute of Environmental Science and Technology (EAWAG)).

Relevance

The appearance of ice on lakes and rivers requires prolonged periods with air temperatures below 0 °C. The deeper the lake, the more cold is needed to cool down the lake so that ice forms. Higher temperatures will affect the duration of ice cover, the freezing and thawing dates and the thickness of the ice cover.

Changes in ice cover are of critical ecological importance for lakes because of their effect on the underwater light levels (Leppäranta *et al.*, 2003), nutrient recycling (Järvinen *et al.*, 2002) and oxygen conditions (Stewart, 1976; Livingstone, 1993), which influence the production and biodiversity of phytoplankton (Rodhe, 1955; Phillips and Fawley, 2002; Weyhenmeyer *et al.*, 1999), and the occurrence of winter fish kills (Greenbank, 1945; Barica and

Mathias, 1979). Less ice may in some cases result in reduced fish kills.

Changes in lake and river ice may affect winter transportation, bridge and pipeline crossings, and winter sports but no quantitative evidence for such effects yet exists (IPCC, 2007). In Europe there is some evidence of a reduction in ice-jam floods due to reduced freshwater freezing during the last century (Svensson *et al.*, 2006).

Past trends

An analysis of long (more than 150 year) ice records from lakes and rivers throughout the northern hemisphere by Magnuson *et al.* (2000) indicated that for a 100 year period, ice cover has been occurring on average 5.7 ± 2.4 days later (± 95 % confidence interval), while ice break-up has been occurring on average 6.3 ± 1.6 days earlier, implying an overall decrease in the duration of ice cover at a mean rate of 12 days per 100 years. These results do not appear to change with latitude, or between North America and Eurasia, or between rivers and lakes.

Changes in ice parameters mostly show trends that are in agreement with observed local temperature increases. Air temperature is the key variable determining the timing of ice break-up (Palecki and Barry, 1986; Livingstone, 1997).

A few longer time-series reveal reduced ice cover (a warming trend) beginning as early as the 16th century, with increasing rates of change after about 1850 (see Figure 5.28). The early and long-term decreasing trend in the ice break-up dates is the result of the end of the Little Ice Age, which lasted from about 1400 to 1900 (Kerr, 1999). In the 20th century, the effects of the North Atlantic Oscillation on the ice regime of European inland waters appears to be stronger than the effects of increasing temperatures.

Photo: © European Environment Agency

Studying ice cover information from 11 Swiss lakes over the last century, Franssen and Scherrer (2008) found that ice cover was significantly reduced in the past 40 years, and especially during the past two decades.

Ice cover of lakes in southern Sweden is more sensitive to climate change than those in the north, where mean winter temperatures are below zero most of the winter. A study of 196 Swedish lakes along a latitudinal temperature gradient revealed that a 1 °C air temperature increase caused an up to 35 days earlier ice break-up in Sweden's warmest southern regions with annual mean air temperatures around 7 °C. It caused only about 5 days earlier break-up in Sweden's coldest northern regions where annual mean air temperatures are around − 2 °C (Weyhenmeyer *et al.*, 2004; Weyhenmeyer, 2007). Ice break-up in Finland has also become significantly earlier from the late 19th century to the present time, except in the very north (Korhonen, 2006).

Projections

Future increases in air temperature associated with climate change are likely to result in generally shorter periods of ice cover on lakes and rivers. The most rapid decrease in the duration of ice cover will occur in the temperate region where the ice season is already short or only occurs in cold winters (Weyhenmeyer *et al.*, 2004). As a result, some of the lakes that now freeze in winter and that mix from top to bottom during two mixing periods each year (dimictic lakes) will potentially change into monomictic (mixing only once) open-water lakes with consequences for vertical mixing, deep-water oxygenation, nutrient recycling and algal productivity. This may lead to an alteration in the ecological status of normally ice-covered lakes in temperate regions.

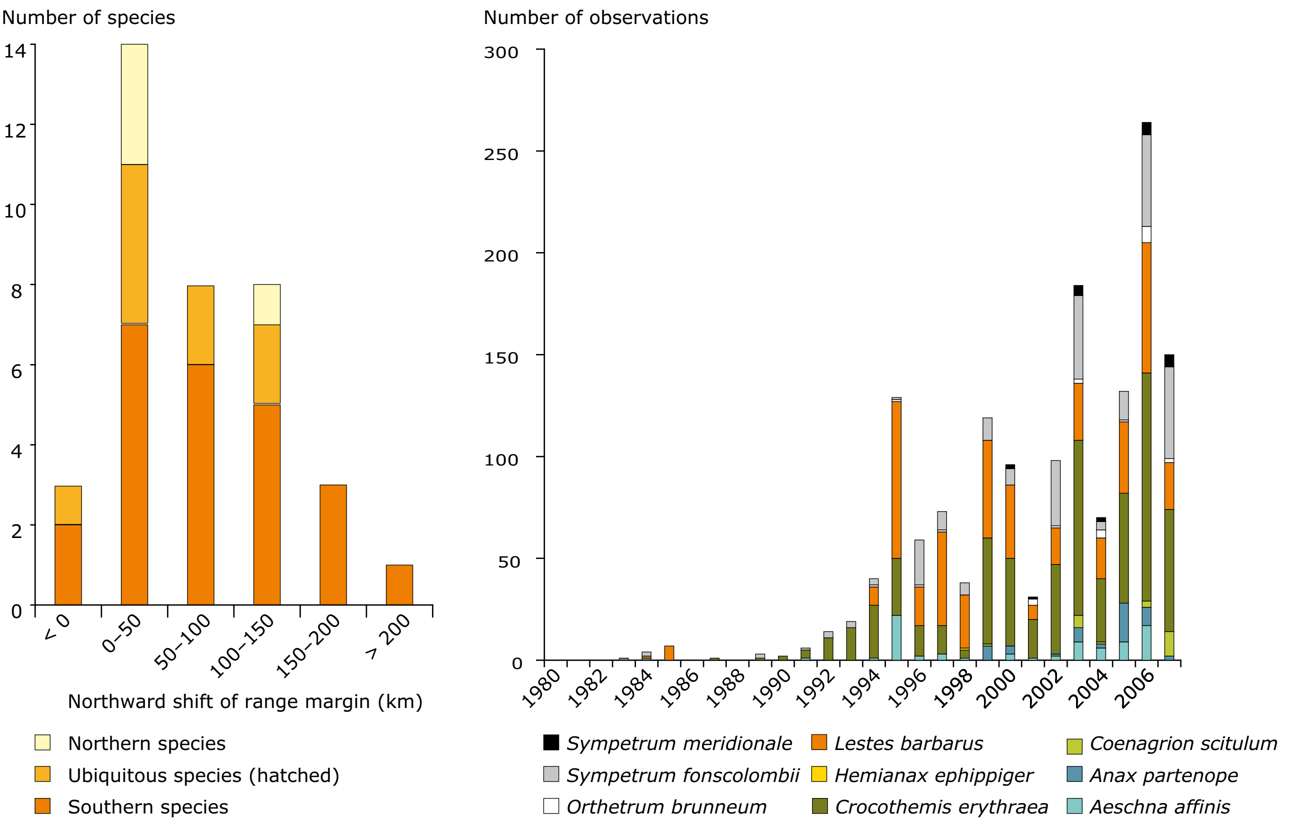
Regional climate model projections for northern Germany, based on the IPCC high emissions SRES A2 and intermediate emissions B2 climate scenarios, imply that for the Müggelsee, the percentage of ice-free winters will increase from about 2 % now to more than 60 % by the end of the century (Livingstone and Adrian, submitted). In contrast, increases in mean annual air temperature are likely to have a much smaller effect on lakes in very cold regions (e.g. northern Scandinavia) until these also reach the threshold of having winter temperature close to zero.

5.6.4 *Freshwater biodiversity and water quality*

Key messages

- Several freshwater species have shifted their ranges to higher latitudes (northward movement) and altitudes in response to climate warming and other factors.
- There are European examples of changes in life cycle events (phenology) such as earlier spring phytoplankton bloom, appearance of clear-water phase, first day of flight and spawning of fish.
- In several European lakes, phytoplankton and zooplankton blooms are occurring one month earlier than 30–40 years ago.
- Climate change can cause enhanced phytoplankton blooms, favouring and stabilising the dominance of harmful cyanobacteria in phytoplankton communities, resulting in increased threats to the ecological status of lakes and enhanced health risks, particularly in water bodies used for public water supply and bathing. This may counteract nutrient load reduction measures.

Figure 5.29 Northward shift and changes in occurrence of selected freshwater species



Note: Left: northward shift of range margins of British Odonata, dragonflies and damselflies, between 1960–1970 and 1985–1995. Right: observed occurrence of southern dragonflies in Belgium, 1980–2007.

Source: Hickling *et al.*, 2005 (left) and Biodiversity Indicators, 2006 (right).

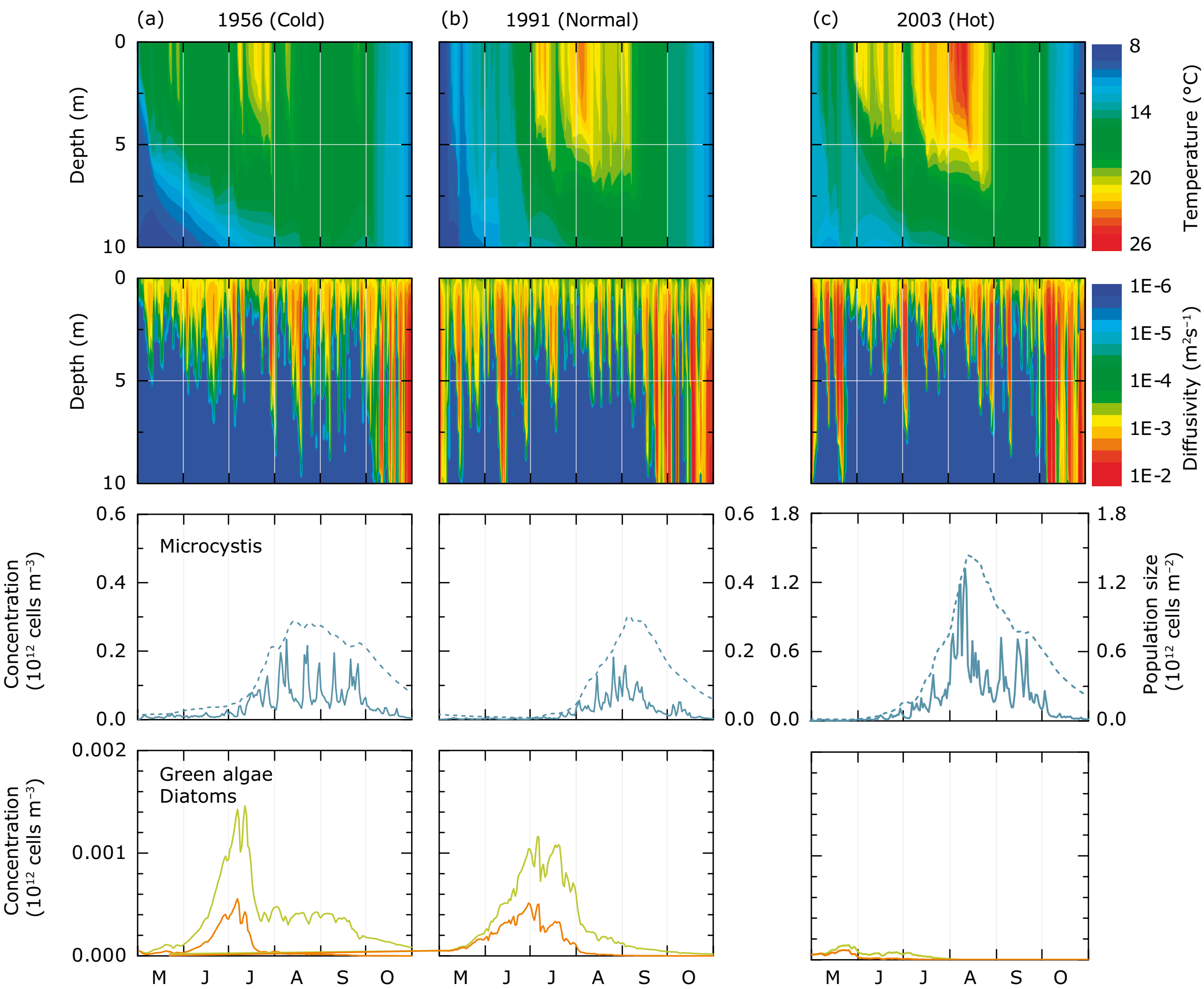
Relevance

Species and habitat dynamics in the face of climate change are complex and have many aspects. Increased temperatures and CO_2 concentrations will have an effect on different processes such as photosynthesis, respiration and decomposition and generally speed up these processes. Climate-induced changes in ice cover period, thermal stratification and nutrient availability and longer growing seasons affect species composition and food web structures.

Water temperature is one of the parameters that determine the overall health of aquatic ecosystems. Most aquatic organisms (e.g. salmonid fish) have a specific range of temperatures that they can tolerate, which determines their spatial distribution along a river or on a regional scale. Climate change could lead to the extinction of some aquatic species or at least could modify their distribution in a river system or move their distribution northwards. Several indications of climate impact on the functioning and biodiversity of freshwater ecosystems have already been observed, such as northward movement, phenology changes and invasive alien species.

Enhanced harmful algal blooms in lakes resulting from climate change may counteract nutrient load reduction measures and also require a revision

Figure 5.30 Model simulation of hydrodynamics and phytoplankton dynamics during three contrasting summers in Lake Nieuwe Meer (the Netherlands)



Note: (a) the cold summer of 1956, (b) the average summer of 1991, and, (c) the hot summer of 2003. Top panels show the temperature contour plots. The second row shows contour plots of the turbulent diffusivities. The third row shows the surface concentrations of Microcystis (solid lines) and the depth-integrated population size of Microcystis (dashed lines). The fourth row shows the surface concentrations of diatoms (orange lines) and green algae (green lines). Note the difference in scale between the Microcystis concentrations (third row) and the concentrations of diatoms and green algae (fourth row).

Source: Jöhnk *et al.*, 2008.

of classification systems for ecological status assessment. The inclusion of additional nutrient load reduction measures in river basin management plans may be needed to obtain good ecological status, as required by the Water Framework Directive. Public health may be threatened and the use of lakes for drinking water and recreation may be reduced.

Past trends

Northward and upward movement
There are European examples of aquatic species (dragonflies, brown trout) that have shifted their ranges to higher latitudes (northward movement) and altitudes in response to climate warming. Thermophilic fish and invertebrate taxa will to a certain extent replace cold-water taxa. Examples include the brown trout in Alpine rivers (Hari *et al.*, 2006), non-migratory British dragonflies and damselflies (Hickling *et al.*, 2005; Figure 5.29 left), and south European Dragonflies in Belgium (Biodiversity Indicators, 2006, see Figure 5.29 right), see also Section 5.7.4 'Distribution of animal species'.

Change in species composition and abundance
Climate change will generally have a eutrophication-like effect (e.g. Schindler, 2001), with enhanced phytoplankton blooms (Wilhelm and Adrian, 2008), and increased dominance of cyanobacteria in phytoplankton communities, resulting in increased threat of harmful cyanobacteria and enhanced health risks, particularly in water bodies used for public water supply and bathing (Jöhnk *et al.*, 2008; Mooij *et al.*, 2005). More frequent extreme precipitation and runoff events are also expected to increase the load of nutrients to waters and in turn result in more eutrophication.

Changes in temperature have already had profound impacts on the species composition of macrozoobenthos (fauna that spend most of their lives buried in sediments) in northern European lakes (Burgmer *et al.*, 2007). Fish and invertebrate communities have been found to respond to increases in water temperature in the upper Rhône River in France (Daufresne *et al.*, 2004, 2007).

Phenology changes
Changes in growth season, earlier ice break-up or periods above a certain temperature will change life-cycle events, such as an earlier spring phytoplankton bloom, appearance of clear-water phase (because large zooplankton will appear earlier), first day of flight of aquatic insects and time of spawning of fish. Prolongation of the growing season can have major effect on population abundances with an increased number of cell divisions or generations per year. Phytoplankton and zooplankton blooms in several European lakes are occurring one month earlier than 30–40 years ago (Weyhenmeyer 1999; 2001; Adrian *et al.*, 2006; Nõges *et al.*, in press). Manca *et al.* (2007) found that increasing temperatures at Lago Maggiore have resulted in earlier and longer zooplankton blooms. Hassall *et al.* (2007) found that British Odonata species over the period 1960 to 2004 changed their first day of flight by 1.5 day per decade.

Invasive freshwater species
Climate change is expected to result in biological invasions of species that originate in warmer regions. For example, the subtropical filamentous highly-toxic cyanobacterium *Cylindrospermopsis raciborskii* thrives in waters that have high temperatures, a stable water column and high nutrient concentrations: it has recently spread rapidly in temperate regions and is now commonly encountered throughout Europe (Dyble *et al.*, 2002). Its spread into drinking and recreational water supplies has caused international public health concerns due to its potential production of toxins. Fish species adapted to warmer waters, such as carp, may replace native species such as perch and trout in many regions (Kolar and Lodge, 2000).

Projections

Many species are projected to shift their ranges to higher latitudes and altitudes in response to climate warming. Southern species will move further north due to further increases of temperature. Species of colder regions will move north and towards higher altitudes or will disappear when their migration is hampered (e.g. due to habitat fragmentation). Some Arctic and alpine species may disappear.

- Increased eutrophication with enhanced algal blooms, also including new harmful invaders such as *Cylindrospermopsis* and *Gonyostomum* semen, is a possibility supported by several recent publications and observations (Findlay *et al.*, 2005; Wilhelm and Adrian, 2008; Jöhnk *et al.*, 2008; Battarbee *et al.*, 2008; Willén and Cronberg, pers. com.), particularly in areas of Europe exposed to more heavy rains that can cause increased nutrient loading and reduced underwater light in lakes.

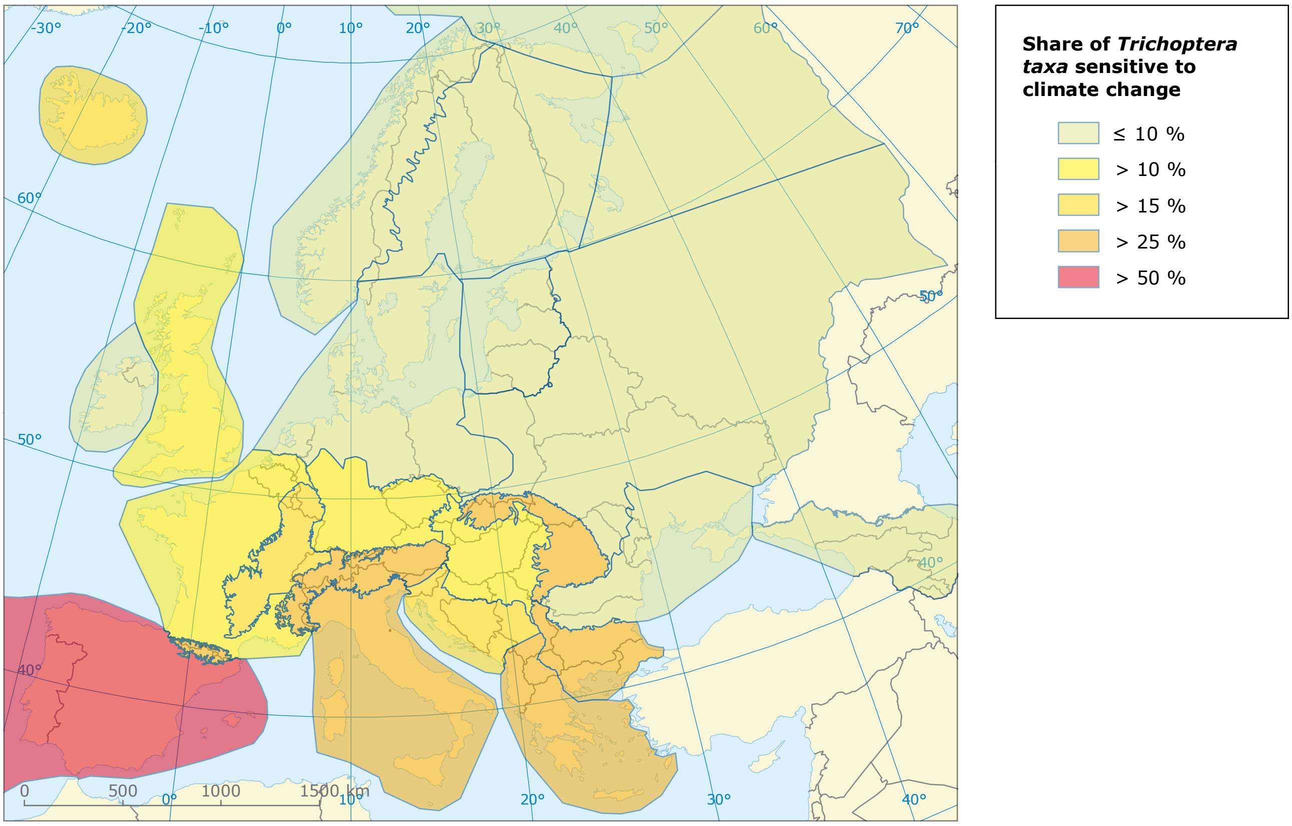
- A comparison of a large set of Danish shallow lakes with a corresponding one located in the colder climate of Canada (Jackson *et al.*, 2007) suggests that warming will decrease winter fish-kills and enhance the overwintering success of planktivorous fish which, in turn, suppress *Daphnia*/zooplankton development. As a result of decreased zooplankton grazing pressure, there will be more phytoplankton biomass build up per unit total phosphorus in warmer climate.

- Where river discharges decrease seasonally, there may be negative impacts on Atlantic salmon. Walsh and Kilsby (2006) found that salmon in northwest England will be affected negatively by climate change by reducing the number of days with suitable flow depths during spawning time.

- In the ongoing European research project *Euro-limpacs* there has been an evaluation of the sensitivity of *Trichoptera taxa* (Caddisflies) to climate change (see Map 5.29). The main results are that more than 20 % of the *Trichoptera* species are projected to be endangered due to climate change in southern Europe (droughts) and in the Alpine region (too high temperatures), whereas the impacts in other parts of Europe would be less pronounced (Hering *et al.*, 2006).

Photo: © Jeroen van Wichelen, Ghent University

Map 5.29 The share of *Trichoptera taxa* sensitive to climate change in the European ecoregions



Note: *Trichoptera taxa* are species with restricted distribution ('endemic species'), species inhabiting the crenal zone (springs), that cannot move further upstream, and species adapted to low water temperatures (cold stenothermy) in European ecoregions. A distinct south-west to north-east gradient is seen: in all ecoregions of north-east Europe the proportion of sensitive taxa is less than 10 %, compared with 51.7 % on the Iberian Peninsula and 42.3 % in Italy. The proportion in Balkan ecoregions and high mountain ranges (Alps, Pyrenees, and Carpathians) is more than 25 %.

Source: Hering *et al.*, 2006.

5.7 Terrestrial ecosystems and biodiversity

5.7.1 Introduction

Climate (change) is an important driving force in the distribution and functioning of natural systems (Parmesan and Yohe, 2003). Europe's biodiversity (its species, habitats and ecosystems) has been modified repeatedly during past glacial and inter-glacial periods, with some species recolonising the continent from ancient *refugia*. Today, ecosystems have an essential role in providing services to humankind such as nutrient cycling, pest control, pollination, quality of life, and hydrological, atmospheric and climatic regulation (Díaz *et al.*, 2006; IPCC, 2007). Impoverishment of Europe's biodiversity may affect the delivery of ecosystem services with potentially serious consequences (Lovejoy and Hannah, 2005). Maintaining and enhancing healthy ecosystems are an important element in climate change mitigation and adaptation actions.

About 60 % of the world's known ecosystems are currently used unsustainably (Reid *et al.*, 2005). In Europe, the richness and abundance of biodiversity is undergoing significant decline. This is in large part due to changes in land use and management, which are resulting in degradation of (semi-)natural habitats, declines in traditional agricultural and forest management on which many habitats depend, and now large-scale land abandonment. Urbanisation, industrialisation, modification of rivers and watercourses, fragmentation of habitats by infrastructure and growing pressure from public access to the countryside for tourism and recreation are also causing widespread biodiversity losses (Millennium Ecosystem Assessment, 2005).

It is likely that these losses of biodiversity will be exacerbated by climate change. Projections suggest that between one fifth and one third of European species could be at increased risk of extinction if global mean temperatures rise more than 2 to 3 °C above pre-industrial levels (Lovejoy and Hannah, 2005; IPCC, 2007). A combination of climate change and the drivers of change outlined above will reduce the adaptive capacity (and resilience) of many species, possibly resulting in different ecosystems and landscapes across Europe. Local and regional extinctions are likely (McKinney and Lockwood, 1999). Species at greatest threat include specialists, those at the top of the food chain, those with latitudinal and altitudinal restrictions, and those with poor dispersal abilities.

The European Commission, through its target to 'halt the loss of biodiversity by 2010 — and beyond', is addressing observed and projected declines in biodiversity and their consequences for human well-being. As part of this process, reducing the impacts of other drivers of change will enhance the ability of species to adapt to climate change (IPCC, 2007). But new areas for conservation are also needed, together with measures to improve connectivity, thus facilitating species movement in fragmented landscapes. As such, the robustness of the European ecological network of Natura 2000 sites should be strengthened, including through more widespread implementation of Article 10 of the Habitats Directive (which relates to the network's coherence).

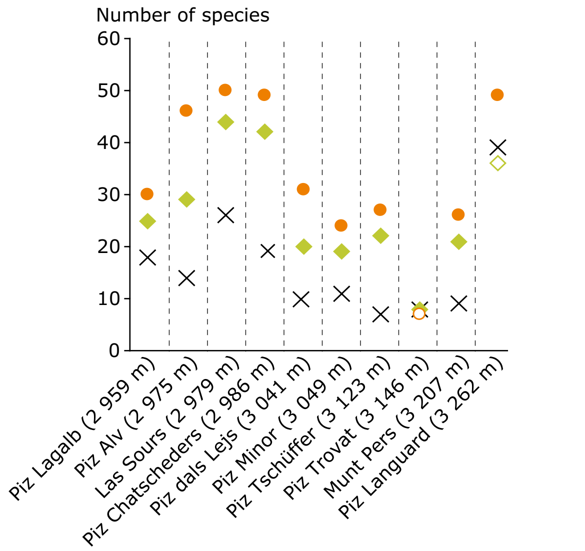
This section outlines the impacts of climate change on biodiversity by showing both observed and projected changes in the distribution and phenology (changes in the timing of seasonal events) of plants and animals, and the implications for communities.

5.7.2 *Distribution of plant species*

Key messages

- Climate change, in particular milder winters, is responsible for the observed northward and uphill distribution shifts of many European plant species. Mountain ecosystems in many parts of Europe are changing as pioneer species expand uphill and cold-adapted species are driven out of their ranges.
- By the late 21st century, distributions of European plant species are projected to have shifted several hundred kilometres to the north, forests are likely to have contracted in the south and expanded in the north, and 60 % of mountain plant species may face extinction.
- The rate of change will exceed the ability of many species to adapt, especially as landscape fragmentation may restrict movement.

Figure 5.31 Increase in species richness on Swiss Alpine mountain summits in 20th century



Note: Endemic, cold-adapted species are declining as pioneer species drive them out of their characteristic niches due warming conditions. ×: 1900s; ◇: 1980s; •: 2003; open symbols indicate a (temporary) decrease in species number (Piz Trovat, Piz Languard).

Source: Walther *et al.*, 2005.

Relevance

The rate of climate change is likely to exceed the adaptive capacity of some wild plant species (IPCC, 2007), whilst others are expected to benefit from changing environmental conditions (Sobrino Vesperinas *et al.*, 2001). Consequently, the composition of many plant communities is changing to the extent that completely new assemblages are appearing. In addition, there is a parallel change in plant distribution and the increased threat of extinction of species at the edge of their geographical and altitudinal ranges — particularly poorly-dispersing endemics. The ecological implications of these changes and the effects on the services that these ecosystems provide are not always clear. Together with the emergence of invasive non-native species, these factors will have challenging consequences for long-term biodiversity conservation (Gitay *et al.*, 2002) and the ability of Europe to meet its target to halt biodiversity loss, not least in relation to the favourable status of Natura 2000 sites.

The adaptive capacity of species is linked to genetic diversity and this too might change under climate change; sensitive and valuable relic populations will be particularly affected.

Past trends

Warmer temperatures in the past 30 years have significantly influenced seasonal patterns across Europe. As evidenced during glacial and inter-glacial periods, the predominant adaptive response of temperature-sensitive plant species has been to shift distributions, resulting in northward and altitudinal movements. One such climate-limited species is holly (*Ilex aquifolium*), which has expanded in southern Scandinavia in a manner consistent and synchronous with recorded regional climate changes, linked in particular with increasing winter temperatures (Walther *et al.*, 2005).

Mountain ecosystems are particularly vulnerable to climate change (IPCC, 2007). There has been a general increase in mountain summit species in Europe since the Little Ice Age in the 18th century. In Switzerland, for example, the uphill shift of Alpine plants showed an accelerating trend towards the end of the 20th century that is likely to be linked with the extraordinarily warm conditions of the 1990s (Walther *et al.*, 2005) (Figure 5.31). Evidence also emerged of declines in cold-adapted species as warming conditions and pioneer species drove these from their characteristic niches. Similar observations are expected from current European monitoring programs (e.g. GLORIA) for which results will be available by the end of 2008. In the Swedish Scandes, the tree line of the Scots pine (*Pinus sylvestris*) rose by 150–200 metres as warmer winters significantly lowered mortality and increased rates of establishment. Observations from other continents show that uphill tree line migration is a global phenomenon that could become a major threat to biodiversity in high mountains (Kullman, 2006; 2007; Pauli *et al.*, 2007).

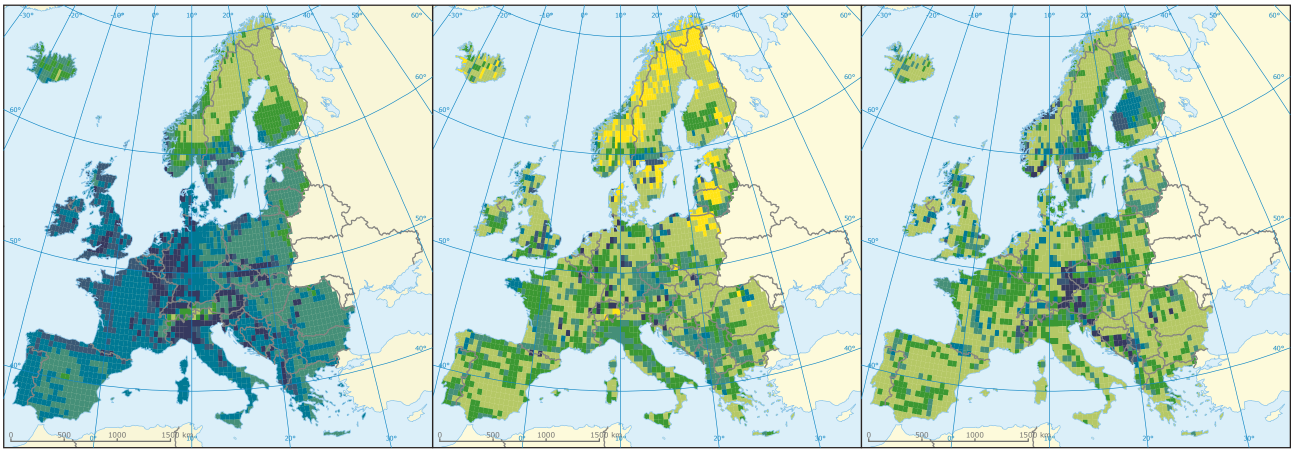
Projections

Projections indicate that, by the late 21st century, the potential range of many European plant species may shift several hundred kilometres in a northerly direction. This is several times faster than past rates as estimated from the Quaternary record or from historic data (Huntley, 2007). The distribution of tree species is also likely change significantly, with forests expanding in the north and contracting in the south, and broadleaved species replacing native coniferous species in western and central Europe (IPCC, 2007).

Modelling of late 21st century distributions of 1 350 European plant species under a range of scenarios led to the conclusion that more than half will be at the edge of their geographic and altitudinal ranges and could become threatened by 2080, with high risks of extinction (Thuiller *et al.*, 2005). The greatest changes are projected for endemic plant species in Mediterranean, Euro-Siberian and many mountain regions. Mountain communities may face up to a 60 % loss of plant species under high emission scenarios, reversing the 20th century trend outlined above (Thuiller *et al.*, 2005; IPCC, 2007).

Bakkenes *et al.* (2006) obtained similar results from modelling stable areas of plant species distribution for this century under different climate change scenarios (Map 5.30). This study suggests that 10–50 % of plant species in European countries are likely to disappear by 2100 from their current location in the absence of climate change mitigation. Again, species in southeast and southwest Europe are likely to be worst affected. This number will be higher if migration is restricted due to continuing fragmentation or if there is competition with invasive species.

Map 5.30 Projected changes in number of plant species in 2050



Projected changes in plant species in 2050, compared to reference year 2000

Number present (year 2000)	Number disappearing	Number appearing
0	0	0
1–25	1–25	1–25
26–50	26–50	26–50
51–100	51–100	51–100
101–150	101–150	101–150
151–200	151–200	151–200
> 200	> 200	> 200

Note: Results for stable area per grid cell, using the EuroMove model with HadCM2 A2 climate scenario.

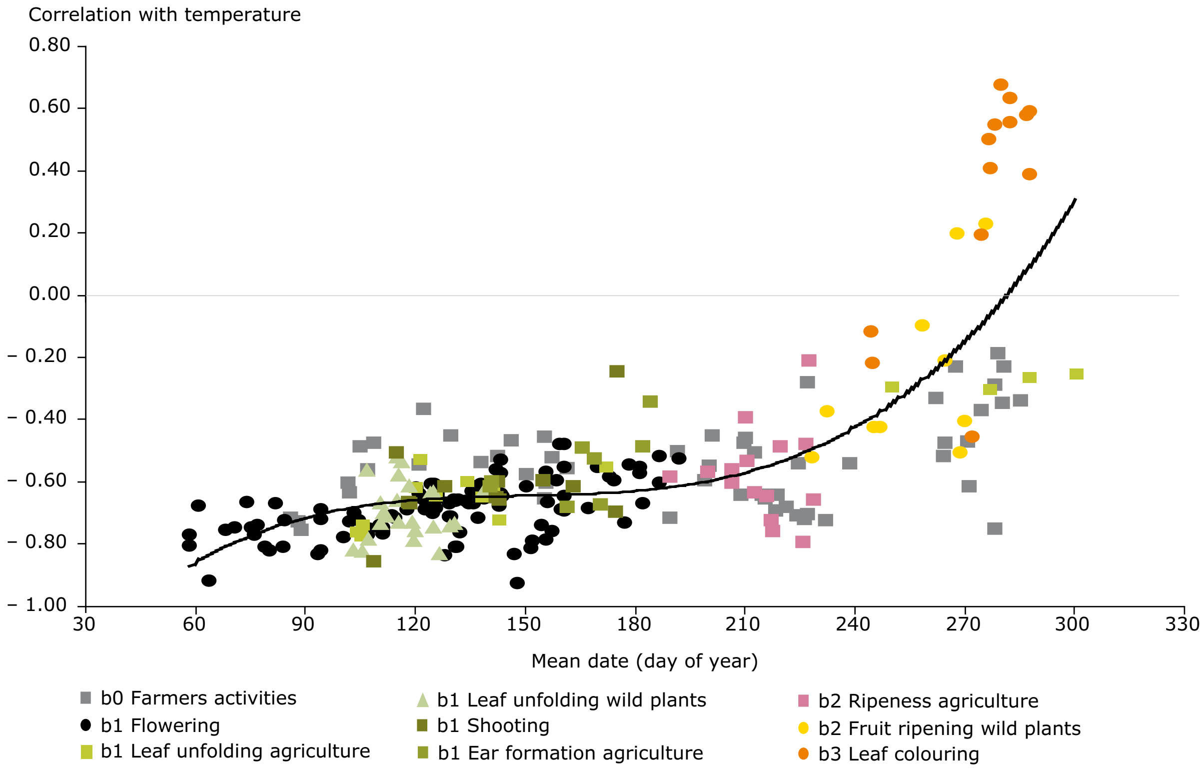
Source: Based on Bakkenes *et al.*, 2006.

5.7.3 *Plant phenology*

Key messages

- The timing of seasonal events in plants is changing across Europe, due mainly to changes in climate conditions; 78 % of leaf unfolding and flowering records show advancing trends and only 3 % a significant delay. Between 1971 and 2000, the average advance of spring and summer was 2.5 days per decade.
- As a consequence of climate-induced changes in plant phenology, the pollen season starts on average 10 days earlier and is longer than 50 years ago.
- Trends in seasonal events will continue to advance as climate warming increases in the years and decades to come.

Figure 5.32 Phenological sensitivity to temperature changes



Note: In a study of 254 national records across nine countries, most phenological changes correlated significantly with mean monthly temperatures of the previous two months. The earlier a spring event occurred, the stronger the effect of temperature.

Countries included: Austria, Belarus/northern Russia, Estonia, Czech Republic, Germany, Poland, Slovenia, Switzerland, Ukraine/southern Russia. Phenophase groups included: (b0) Farmers activities, (b1) Spring and summer with different leafing, shooting and flowering phases, (b2) Autumn fruit ripening and (b3) Leaf colouring of deciduous trees in fall.

Source: Menzel *et al.*, 2006.

Relevance

Phenology is the study of changes in the timing of seasonal events such as budburst, flowering, dormancy, migration and hibernation. Some phenological responses are triggered principally by temperature, while others are more responsive to day length (Menzel *et al.*, 2006). Changes in phenology are linked with the growing season and affect ecosystem functioning and productivity.

Farming, forestry and gardening, as well as wildlife, are affected. The timing of tilling, sowing and harvesting is changing, fruit is ripening earlier due to warmer summers (Menzel *et al.*, 2006), and grass in municipal parks and on road verges requires cutting more frequently and for longer.

Changes in flowering have implications for the timing and intensity of the pollen season; this is showing an advancing trend as many species start to flower earlier. Allied to this, the concentration of pollen in the air is increasing (Nordic Council, 2005).

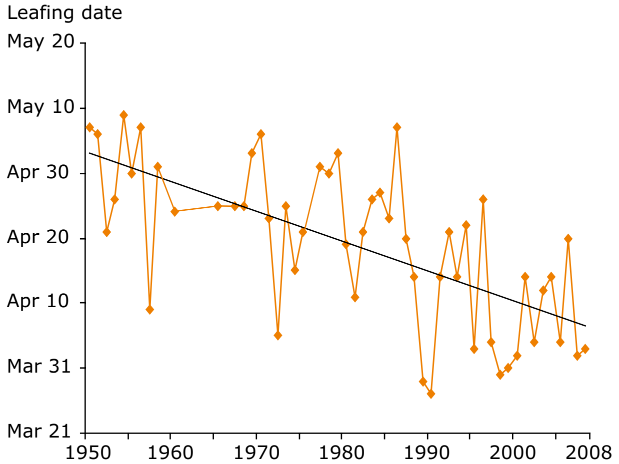
Photo: © European Environment Agency

Past trends

There is clear evidence of changing phenology across Europe in recent decades (Parmesan and Yohe, 2003; Root *et al.*, 2003; Menzel *et al.*, 2006) (Figure 5.32). Overall, 62 % of the observed variability in the timing of life cycle events can be explained by climate (van Vliet, 2008). However, variability differs between events, with those occurring earlier (i.e. spring) being more variable than later events (Menzel *et al.*, 2006). For example:

- 78 % of all leaf unfolding, flowering and fruiting records across Europe show an advancing trend and only 3 % a significant delay. The average advance of spring/summer phenological events is occurring at a rate of 2.5 days per decade (Menzel *et al.*, 2006).
- The pollen season currently starts on average 10 days earlier and is of longer duration than 50 years ago.
- In Britain, the first flowering date for 385 plant species has advanced by 4.5 days on average during the past decade in comparison with the previous four decades (Fitter and Fitter, 2002); oak leafing has advanced three weeks in the last 50 years (DEFRA, 2007) (Figure 5.33).
- In the Arctic, rapid climate-induced advancement of spring phenomena (e.g. flowering, egg laying) has been observed during the last 10 years. The strong responses of Arctic ecosystems and large variability within species illustrate how easily biological interactions can be disrupted by climate change (Høye *et al.*, 2007).

Figure 5.33 Oak (*Quercus sp*) leafing date in Surrey (United Kingdom) 1950–2008



Note: Annual observations (connected by straight lines); black line: average change in leafing date (showing advancement).

Source: Nature's Calendar, the United Kingdom.

Projections

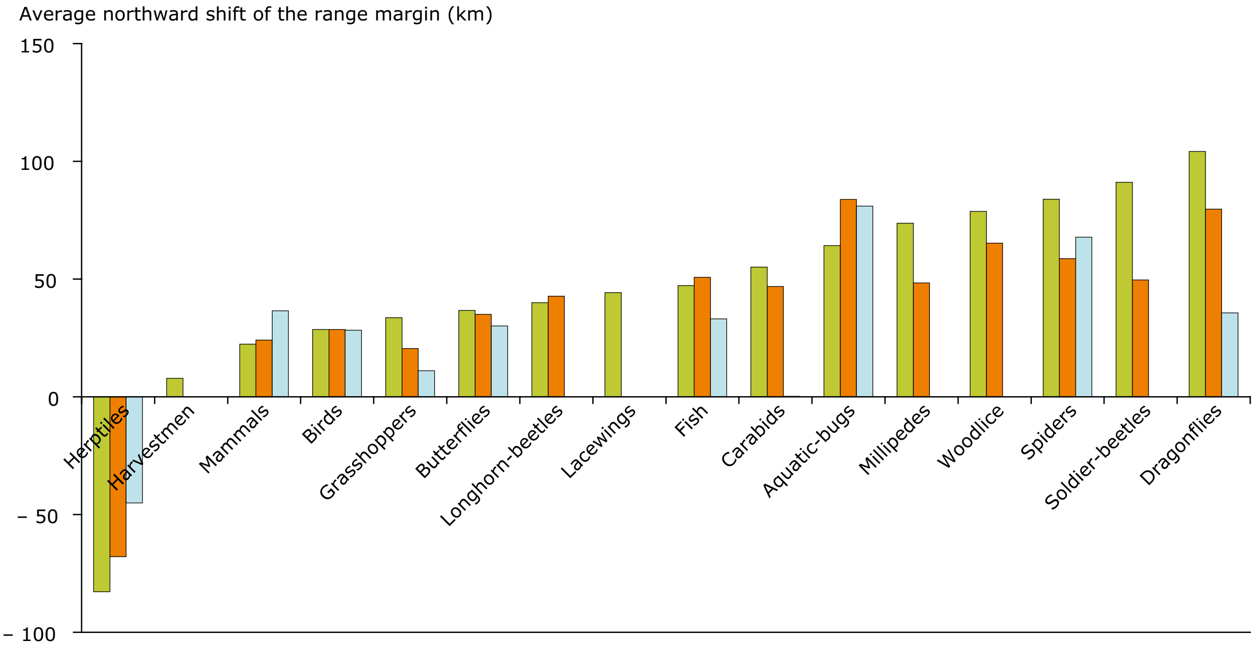
Phenological changes will alter growing seasons, ecosystem production, population-level interactions and community dynamics (Fitter and Fitter, 2002). Different species show different phenological responses; for example, annuals and insect-pollinated species are more likely to flower early than perennials and wind-pollinated species (Fitter and Fitter, 2002). Ecological research is evaluating these response thresholds to better understand what the wider effects might be. While advancing trends in seasonal events will continue as climate warming increases in the years and decades to come, it is uncertain how different species will respond when temperature thresholds are reached and whether linear relationships between temperature and growing season will be realised in the future.

5.7.4 *Distribution of animal species*

Key messages

- Europe's birds, insects, mammals and other groups are moving northwards and uphill, largely in response to observed climate change. But rates of distribution change are not necessarily keeping pace with changing climate.
- A combination of the rate of climate change, habitat fragmentation and other obstacles will impede the movement of many animal species, possibly leading to a progressive decline in European biodiversity.
- Distribution changes are projected to continue. Suitable climatic conditions for Europe's breeding birds are projected to shift nearly 550 km northeast by the end of the century, with the average range size shrinking by 20 %. Projections for 120 native European mammals suggest that up to 9 % (assuming no migration) risk extinction during the 21st century.

Figure 5.34 Latitudinal shifts in northern range margins in the United Kingdom for selected groups of animal species over the past 40 years



Note: Results for 16 taxonomic groups of animal species are given for three levels of data sub-sampling (recorded, green; well-recorded, orange; heavily recorded, blue). Only species occupying more than twenty 10 km grid squares were included in the analysis.

Source: Hickling *et al.*, 2006.

Relevance

The northward shift in distribution of animal species has a range of potential consequences for agriculture (livestock and crops), human health, as well as for biodiversity and its conservation (Sparks *et al.*, 2007). The distribution of many animal species will be particularly affected by climate change if landscape fragmentation impedes their movement to more suitable climatic conditions. This will also affect the ability of Europe to meet its biodiversity target (above). In addition, warmer conditions, particularly warmers winters, are allowing the establishment of new pest species such as the European corn borer (*Ostrinia nubilalis*), American bollworm (*Heliothis armigera*), gypsy moth (*Lymantria dispar*) and some

Sooty copper (*Heodes tityrus*)

Photo: © Guy Padfield, http://www.guypadfield.com

migratory moths and butterflies (see Section 5.7.5). Health risks associated with vector-borne diseases are linked to invasions of species such as ticks and mosquitoes (see Section 5.10).

Past trends

The northward and uphill movement of a wide variety of animal species has been observed over recent decades across Europe. These observations are partly attributable to observed changes in climatic conditions, whilst others are triggered more by land-use and other environmental changes.

In Britain, 275 of 329 animal species analysed over the last 25 years shifted their ranges northwards by 31–60 km, 52 shifted southwards, and two did not move (UKCIP, 2005; Hickling *et al.*, 2006) (Figure 5.34). However, many species, including butterflies, are failing to move as quickly as might be expected under the current rate of climate change (Warren *et al.*, 2001).

Climate change has also already influenced the species richness and composition of European bird communities (Lemoine *et al.*, 2007; Gregory *et al.*, 2008). A recent study of 122 terrestrial bird species indicated that, from around 1985, climate change has influenced population trends across Europe, with impacts becoming stronger over time (Figure 5.35). The study shows that 92 species have declined their populations because of climate change, whereas 30 species have generally increased (Gregory *et al.*, 2008).

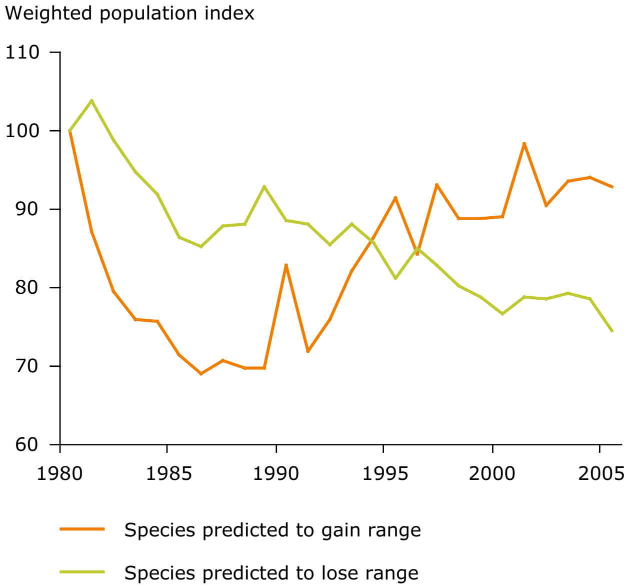
In a study of 57 non-migratory European butterflies, 36 had shifted their ranges to the north by 35–240 km and only two had shifted to the south (Parmesan *et al.*, 1999). The sooty copper (*Heodes tityrus*), for example, spread north from Catalonia and by 2006 had established breeding populations on the Baltic coast (Parmesan *et al.*, 1999). In Spain, the habitat of 16 mountain-restricted butterflies reduced by about one third over the last 30 years; lower altitudinal limits rose on average by 212 m — in line with a 1.3 °C rise in mean annual temperature (Wilson *et al.*, 2005).

In Germany, the once rare scarlet darter dragonfly (*Crocothemis erythraea*) has spread from the south, paralleling observed changes in climate, and is now found in every federal state (Ott, 2007). Similarly, the spread of the comma butterfly in the Netherlands has been linked to recent climate change patterns.

Projections

Projections suggest that the northward and uphill movement of many animal species will continue this century. Widespread species may be less vulnerable, while threatened endemics — already

Figure 5.35 Impact of climate change on populations of European birds, 1980–2005



Note: Weighted composite population trends under climate change were modelled as an index for two groups of widespread European land birds for 1980 to 2005, using climate envelope models. The index is set to 100 in 1980. The orange line shows the modelled weighted composite trend of 30 bird species. It shows an increase of their geographical range in the study region. The green line shows the modelled trend of 92 species that have lost range. Range changes were modelled by averaging using three global climate models and two emissions scenarios.

Source: Gregory *et al.*, 2008.

under pressure — will be at greatest risk, although there will be spatial variation (Levinsky *et al.*, 2007; Lemoine *et al.*, 2007). An important constraint will be the ability of species to move. This ability represents a significant research challenge, especially in the context of the effectiveness of ecological networks under a fast-changing climate.

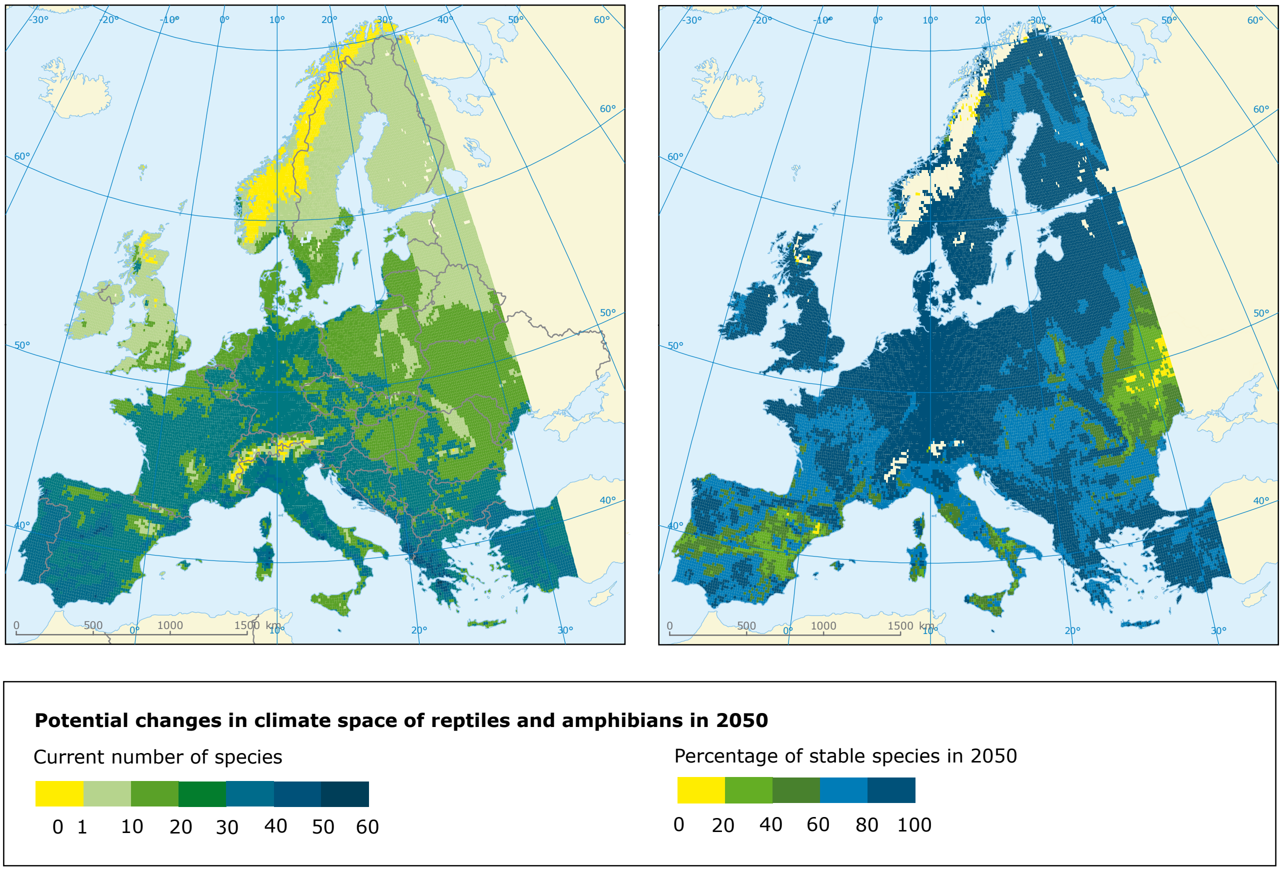
The limited dispersal ability of many reptile and amphibians, coupled with the fragmentation of ecological networks, is very likely to reduce the ranges of many species (Hickling *et al.*, 2006; Araújo *et al.*, 2006), particularly those in the Iberian Peninsula and parts of Italy (Map 5.31).

A study of 120 native terrestrial mammals projected that species richness is likely to reduce dramatically this century in the Mediterranean region, but increase towards the northeast and in mountainous areas such as the Alps and Pyrenees, assuming that movement through fragmented landscapes is possible.

Under a 3 °C climate warming scenario (above pre-industrial levels), the ranges of European breeding birds are projected to shift by the end of the 21st century by about 550 km to the northeast, with average range size being 20 % smaller. Arctic, sub-Arctic, and some Iberian species are projected to suffer the greatest range losses (Huntley *et al.*, 2008).

In polar regions, projected reductions in sea ice will drastically reduce habitat for polar bears, seals and other ice-dependent species (IPCC, 2007). In addition to climate change, these top predators will also be affected by declining fish stocks.

Map 5.31 Projected impact of climate change on the potential distribution of reptiles and amphibians in 2050



Note: Projected data based on the Generalised Linear Model map using the HadCM3 A2 scenario for the 2050s are compared with the current situation.

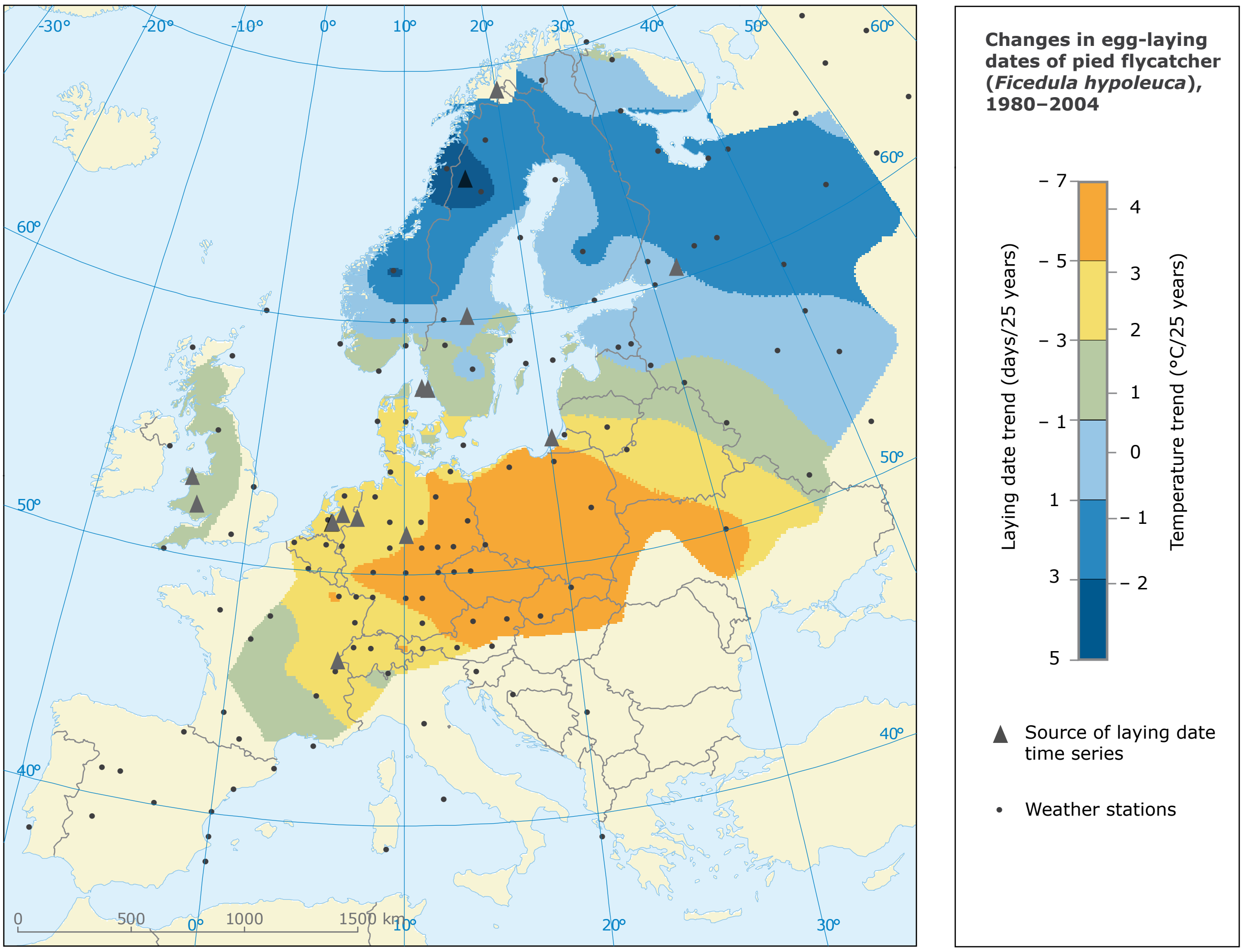
Source: Bakkenes, 2007, based on Araújo *et al.*, 2006.

5.7.5 *Animal phenology*

Key messages

- Climatic warming has caused advancement in the life cycles of many animal groups, including frogs spawning, birds nesting and the arrival of migrant birds and butterflies. Seasonal advancement is particularly strong and rapid in the Arctic.
- Breeding seasons are lengthening, allowing extra generations of temperature-sensitive insects such as butterflies, dragonflies and pest species to be produced during the year.
- These trends are projected to continue as climate warming increases in the decades to come. Populations may explode if the young are not exposed to normal predation pressures. Conversely, populations may crash if the emergence of vulnerable young is not in synchrony with their main food source or if shorter hibernation times lead to declines in body condition.

Map 5.32 Changes in egg-laying dates (1980–2004) of the pied flycatcher (*Ficedula hypoleuca*)



Note: Dots: weather stations used to calculate changes in local egg-laying dates (derived from temperature data); triangles: location of pied flycatcher laying date time series.

Source: Both and Marvelde, 2007.

Relevance

Climate warming affects the life cycles of many animal species, particularly those such as butterflies, dragonflies and damselflies that are sensitive to temperature. Milder springs are allowing earlier onset of breeding and extra generations to emerge during the year. Furthermore, populations may explode if the young are not exposed to normal predation pressures. Conversely, populations may crash if the emergence of vulnerable young is not in synchrony with their food source or if shorter hibernation times lead to declines in body condition — as evidenced in the lower survival rates of some amphibians (Reading, 2007).

Insect pests are likely to become more abundant as temperatures increase (Cannon, 1998). As the impacts of climate change on ecosystems favour generalists, and as warmer temperatures increase insect survival and reproduction rates, more frequent, severe and unpredictable pest outbreaks may occur (McKinney and Lockwood, 1999). In temperate regions, milder winters are allowing increased rates of winter survival (Bale *et al.*, 2002) and it has been estimated that, with a 2 °C temperature increase, some insects could undergo up to five additional life cycles per season (Yamamura and Kiritani, 1998).

Past trends

As spring temperatures increased in Europe over the past 30 years, many organisms responded by advancing the timing of their growth and reproduction.

A study in Britain (Crick and Sparks, 1999) analysed 74 258 records for 65 bird species from 1971 to 1995. The study showed significant trends towards earlier (8.8 days on average) laying dates for 20 species (31 %), with only one species laying significantly later. The effects, however, are not necessarily uniform. The predicted egg-laying date for the pied flycatcher (*Ficedula hypoleuca*), for example, shows significant advancement during the period 1980 to 2004 in western and central Europe, but delays in northern Europe (Map 5.32); both are strongly driven by temperature trends (Both and Marvelde, 2007).

Strong and rapid phenological changes have been observed in the high latitudes in response to warming of the region occurring at twice the global average rate (Høye *et al.*, 2007). The date of snowmelt in northeast Greenland has advanced by an average of 14.6 days since the mid 1990s, resulting in earlier egg-laying dates for birds in the region.

Projections

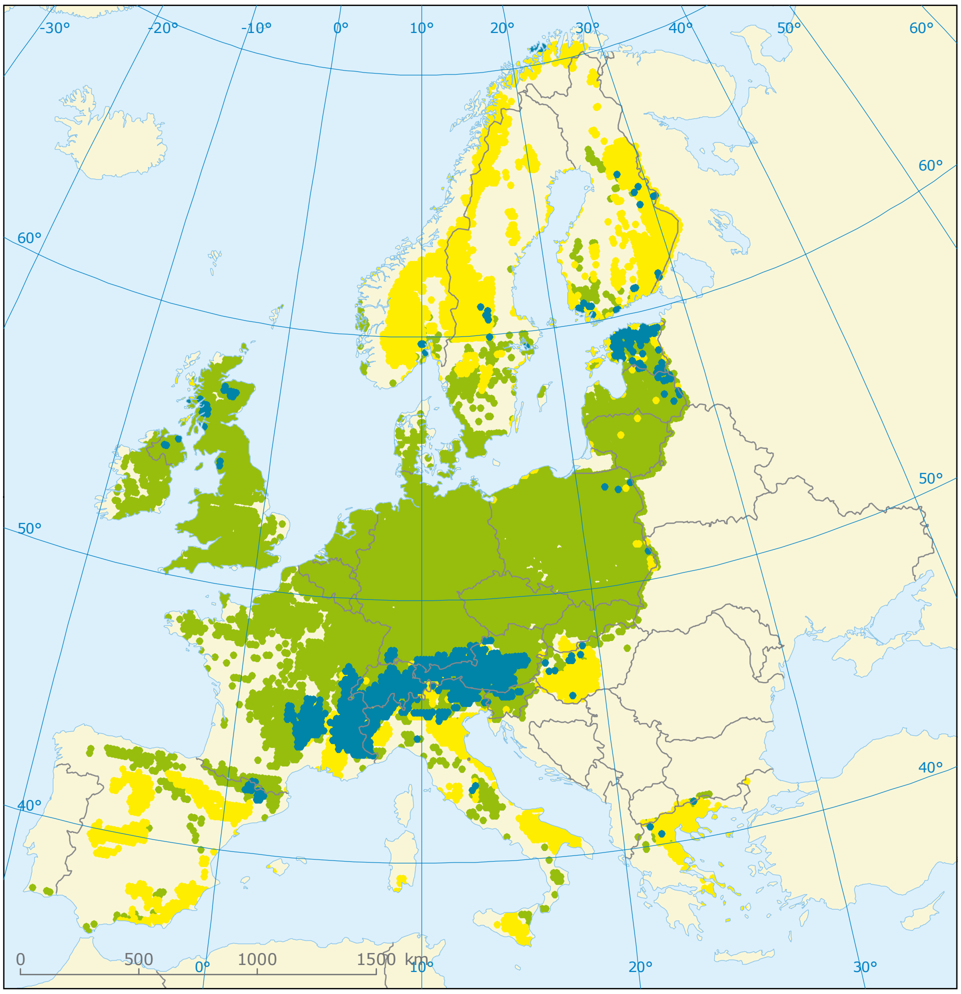
The future impacts of climate change on animal phenology are poorly understood, but could include increasing trophic mismatch and disturbance to ecosystem functioning. The trend towards warmer springs may continue to induce earlier breeding and migration activity. Unpredictable cold snaps are likely to cause high mortality amongst early movers. Meanwhile, species whose life cycles are calibrated according to day length, and which do not respond so readily to changing temperatures, will not be able to exploit earlier spring resources unless they can adapt.

5.7.6 *Species-ecosystem relationships*

Key messages

- The stability of ecosystems and, therefore, the services that they provide, will become increasingly affected by climate change due to species-specific responses and, thus, the disruption of established biotic interactions.
- The changing range of host species has major implications for range expansions of species and places additional pressures on those of conservation importance.

Map 5.33 Current potential niche space of the butterfly Titania fritillary (*Boloria titania*) and its host plant American bistort (*Polygonum bistorta*)



Current potential niche space of the butterfly Titania fritillary (*Boloria titania*) and its host plant American bistort (*Polygonum bistorta*)

Niche space of *Polygonum bistorta*

Niche space of *Boloria titania*

Overlap of *Polygonum bistorta* and *Boloria titania*

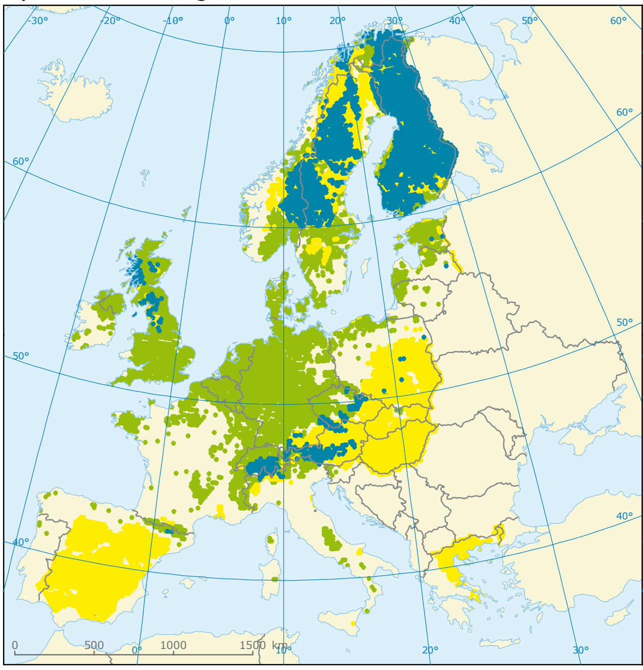
Source: Schweiger *et al.*, in press.

Relevance

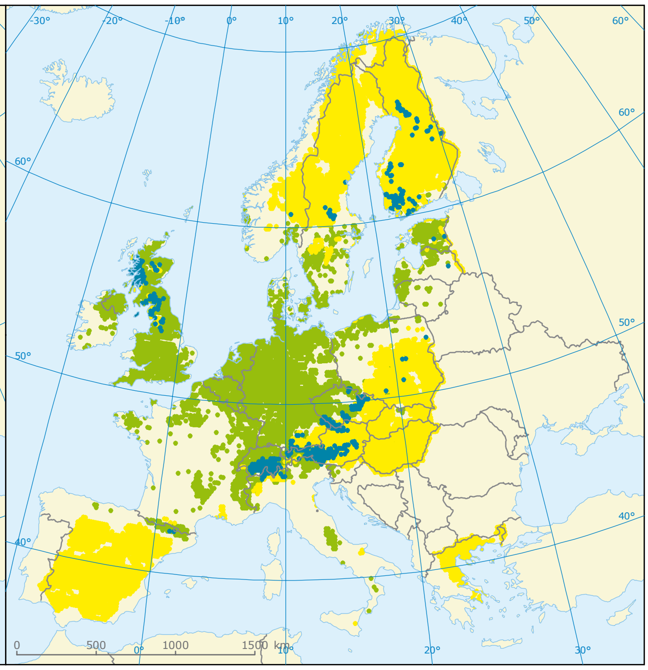
Suitable climate is an important factor in determining the distribution of species and the composition and stability of ecosystems. For many animal species, a major constraint on successful colonization of new areas is the absence of ecologically-linked host plants (Schweiger *et al.*, in press). Advancements in spring activity may result in asynchrony between food sources and breeding, causing starvation of young that emerge too early, and the disruption of predator-prey relationships.

Map 5.34 Relationship between projected distribution space of the butterfly Titania fritillary (*Boloria titania*) and its host plant American bistort (*Polygonum bistorta*) for 2080

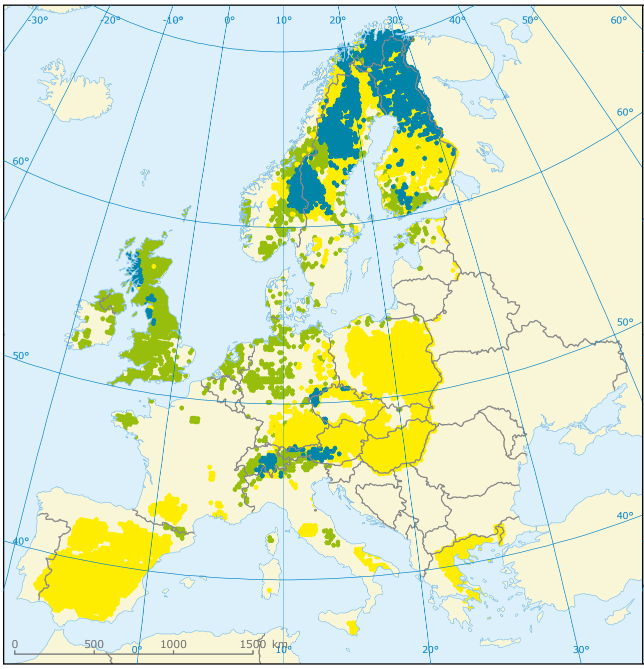
a) Moderate change



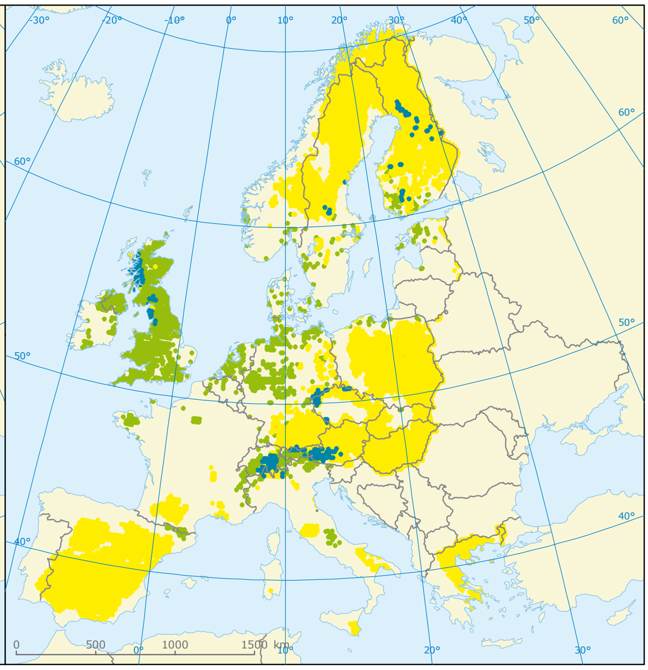
b) Moderate change



c) High change



d) High change



Relationship between projected distribution space of the butterfly Titania fritillary (*Boloria titania*) and its host plant American bistort (*Polygonum bistorta*) for moderate (a, b) and high (c, d) climate change scenarios for 2080 under the assumption of unlimited (a, c) and no (b, d) dispersal of its host plant

- Niche space of *Polygonum bistorta*
- Niche space of *Boloria titania*
- Overlap of *Polygonum bistorta* and *Boloria titania*, which is the butterfly's potential future niche space

Note: Global change scenarios based on storylines developed within the EU-funded project ALARM (Settele *et al.*, 2005, Spangenberg 2007, www.alarmproject.net).

Source: Schweiger *et al.*, in press.

This so-called trophic mismatch has been demonstrated for various animal groups, including birds (Both *et al.*, 2006), and in some cases is causing crashes or explosions in populations. Additionally, extreme events such as floods, drought and fire can disrupt ecosystems, preventing growth of key plant species and limiting nesting, breeding and feeding opportunities for animals.

Past trends

Many butterfly species are moving northward (see Section 5.7.4), but often with overall declines in abundance and range size (Warren *et al.*, 2001). Biotic interactions are important factors in explaining the distributions of butterflies, because they are often host-specific. For example, many parts of Europe are climatically suitable for the butterfly Titania fritillary (*Boloria titania*) (Map 5.33) and the species may even be able to migrate quickly in response to climate change. However, an important constraint to range expansion is the presence of its host plant American bistort (*Polygonum bistorta*) (Schweiger *et al.*, in press). Likewise, the current distribution of the clouded Apollo (*Parnassius mnemosyne*) is explained not only by climate suitability, but also by the presence of its Corydalis host plant (Araújo and Luoto, 2007).

Climate change has also had a disruptive effect on Scottish seabird communities and their food webs. During 2004 and 2005, major population crashes have been observed. In Shetland, over 1 000 guillemot nests and 24 000 nests of the Arctic tern were almost entirely deserted, and on the nearby island of Foula, the world's largest colony of great skuas saw only a few living chicks. The cause was a drastic reduction in the populations of sandeel, their principal food source. The disappearance of the sandeel was due, in turn, to the northward movement of cold-water plankton on which these fish feed (see Section 5.4). The plankton's range had shifted because the waters between Britain and Scandinavia had become too warm for it to survive there. Since 1984, some seabird species around Scotland have decreased by 60–70 % (CEH, 2005).

Projections

The response to climate change of the butterfly Titania fritillary (*Boloria titania*) and its host plant American bistort (*Polygonum bistorta*) is likely to lead to a reduction in range overlap and, thus, an uncertain future for this specialist butterfly. Played out on a larger scale, these trophic mismatches benefit generalists at the expense of specialists, putting additional pressures on the capacity of ecosystems to provide certain services and on species of conservation importance (McKinney and Lockwood, 1999; Reid *et al.*, 2005; Biesmeijer *et al.*, 2006).

5.8 Soil

5.8.1 Introduction

Climate is an important factor in soil development and a major driver of the processes of soil formation. At the same time, changes in the bio-physical nature of soil, due to rising temperatures, changing precipitation intensity and frequency and more severe droughts, are likely to release substantial amounts of greenhouse gases. However quantitative information, from observations and modelling of the impacts of climate change on soil and the various related feedbacks, is very limited. To date, assessments have relied mainly on local case studies that have analysed how soil reacts under changing climate in combination with evolving agricultural and forest practices. Indicators with full European coverage, to help policymakers identify appropriate adaptation measures, are absent, as can be seen from the limited number of indicators in this chapter. There is an urgent need to address this unsatisfactory situation through the establishment of appropriate monitoring schemes.

Soil has many biological, chemical and physical characteristics with a marked spatial and temporal variability. Changing climate will affect these characteristics and may also have serious consequences for the well-being of people, who are dependent on the broad range of environmental goods and services regulated by soil. Soil is one of the key life-support systems on the planet, responsible for major ecological and other functions such as:

- supply of water and nutrients for plant growth and food production (ecosystems, agriculture and forestry);
- regulation of the water cycle;
- nutrient cycles, storage of carbon and regulation of greenhouses gases;
- trapping of contaminants (buffering capacity);
- source of raw material (e.g. clay minerals);
- preservation of cultural heritage;
- habitats for animal and plant species, maintaining their biological and genetic diversity;
- support to human settlements, providing a basis for buildings and infrastructures, disposal of waste material, slope stability.

The EU's Thematic Strategy for Soil Protection (EC, 2006) has stated that several soil functions are under serious pressure in many parts of Europe. The understanding of soil as an important contributor to water systems, the global carbon cycle and other systems is still evolving and needs to be developed further; so far soil has been perceived mainly in the context of arable land and fertility for crop production. The perception of soil as an environmental medium providing substantial goods and services for all land and aquatic ecosystems has developed over recent decades but still with a focus on economic aspects and valuing different types of land use.

Significant projected changes in precipitation patterns will affect soil formation and functions. Soil as part of the soil-water-plant system contributes and influences changes in groundwater recharge, water quality through buffering capacity, plant growth and evapotranspiration through water available to roots, and run-off through retention capacity. This is vital for land and water management. Better and more quantitative understanding of this system is needed to improve forecasts and possible response actions. Indicators with sufficient resolution in time and space are needed to link observations and new models which include climate change.

Based on the current limited amount of observations and some modelling, the following issues are highlighted in this chapter. Soil organic matter drives the majority of soil functions; any reduction can lead to a decrease in fertility and biodiversity (see Box 5.10), a loss of soil structure, reduced water retention capacity and increased risk of erosion and compaction. Changes in rainfall and wind patterns will lead to an increase in erosion in vulnerable soils which often suffer from low organic matter content. Climate change will further increase the risk of desertification, which is already affecting southern Europe and is expected to move gradually northward (see Box 5.11). Desertification ([4]) is an advanced stage of land degradation where the soil has lost part of its capability to support human communities and ecosystems. By absorbing water, soil organic matter can contribute to the mitigation of flooding following extreme rainfall events, while storing water in the event of more frequent and severe droughts (see

([4]) Desertification is defined by the United Nation Convention to Combat Desertification (UNCCD) as 'land degradation in arid, semiarid and sub-humid areas resulting from various factors, including climatic variations and human activities' (UNCCD, 1997).

Section 5.5). However evaluation of the impact of climate change remains difficult. Changes to features such as texture and mineralogical composition will only occur over long 'geological' time spans, while properties such as pH, organic matter content or microbial activity will show a more rapid response. In addition, the response of a particular soil type may be both positive and negative, depending on its function. Rising temperatures and precipitation may support increased agricultural productivity (see Section 5.9) but may also increase the risk of erosion.

Soil can also act as a carbon sink, absorbing carbon dioxide from the atmosphere and thus mitigating global warming. In areas with low temperatures and sufficient moisture, the decomposition of dead biomass (leaves, stems, roots of plants) is reduced, leading to accumulations of soil organic matter. Increasing temperatures will accelerate decay rates, leading to increased carbon dioxide and methane emissions from soil. Appropriate wetland management and land-use practices should thus be enhanced to maintain or enhance soil carbon stocks.

Box 5.10 The impacts of climate change on soil biodiversity

Key messages

- Soil organisms control numerous ecosystem processes, supplying the environment and society with a number of important economic and ecosystem goods and services.
- Climate change alters the habitat of soil biota, which affects the diversity and structure of species and their abundance. Ecosystem functioning, including nutrient supply, carbon and nitrogen cycles, is modified consequently. However, quantified knowledge of these impacts is limited.

Soil biodiversity controls several processes such as organic matter and nutrient cycling, degradation of organic pollutants, nitrogen biotic fixation, plant-microbe symbiotic nutrient uptake, plant growth promotion and plant protection, maintenance of soil physical structure and pollination. Perhaps the most important potential impacts of climate change on soil relate to below-surface biodiversity, which ranges from bacteria, fungi, microbes, microscopic invertebrates to larger invertebrates such as ants, earthworms and termites. Because the majority of soil and sediment biodiversity is hidden beneath the surface, this species richness remains mostly unknown, poorly mapped, and rarely considered in models of climate change or adaptation plans (Behan-Pelletier and Newton, 1999; Paustian *et al.*, 2000; Wolters *et al.*, 2000). Yet, the biological diversity of soils is estimated to be greater than that in above-ground systems (Wall and Virginia, 2000). This vast biodiversity is critical to the well-being of all life, both below and above the surface: it provides ecosystem services such as filtering of air and water, control of erosion, regulation of the global cycles of nutrients, carbon, nitrogen, and phosphorus (Brussard *et al.*, 1997), waste recycling through decomposition, bio-control of plant and human pests, and soil fertility.

The SCOPE Committee on Soil and Sediment Biodiversity and Ecosystem Functioning recently synthesized knowledge on below-ground species diversity and ecosystem functioning in a series of international workshops (Behan-Pelletier and Newton, 1999; Brussaard *et al.*, 1997, 2007; Hooper *et al.*, 2000; Wolters *et al.*, 2000). Most of the stages involved in soil ecosystem processes are performed by groups of species from many phyla, resulting in high species redundancy (different species performing same ecosystem process). Some critical processes are performed by a few 'keystone' taxa (e.g. mostly larger invertebrates such as termites, earthworms, enchytraeids).

Soils contain a large amount of carbon, and CO_2 release to the atmosphere depends to a large degree on the activities of soil biota. Soil biota regulate the decay process or decomposition, which directly affects carbon level in soils. Climate-induced loss of key invertebrates in a variety of low-diversity ecosystems that are widespread throughout the world can contribute to significant changes in carbon cycle and hence carbon pools and fluxes through the modification of ecosystem functioning (Ayres *et al.*, 2008; Barrett *et al.*, 2008; Poage *et al.*, 2008).

Our understanding of the soil species involved in decomposition and whether individual soil species have an effect on ecosystem processes is limited. For example, the relationship between the number of species of any soil group and an ecosystem process, such as the rate of decomposition, has not been established in field studies. Thus when soils are degraded, knowledge of the effects on their biological diversity and ecosystem services is largely missing.

Climate change can affect soil biodiversity directly, by altering the soil temperature and moisture, and indirectly, altering vegetation communities and productivity, and the rate of organic matter decomposition. Not all soil biota, however, will be affected by climate change to the same extent; according to Wall and collaborators (2001), termites and enchytraeids will be the most affected. Effects of warming may be larger in ecosystems that are currently limited by temperature, such as the arctic tundra and semi-polar deserts (Swift *et al.*, 1998; Convey *et al.*, 2002), and mountain areas. In research carried out in the Swedish Lapland using the environmental manipulation approach, it has been demonstrated that a temperature rise results in an increase in bacteria, fungi and nematode density, but a reduction of biodiversity (Ruess *et al.*, 1999).

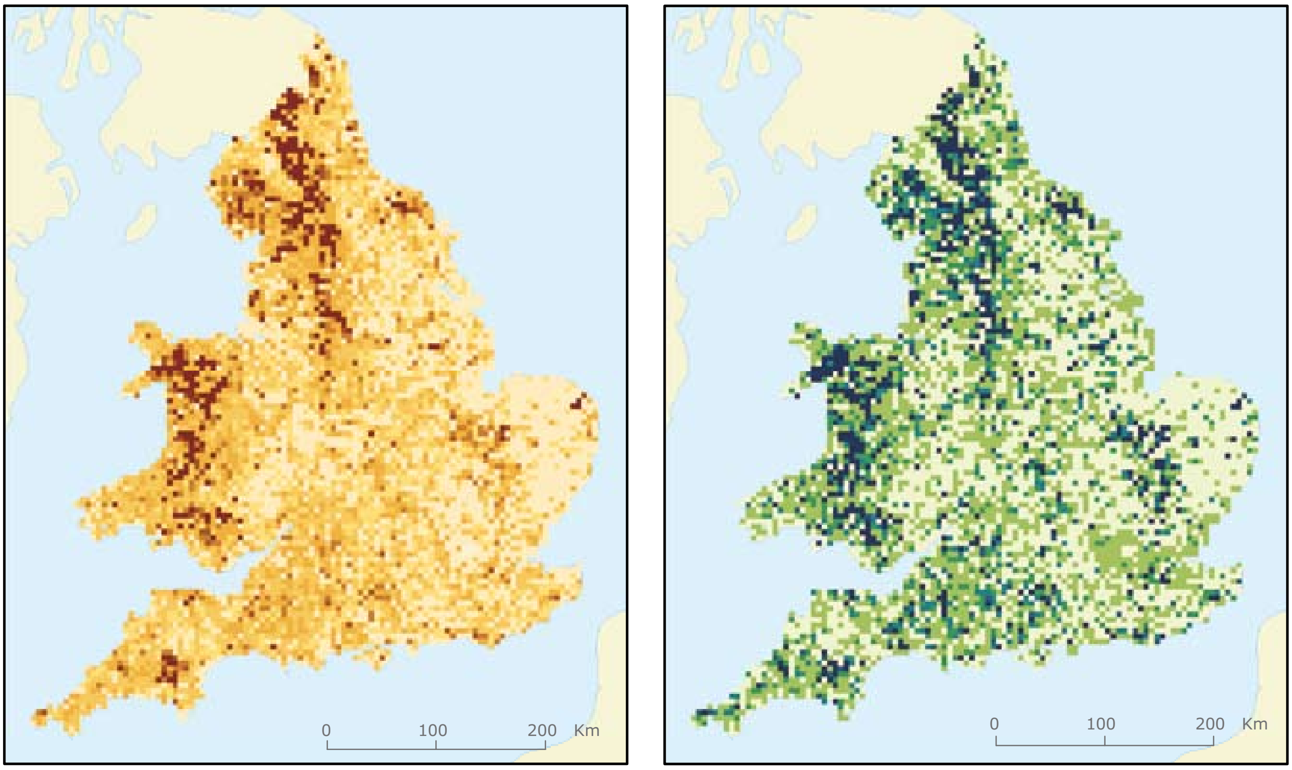
The interrelation between soil fauna and vegetation, for example forests, is critical (Binkley and Cristian, 1998; Gonzalez and Seastedt, 2001; Hooper *et al.*, 2000). The Global Litter Invertebrate Decomposition Experiment (http://www.nrel.colostate.edu/projects/glide/) shows that the soil litter and organisms found under different tree species are highly specific. The loss of tree species due to climate change might cause the loss of the associated soil biodiversity. These ecosystem transformations can affect the capacity of the soil to store carbon. Once soil biodiversity and the species and services it provides are lost or damaged, remediation and restoration takes an extremely long time and in some instances the loss of some species is irreversible.

5.8.2 *Soil organic carbon*

Key messages

- Soil in the EU contains around 71 gigatonnes of organic carbon, nearly 10 % of the carbon accumulated in the atmosphere. An increase in temperature and a reduction in moisture tend to accelerate the decomposition of organic material, leading to a decline in soil organic carbon stocks in Europe and an increase in CO_2 emissions to the atmosphere. This could wipe out all the savings that other sectors of the economy are achieving to reduce anthropogenic greenhouse gas emissions.
- Losses of soil organic carbon have already been observed in measurements in various European regions over the past 25 years.
- The projected changes in the climate during the 21st century will change the contribution of soil to the CO_2 cycle in most areas of the EU. Adapted land-use and management practices could be implemented to counterbalance the climate-induced decline of carbon levels in soil.

Map 5.35 Changes in soil organic carbon content across England and Wales between 1978 and 2003



Change in soil organic carbon contents across England and Wales between 1978 and 2003

Left: carbon contents in the original samplings (1978–1983)

Original C_{org} (g/kg)

< 20 | 20–30 | 30–50 | 50–100 | 100–200 | 200–300 | > 300

Right: rates of change calculated from the change over the different sampling intervals (1994–2003)

Rate of change (g/kg/yr)

< −2.0 | −2.0 to −1.5 | −1.5 to −1.0 | −1.0 to −0.5 | −0.5 to 0.0 | > 0.0

Source: Bellamy *et al.*, 2005.

Relevance

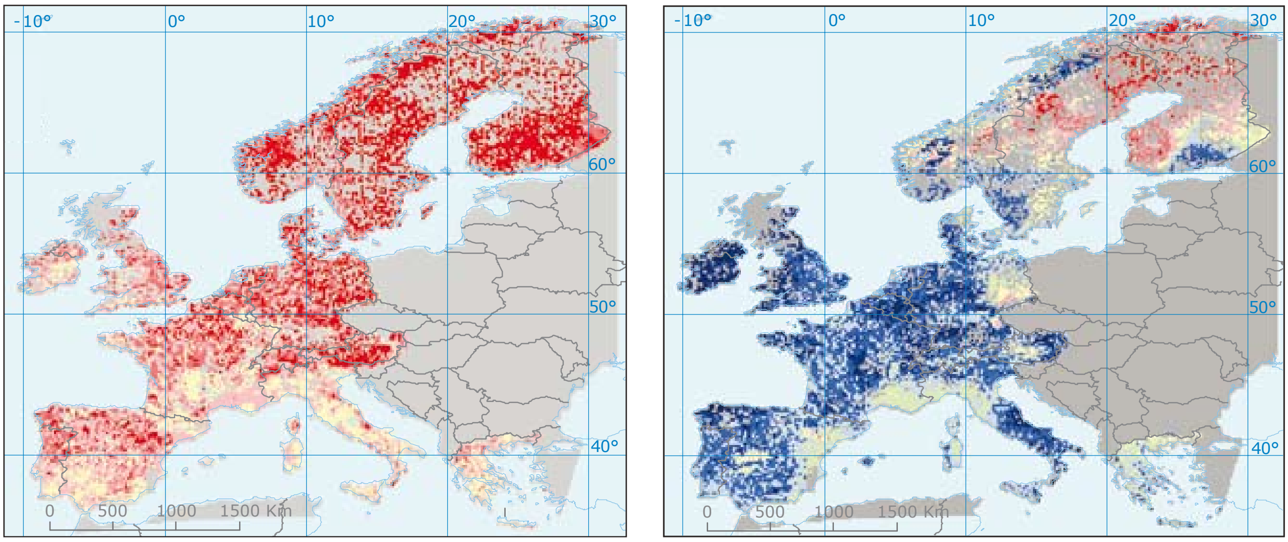
Organic carbon in the soil is a dynamic part of the carbon cycle, which includes the atmosphere, water and constituents of the above- and below-ground biosphere. The main source of organic carbon is organisms that synthesise their food from inorganic substances (autotrophic), such as photosynthesising plants. In this process atmospheric carbon is used to build organic materials and enters the soil layers through decomposition and the formation of humus.

Climatic conditions strongly influence both the trends and rates of accumulation and transformation of organic substances in the soil. Increases in temperature and aridity (see Box 5.11) lead to a decrease in the amount of organic carbon in soils in affected areas. Lower levels of organic carbon in the soil are generally detrimental to soil fertility and water retention capacity and tend to increase soil compaction, which leads to increases in surface water run-off and erosion. Other effects of lower organic carbon levels are a depletion of biodiversity and an increased susceptibility to acid or alkaline conditions. The projected changes will accelerate the release of CO_2 from the soil, contributing to higher concentrations in the atmosphere (Janssens, 2004; Bellamy, 2005). The main measures to reduce the detrimental effect of higher temperatures combined with lower soil moisture on the amount of soil organic carbon are changes in land cover and adaptation of land-management practices (Liski *et al.*, 2002; Janssens *et al.*, 2004; Smith *et al.*, 2005, 2006). Under given climatic conditions, grassland and forests tend to have higher stocks of organic carbon than arable land and are seen as net sinks for carbon (Vleeshouwers and Verhagen, 2002). Land-management practices aim at increasing net primary production and reducing losses of above-ground biomass from decomposition. Adaptive measures on agricultural land are changes in farming practices, such as a reduction in tilling or retaining crop residues after harvesting.

Past trends

In the past, losses in organic carbon in the soil were driven mainly by conversion of land for the production of agricultural crops. A survey

Map 5.36 Projected changes in soil organic carbon for cropland 1990–2080



Projected changes in soil organic carbon for cropland 1990–2080

Left: climate change only; right: including changes in net primary production (NPP) and technology

t C/ha

> 20 | 15 | 10 | 5 | 2 | 0 | – 2 | – 5 | – 10 | – 15

Source: Smith *et al.*, 2005.

of Belgian croplands (210 000 soil samples taken between 1989 and 1999) indicates a mean annual loss in organic carbon of 76 gCm^{-2} (Sleutel *et al.*, 2003). A large-scale inventory in Austria estimated that croplands were losing 24 gCm^{-2} annually (Dersch and Boehm, 1997). The general intensification of farming in the past is likely to have exceeded the effect of changes in the climate on soil organic carbon on agricultural land. Peat lands in Europe have been a significant sink for atmospheric CO_2 since the last glacial maximum. Currently they are estimated to hold about 42 Gt carbon, about 60 % of all carbon stocked in European soils, and are therefore a considerable component of the European carbon budget (Byrne *et al.*, 2004). The annual loss of carbon due to drainage of peat lands is in the range of 0 to 47 gCm^{-2} (Lappalainen, 1996).

Projections

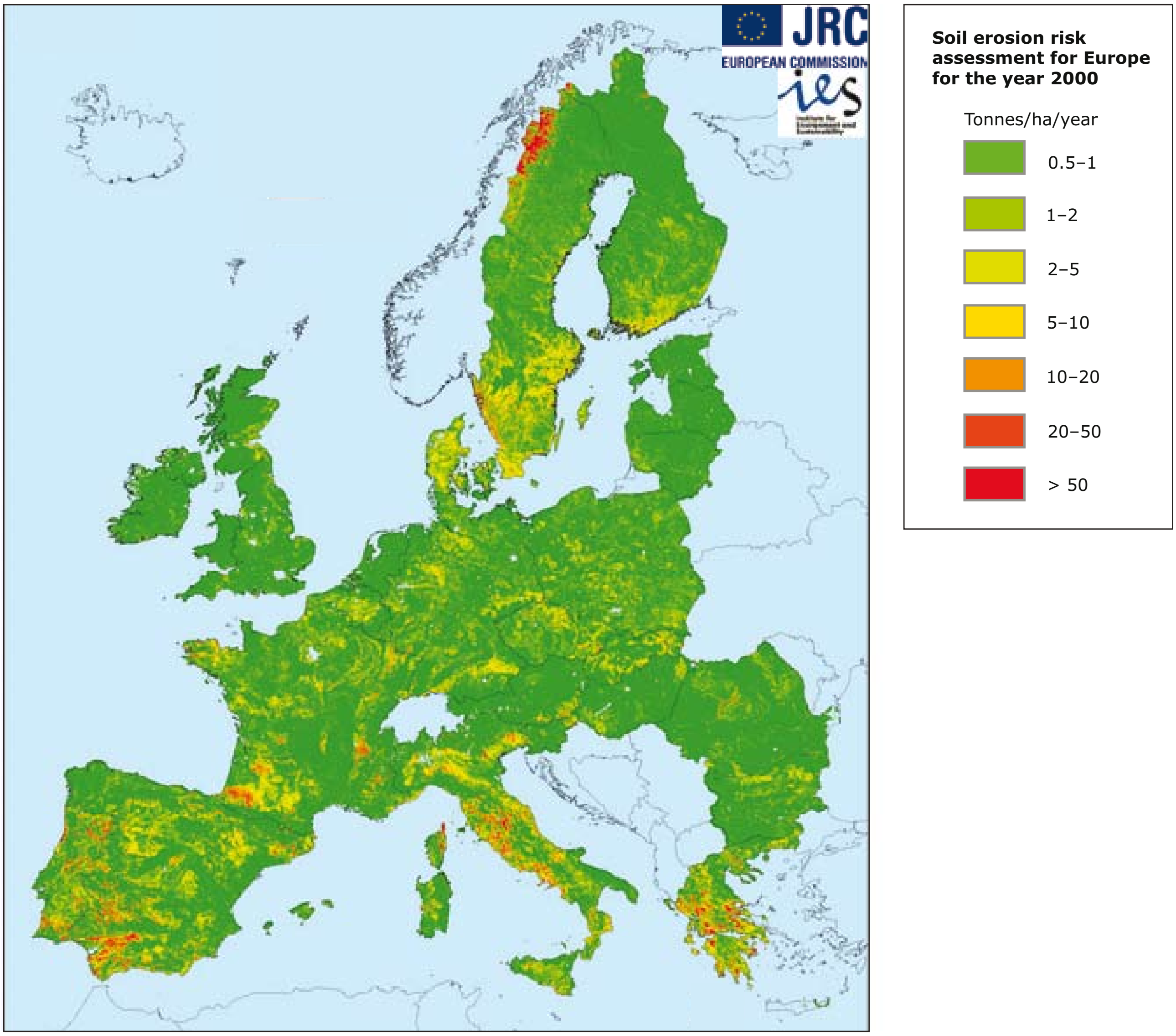
The amount of organic carbon in the soil is determined mainly by the balance between net primary production (NPP) from vegetation and the rate of decomposition of the organic material. Without an increase in NPP, soil carbon for cropland may decrease by 9 to 12 t C ha^{-1}. When taking account of changes in NPP and technological advances, the amount of organic carbon on cropland could increase by 1–7 t C ha^{-1} (Smith, *et al.*, 2005). Map 5.36 shows that climate change may cause loss (red) of soil organic carbon for most areas in Europe. This decline could be reversed (blue) if adaptation measures in the agricultural sector to enhance soil carbon were implemented. It should be noted that these modelled projected changes are very uncertain.

5.8.3 *Soil erosion by water*

Key messages

- An estimated 115 million hectares, 12 % of the total EU land area, are subject to water erosion.
- The projected changes in the climate during the 21st century, with increased variations in rainfall pattern and intensity, will make soils more susceptible to erosion.
- The off-site effects of soil erosion will increase with climate change and related changes in rainfall pattern and intensity.

Map 5.27 Soil erosion risk assessment for Europe for the year 2000



Note: Results obtained with application of two models (PESERA and RUSLE, JRC). Areas with yellow and red shades are highly vulnerable to soil erosion by water.

Source: Joint Research Centre (JRC), INRA (France), (http://eusoils.jrc.it/ESDB_Archive/serae/Serae_data.html).

Relevance

Climate change will influence soil erosion processes. Excess water due to intense or prolonged precipitation can cause tremendous damage to soil. Sheet-wash, rill and gully development can strip the topsoil from the land, thus effectively destroying the capability of the soil to provide economic or environmental services. Favis-Mortlock and Boardman (1995), using the Erosion Productivity Impact Calculator (EPIC) model (Williams and Sharpley, 1989), found that a 7 % increase in precipitation could lead to a 26 % increase in erosion in the United Kingdom. In high mountain regions like the Alps, decreasing permafrost (observed and projected) can lead, for example, to more landslides with substantial impact on infrastructure (roads, railways, cable cars) and economic sectors like tourism (see Section 5.3).

Many of the soil erosion risk models contain a rainfall erosivity factor and a soil erodibility factor that reflect average-year precipitation conditions. However, currently available values for the rainfall erosivity and soil erodibility factors may inadequately represent low-probability return-period storms and the more frequent and intense storms under projected climate change.

The relationship between climate change and soil erosion is complex and needs to be better defined, investigated and monitored in order to have a clear picture of future trends. Measurements and models with more detailed temporal and spatial distribution of precipitation and impacts on soil erosion or risk of erosion should be developed, as should indicators for assessing appropriate measures.

Past trends

Past trends for erosion are not available on the European scale. Based on EU-wide modelling, an estimated 115 million hectares or 12 % of the total EU land area is (in 2000) subject to water erosion (see Map 5.37). In this assessment the risk of erosion by water was calculated by using yearly average values for precipitation. However such risks are in fact to a large extent determined by extreme precipitation events (e.g. daily, hourly). The uncertainty of this modelled erosion risk is therefore high, especially at the local level.

Projections

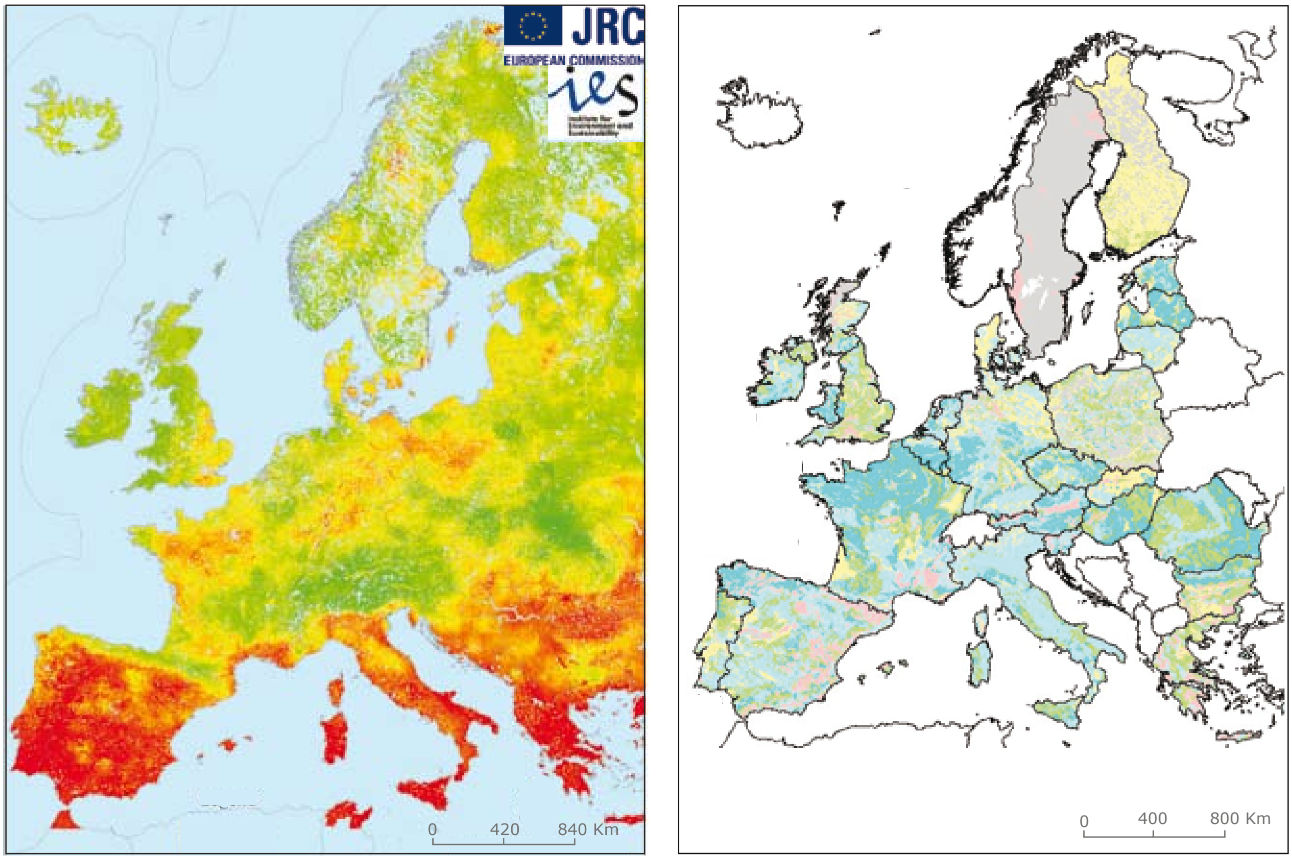
Several studies have been conducted to model the effects of future climate change on soil erosion (e.g. Kirkby *et al.*, 2004). These show a non-linear spatial and temporal response of soil erosion to climate change, with relatively large increases in erosion during wet years compared with dry years, and sporadic increases spatially. Erosion is projected to increase with increases in precipitation amount and intensity, and to decrease with increases in ground cover and canopy cover (IPCC, 2007a).

5.8.4 *Water retention*

Key messages

- Water retention capacity and soil moisture content will be affected by rising temperatures and by a decline in soil organic matter due to both climate change and land-management changes.
- Projections (for 2071–2100) show a general reduction in summer soil moisture over most of Europe, significant reductions in the Mediterranean region, and increases in the north-eastern part of Europe.
- Maintaining water retention capacity is important to reducing the impacts of intense rainfall and droughts, which are projected to become more frequent and severe.

Map 5.38 Modelled soil moisture in Europe



Modelled soil moisture in Europe

Left: modelled daily soil moisture 15 July 2008

Very dry — Very wet

Right: modelled subsoil available water capacity (AWC)

Very low (~ 0 mm/m)
Low (< 100 mm/m)
Medium (100–140 mm/m)
Very high (> 190 mm/m)
No data or not applicable

Note: Left: example of a forecast of topsoil moisture (15 July, 2008), right: subsoil available water capacity derived from modelling data.

Sources: European Soil Data Centre (ESDAC), http://eusoils.jrc.ec.europa.eu/library/esdac/index.html (left); and European Flood Alert System (EFAS) http://efas.jrc.ec.europa.eu/ (right).

Relevance

Soil water retention is a major soil hydraulic property that governs soil functioning in ecosystems and greatly affects soil management. Soil moisture forms a major buffer against flooding, and water capacity in subsoil is a major steering factor for plant growth. The effects of changes in soil water retention depend on the proportions of the textural components and the amount of organic carbon present in the soil. At low carbon contents, an increase in carbon content leads to an increase in water retention in coarse soils and a decrease in fine-textured soils. At high carbon contents, an increase in carbon content results in an increase in water retention for all soil textures (Rawls *et al.*, 2003). Soil organic matter can absorb up to twenty times its weight in water. Changes in temperature result in changes in evapotranspiration, soil moisture, and infiltration. These will also influence groundwater recharge by changing the ratio of surface run-off to infiltration. Projections for climate change indicate greater droughts in some areas, which might lead to substantial reductions in summertime soil moisture, and more rainfall — even too much — in others, and also increases in the off-site impacts of soil erosion. Maintaining or even enhancing the water retention capacity of soils can therefore play a positive role in mitigating the impacts of more extreme rainfall intensity and more frequent and severe droughts. Harmonised time-series on relevant soil properties are not available but should be developed. The development of projections for the soil characteristics presented here (subsoil available water capacity and topsoil moisture), which depend entirely on soil properties, is difficult due to lack of data to validate the models. Further research is needed using satellite information and linking this to representative observed data.

Past trends

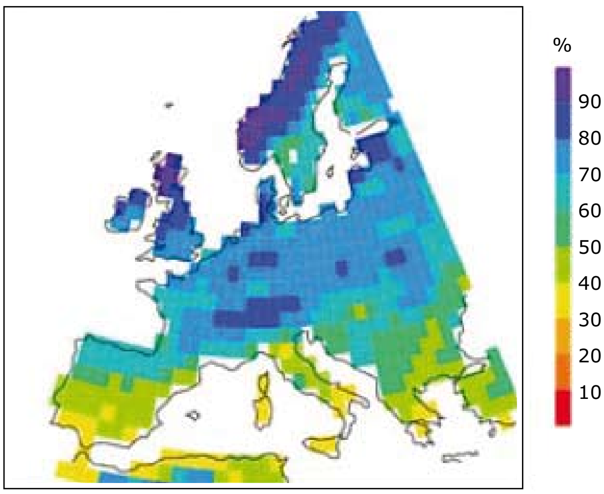
There is no clear indication on past trends for water retention across the EU except for local field data. However several models can be used to assess soil moisture, for both subsoil and topsoil. Map 5.38, right shows the subsoil available water capacity derived from modelling data. Capacity is high in north-western and central Europe and low in parts of the Mediterranean. Forecasts of soil moisture trends (an example for 15 July 2008 is shown in Map 5.38, left) show very wet topsoils in north-western and central Europe and dry topsoils in the Mediterranean.

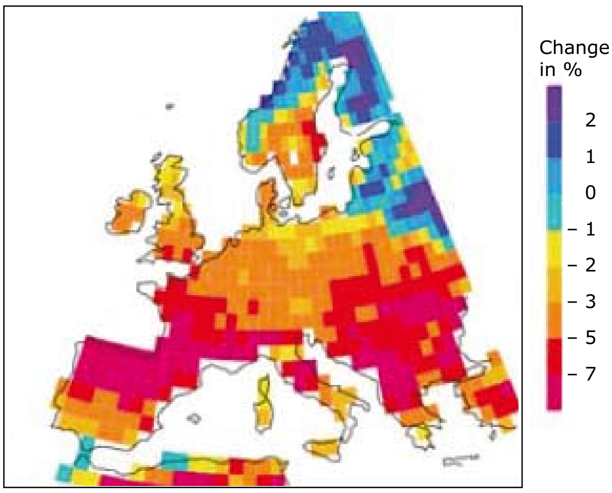
Long-term past trend analysis of these modelled characteristics is not possible due to lack of information over a sufficient time-period for the main soil properties that are the input parameters for the models used.

Projections

Map 5.39 presents summer soil moisture over continental Europe for the IPCC A2 scenario (2071–2100), compared with 1961–1990. The projections show a general reduction in summer soil moisture over most of Europe and significant reductions in the Mediterranean region, while the north-eastern part of Europe will experience an increase in summer soil moisture.

Map 5.39 Modelled summer soil moisture (1961–1990) and projected changes (2071–2100) over Europe





Note: Simulated soil moisture by ECHAM5/T106L31 for the baseline period (1961–1990) (left) and relative changes in % under the IPCC A2 scenario (2071–2100) (right).

Source: Calanca *et al.*, 2006.

Box 5.11 Soil degradation and loss under desertification

Key messages

- Soil degradation is already intense in parts of the Mediterranean and central-eastern Europe. Soil degradation, together with prolonged drought periods and increased numbers of fires, leading to marginalisation and even land abandonment, is already contributing to an increased risk of desertification.
- The risk of desertification is expected to be the highest in areas with projected decreases in precipitation, increases in the frequency of summer droughts and the incidence of forest fires, and intensive land-use.
- In many cases, desertification is irreversible, leading to adverse social, economic and environmental effects.

Soil, under desertification processes (an advanced stage of land degradation), loses part of its capability to support human communities and ecosystems. Quantitative information on the causal factors is scarce and the most common approach to assessing the sensitivity of soil to desertification and drought is to use models (EC, 2004).

Climatic conditions make the Mediterranean region one of the areas most severely affected by land degradation. Much of the region is semi-arid and subject to seasonal droughts, high rainfall variability and sudden intense precipitation. Some areas, especially along the northwest coasts of the Black Sea, are classified as semi-arid. The level of soil degradation is severe in most of the region, and very severe in some parts, for example along the Adriatic, where soil cover has almost disappeared in some areas (UNCCD, 2008; EEA, 2007). 12 of the 27 European Union Member States declared themselves as affected countries under the 1992 United Nation Convention on Combating Desertification (UNCCD): in the Mediterranean: Cyprus, Greece, Italy, Malta, Portugal, Slovenia and Spain and in central and eastern Europe: Hungary, Latvia, Slovak Republic, Bulgaria and Romania.

In addition, other physical factors, such as steep slopes and the frequency of soil types susceptible to degradation, increase the vulnerability. These factors, coupled with changes in land use, the cessation of soil erosion protection measures due to the abandonment of marginal land, and increases in the frequency and extension of forest fires, have had a strong impact on soil vulnerability. Individual storms in the region have been known to remove 100 tonnes of soil from a hectare of land, and frequently remove 20 to 40 tonnes. In the most extreme cases, soil degradation has led to desertification (EEA, 2005).

Soil loss, in turn, reduces the regeneration potential of the ecosystems. The areas most sensitive to this are those with shallow soils, steep slopes and slow rates of recovery of the vegetative cover. For example, burned forests in dry areas with shallow soils often do not regenerate (WWF, 2007).

Changes in data quality and the methodology of the indicator make the analysis of desertification difficult. Nevertheless, an increase in vulnerability in affected regions has been observed in recent decades (IPCC, 2007b; EEA, 2004ab; EEA, 2005b; national reports of affected country parties to the UNCCD (*), ECCE, 2005).

The Mediterranean lies in a transition zone between the arid climate of northern Africa and the temperate and wet climate of central Europe. Even minor shifts in large-scale climatic factors could result in relatively large impacts on the climatic regime of Mediterranean areas. Summer warming and drying are expected to result in an increase in arid and semi-arid climates throughout the region. Furthermore, due to the complex topography and coastlines of the region, shifts in climates could lead to quite different effects at local scales (Gao *et al.*, 2006).

In these sensitive areas, therefore, vulnerabilities are likely to increase due to projected climate change. The projected decrease in summer precipitation in southern Europe, the increase in the frequency of summer droughts and the increased incidence of forest fires will probably induce greater risks of soil erosion (IPCC, 2007a). In sensitive areas, climate change is likely to increase the regional differences in terms of quality and availability of natural resources and ecosystems, and to pose challenges to the main economic sectors (such as agriculture and tourism) (IPCC, 2007b; ECCE, 2005). In currently affected areas, desertification is likely to become irreversible if the environment becomes drier; the pressure from human activities will increase and the soil will be further degraded.

(*) National reports are available through the UNCCD website at: http://www.unccd.int.

5.9 Agriculture and forestry

5.9.1 Introduction

The impacts of medium and long-term climate change on agriculture and forestry are often difficult to analyse separately from non-climate influences related to the management of the resources (Hafner, 2003). However, there is growing evidence that processes such as changes in phenology, length of growing season and northwards shift of crops and forest species can be related to climate change (IPCC, 2007a). There are also increasing impacts due to an increased frequency of some extreme events which can be attributed to climate change.

Potential positive impacts of climate change on agriculture in general are related to longer growing seasons and new cropping opportunities in northern Europe, and increased photosynthesis and CO_2 fertilisation throughout Europe. These possible benefits are counterbalanced by potentially negative impacts that include increased water demand and periods of water deficit, increased pesticide requirements and crop damage, and fewer cropping opportunities in some regions in southern Europe (Olesen and Bindi, 2004; Maracchi *et al.*, 2005; Chmielewski *et al.*, 2004; Menzel *et al.*, 2003). In general, changes in atmospheric CO_2 levels and increases in temperature are changing the quality and composition of crops and grasslands and also the range of native/alien pests and diseases. These may affect livestock and ultimately humans as well as crops. In addition, the increase in ozone concentrations related to climate change (Meleux *et al.*, 2007) is projected to have significant negative impacts on agriculture, mainly in northern mid-latitudes (Reilly *et al.*, 2007).

The link of forestry with climate change is twofold. Forests play a fundamental role in mitigating climate change because they act as sinks for carbon dioxide. However, they are also very vulnerable to changes in temperature, precipitation and extreme weather events which can have destructive impacts and reduce the carbon sequestration potential of the forest. Events such as forest fires have an even more negative effect since destroying the forest increases the amount of carbon dioxide in the atmosphere. The majority of forests in central Europe are growing faster than in the past, partly because of regional warming. In contrast, the extended heat-wave of 2003 caused a significant reduction in biomass production of forests (Gabron, 2005).

Although the economic impacts of climate change on agriculture and forestry in Europe are very difficult to determine because of the effects of policies and market influences and continuous technological development in farming and silviculture techniques, there is evidence of wider vulnerability for both sectors (see also Chapter 6). Management actions can counteract but may also exacerbate the effects of climate change and will play an important role in measures for adaptation to climate change (AEA, 2007).

The indicators included in this section are related to agricultural production, phenology, forestry growth and distribution, and the observed and projected impacts of forest fires.

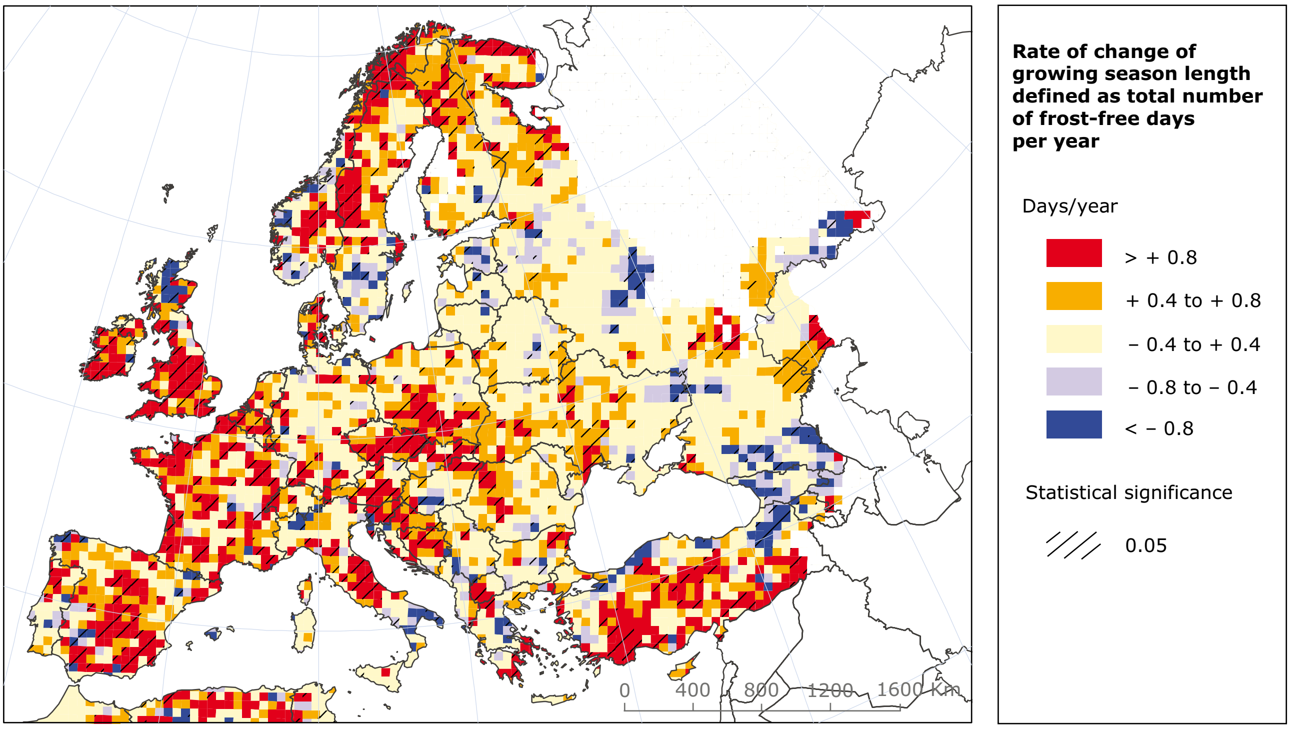
Good data availability and quality are essential for monitoring trends and threats relating to European forests and agricultural products. The International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP-Forest), originally set up to monitor the effects of air pollution, now includes surveys that could also be used to monitor the effects of climate change (e.g. phenology). Another clear step forward in the collection of relevant information is being achieved by the establishment of the European Data Centres on Soil and Forestry.

5.9.2 *Growing season for agricultural crops*

Key messages

- There is evidence that the length of the growing season of several agricultural crops in Europe has changed.
- A longer growing season increases crop yields and insect populations and favours the introduction of new species in areas that were not previously suitable for these species. These observed facts are particularly important for the northern latitudes.
- Locally at southern latitudes, the trend is towards a shortening of the growing season, with consequent higher risk of frost damage from delayed spring frosts.

Map 5.40 Rate of change of crop growing season length 1975–2007



Note: The rate of change (number of days per year) of the duration of the growing season (defined as total number of frost-free days per year) as actually recorded during the period 1975–2007.

Source: MARS/STAT database (Genovese, 2004a, 2004b).

Relevance

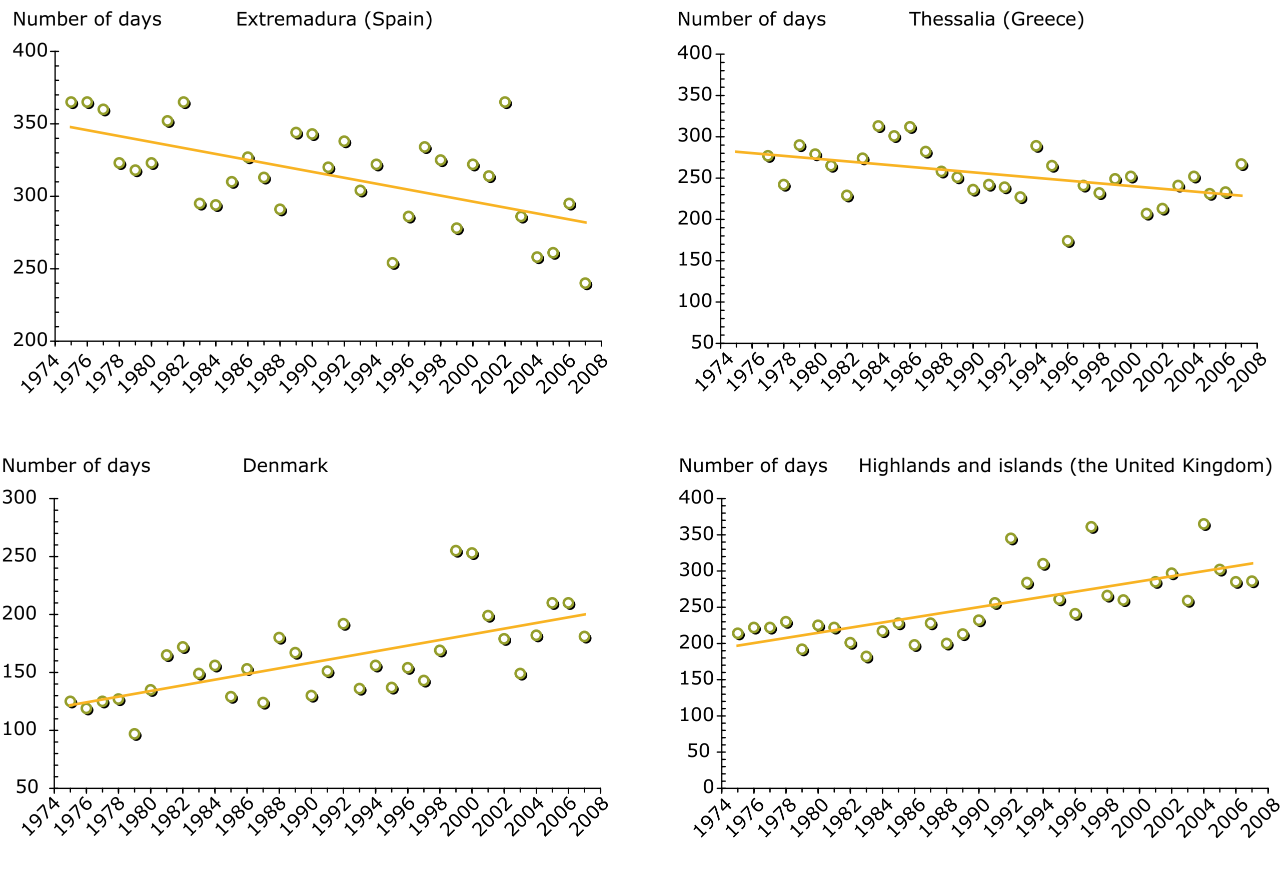
Increasing air temperatures are significantly affecting the duration of the growing season over large areas of Europe (Scheifinger *et al.*, 2003). The number of consecutive days with temperatures above 0 °C can be assumed to be the period favourable for growth. The timing and length of this frost-free period is of interest to naturalists, farmers and gardeners among others. The impact on plants and animals is reported mainly as a clear trend towards an earlier start of growth in spring and its prolongation into autumn (Menzel and Fabian, 1999). A longer growing season allows the proliferation of species that have optimal conditions for development and an increase in their productivity (e.g. crop yields, insect population), and the introduction of new species (very sensitive to frost) in areas previously limited by unfavourable thermal conditions. Changes in management practices, e.g. changes in the species grown, different varieties, or adaptations of the crop calendar, can counteract the negative effects of a changing growing season (pests) and capture the benefits (agricultural crops).

Photo: © European Environment Agency

Past trends

Many studies report a lengthening of the period between the occurrence of the last spring frost and the first autumn frost. This has occurred in recent decades in several areas in Europe and more generally in the northern hemisphere (Keeling *et al.*, 1996; Myneni *et al.*, 1997; Magnuson *et al.*, 2000; McCarthy *et al.*, 2001; Menzel and Estrella, 2001; Tucker *et al.*, 2001; Zhou *et al.*, 2001; Walther *et al.*, 2002; Root *et al.*, 2003; Tait and Zheng, 2003; Yan *et al.*, 2002; Robeson, 2002; Way *et al.*, 1997). An analysis of the growing period in Europe between 1975 and 2007 (Figure 5.36) shows a general and clear increasing trend. The trend is not uniformly spread over Europe. The highest rates of change (about 0.5–0.7 days per year) were recorded in central and southern Spain, central Italy, along the Atlantic shores, and in the British Isles, Denmark and the central part of Europe. The extension of the growing season is either due to a reduction in spring frost events or to a progressive delay in the start of autumn frosts. However, a decline has been observed in the Mediterranean countries, in the Black Sea area and in parts of Russia. In areas where

Figure 5.36 Length of frost-free period in selected European areas 1975–2007



Source: MARS/STAT database (Genovese, 2004a, 2004b).

a decrease in the length of frost-free period occurred, in particular in southern Europe, the plants are more at risk from frost damage due to a delay in the last winter-spring frost.

Projections

Following the observed trends (which have accelerated even more in the past decade) and in line with projections for temperature increase, a further lengthening of the growing season (both an earlier onset of spring and a delay of autumn) as well as a northward shift of species is projected. The latter is already widely reported (Aerts *et al.*, 2006). The length of the growing season will be influenced mainly by the increase in temperatures in autumn and spring (Ainsworth and Long, 2005; Norby *et al.*, 2003; Kimball *et al.*, 2002; Jablonski *et al.*, 2002).

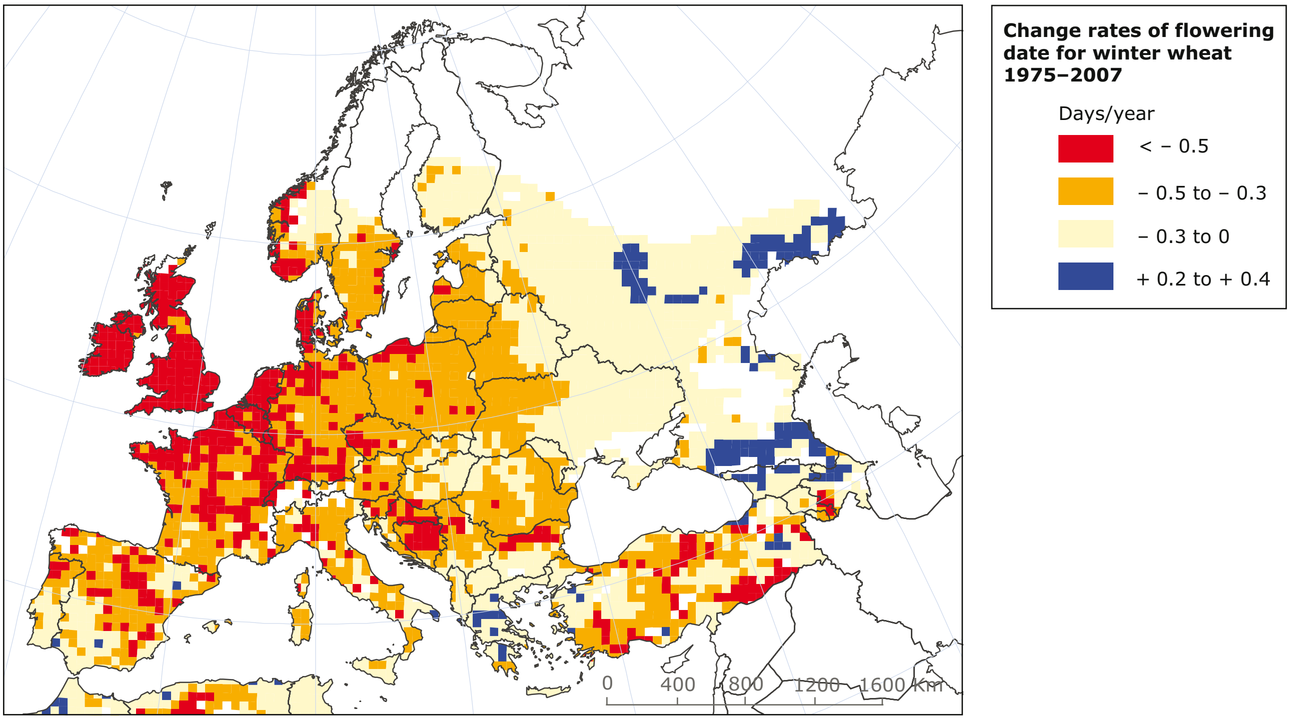
According to the IPCC analysis, Europe will warm in all seasons for all scenarios, but warming will be greater in western and southern Europe in summer and northern and eastern Europe in winter. More lengthening of the growing season is therefore expected in these northern and eastern areas, while in western and southern Europe the limited water availability and high temperatures stress during summer will hinder plant growth.

5.9.3 *Timing of the cycle of agricultural crops (agrophenology)*

Key messages

- There is evidence that the flowering and maturity of several species in Europe now occurs two or three weeks earlier than in the past.
- The shortening of the phenological phases is expected to continue if temperatures continue to increase.
- Adaptations of farm practices will be crucial to reduce or avoid negative impacts of crop-cycle shortening.

Map 5.41 Modelled change of flowering date for winter wheat 1975–2007



Note: The day of the year of flowering has been simulated by using a crop growth model (CGMS — Crop Growth Monitoring System).

Source: MARS/STAT database (Genovese, 2004a, 2004b).

Relevance

Changes in crop phenology provide important evidence of responses to recent regional climate change (IPCC, 2007). Although phenological changes are often influenced by management practices and new farming technologies, recent warming in Europe has clearly advanced a significant part of the agricultural calendar. Specific stages of growth (e.g. flowering, grain filling) are particularly sensitive to weather conditions and critical for final yield. The timing of the crop cycle (agrophenology) determines the productive success of the crop. In general, a longer crop cycle is strongly correlated with higher yields, since a longer cycle permits maximum use of the available thermal energy, solar radiation and water resources. The impacts of unfavourable meteorological conditions and extreme events vary considerably, depending on the timing of occurrence and the development stage of the crops. However, shortening of the growth period can also help avoid summer stress conditions in areas prone to drought. European farmers have already adapted their practices to the changing climate by selecting suitable varieties or adapting the crop calendar, and can be expected to do so increasingly in the future.

Past trends

Several studies have collected data and observed changes in the phenological phases of several perennial crops in Europe, such as the advance in the start of the growing season of fruit trees (2.3 days/10 years), cherry tree blossom (2.0 days/10 years), and apple tree blossom (2.2 days/10 years), in line with increases of up to 1.4 °C in mean annual air temperature in Germany (Chmielewski *et al.*, 2004), and the advance of apricot and peach tree flowering by 1–3 weeks over the past 30 years for in France (Chuine *et al.*, 2004).

Sowing or planting dates of several agricultural crops have been advanced, by 5 days for potatoes in Finland, 10 days for maize and sugar beet in Germany and 20 days for maize in France (IPCC, 2007).

Projections

Assuming that the warming trend will continue, further reductions in the number of days required for flower opening (anthesis) and maturity may be expected for areas in western Europe, where phenological changes are strongly accelerating (ECCE, 2005). However, the rate of the reduction of these phases may gradually decrease with a further increase in temperature due to a reduced efficiency of photosynthesis at high temperatures.

Box 5.12 Grapevine phenology

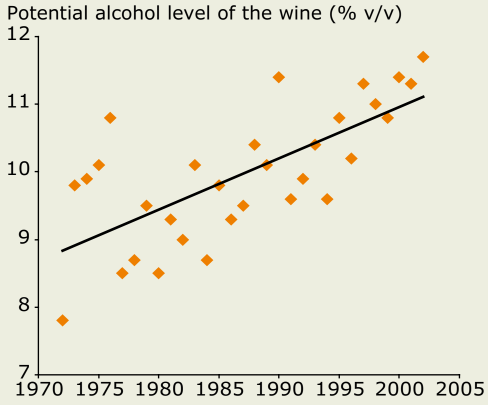
Wine quality is determined by various parameters: grape variety, rootstock, soil type, cultivation techniques, and climatic characteristics. The first three are generally constant over time, while cultivation techniques are most often responsible for long-term variability. Climate influences year-to-year variability and is responsible for variations in the amount and quality of wines.

Wine production areas, and particularly those for premium wines, are limited to regions climatically conducive to growing grapes with balanced composition and degree to which they reflect their origin ('varietal typicity'). Three conditions are required: (i) adequate heat accumulation; (ii) low risk of severe frost damage; and (iii) the absence of extreme heat. Moreover, vines are resistant to limited water availability in summer and it is essential to have no rainfall during harvest time, in order to increase sugar concentration and reduce disease development.

Observed climate change during recent years has resulted in a general increase in wine quality, due mainly to the increase in temperature and reduction of rainfall, particularly during the last part of the ripening period, with a gradual increase in potential alcohol levels (Duchêne and Schneider, 2005). Future possible impacts are:

- seasonal shift: a move forward in time of all the phenological phases with an increase of frost risk and a shortening of the ripening period. As a possible effect, the harvest time may occur during periods of high temperatures, with negative effect on wine quality;
- expansion of wine production areas, to north and more elevated regions;
- water stress due to a reduction of available water;
- modification of pest and disease development;
- increase of sugar concentration resulting in wine with high alcohol and low acidity. The consequence is a reduced possibility of wine ageing and poorer phenolic ripening;
- modification of natural yeast composition.

Figure 5.37 Potential alcohol level at harvest for Riesling in Alsace (France) 1972–2003



Note: Reprinted with permission from Duchêne and Schneider, Grapevine and climatic changes: a glance at the situation in Alsace. Agron. Sustain. Dev. 25 (2005) 93–99. Copyright: 2005 INRA, EDP Sciences. Permission has been kindly given by Dr. Eric Lichtfouse, Editor-in-Chief of Agronomy for Sustainable Development. http://www.agronomy-journal.org.

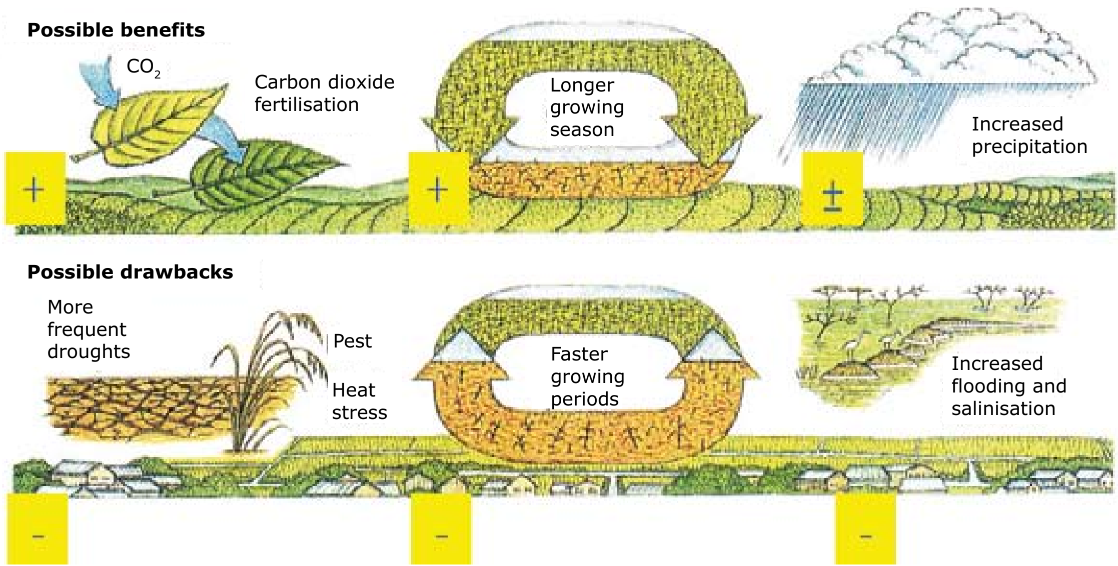
Source: Duchêne and Schneider, 2005.

5.9.4 *Crop-yield variability*

Key messages

- Climate and its variability are largely responsible for variations in crop suitability and productivity in Europe.
- Since the beginning of the 21st century, the variability of crop yields has increased as a consequence of extreme climatic events, e.g. the summer heat of 2003 and the spring drought of 2007.
- As a consequence of climatic change, such events are projected to increase in frequency and magnitude, and crop yields to become more variable. Changes in farming practices and land management can act as risk-mitigating measures.

Figure 5.38 Agro-ecosystem processes and a changing climate



Note: A changing climate will affect agro-ecosystems in various ways, with either benefits or negative consequences dominating in different agricultural regions. Rising atmospheric CO_2 concentration, higher temperatures, changing patterns of precipitation, and changing frequencies of extreme events will have significant effects on crop production, with associated consequences for water resources and pest/disease distributions.

Source: Bongaarts, 1994.

Relevance

Climate change introduces new uncertainties for the future of the agricultural sector. Climatic conditions are projected to become more erratic with an increase in the frequency of extreme events (floods, hurricanes, heat waves, severe droughts) (Parry, 2000). Biomass production of plants, and thus crop yields, are fundamentally determined by climatic conditions, i.e. the stable availability of energy (radiation, temperature) and water (rain) to support growth. Other environmental and anthropogenic factors, such as soil fertility, crop varieties and farming practices, also influence crop yields. These factors imply that, in principle, many adaptation options are available to adjust agricultural practices to the changing climate, but that opportunities differ between regions.

Past trends

While the area under arable cultivation in most of western Europe has decreased over the past 40 years, crop yields have increased almost continuously (Eurostat). This trend has persisted into the 21st century, although crop-yield variability

Photo: © Pawel Kazmierczyk

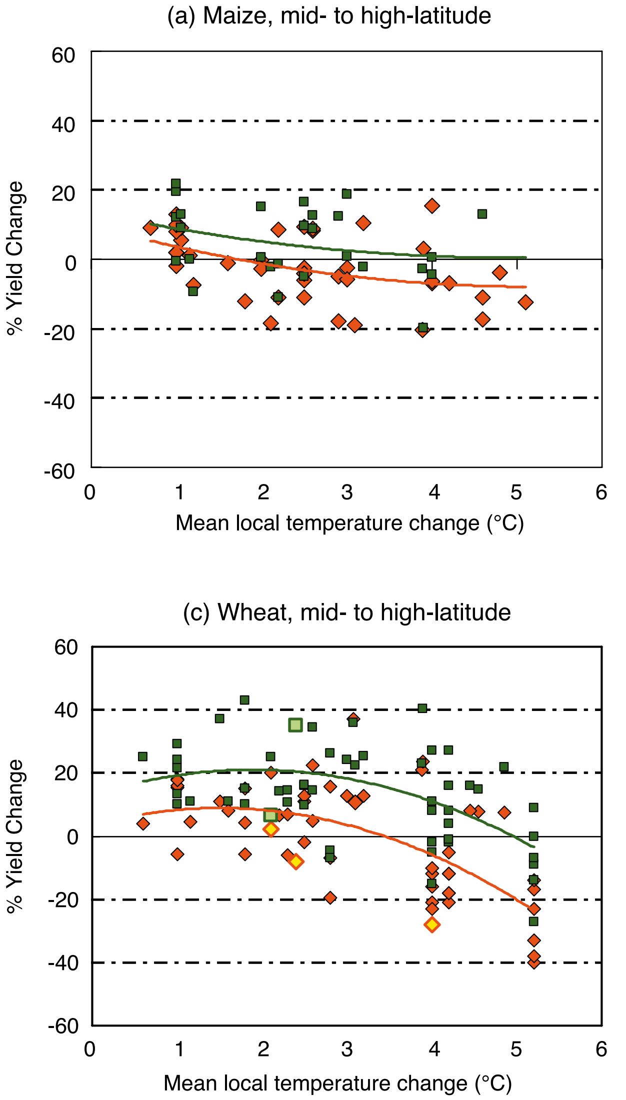
increased as a consequence of several extreme meteorological events in short succession: a late frost in 2003 followed by a severe drought reduced cereal yields over most of Europe, a drought in 2005 severely affected western Europe (Iberian Peninsula), and an early drought in 2006 was followed by extreme rains during the summer, resulting in lower cereal production, especially in eastern Europe (EC, MARS Bulletins, 2008). Alexander *et al.* (2006) found a general increase in the intensity of precipitation events observed at the global level. For the Mediterranean area, where climate vulnerability is high, several studies found an increasing trend towards more intense precipitation and a decrease in total precipitation (Alpert *et al.*, 2002; Maheras *et al.*, 2004; Brunetti *et al.*, 2004). In general, it is difficult to separate the climate effects from those of improved agricultural techniques in the development of historic crop yields. Adaptive management is expected to continue to help reduce the risks to agricultural yields from climate change, and to make better use of opportunities.

Projections

The effects on agricultural yields of increasing mean daily temperatures depend on their magnitude and geographic extent. The production areas of some crops could expand northwards in Europe, e.g. for maize. With an increase in mean annual temperature of 2 °C, cereal yields are expected to increase, partly because of the fertilisation effect of the increase in CO_2 (Parry *et al.*, 2004). However, an increase of 4 °C or more will shorten the crop cycle and the CO_2 effect will not compensate for the resulting loss of yield. Crop yields are also at risk from more intensive precipitation and prolonged periods of drought, particularly in areas bordering the Mediterranean basin.

Figure 5.39 shows the sensitivity of maize and wheat yields to climate change, as derived from the results of 69 published studies. These span a range of precipitation changes and CO_2 concentrations, and vary in how they represent future changes in climate variability. Responses include cases without adaptation (red dots) and with adaptation (dark green dots). Adaptation represented in these studies includes changes in planting dates and crop varieties, and shifts from rain-fed to irrigated conditions.

Figure 5.39 Sensitivity of cereal yields to climate change for maize and wheat



Note: A small increase in temperature has a positive impact on cereals yield, while a high increase (3–5 °C) has a negative impact. Lines are best-fit polynomials and are used here to summarise results across studies rather than as a predictive tool.

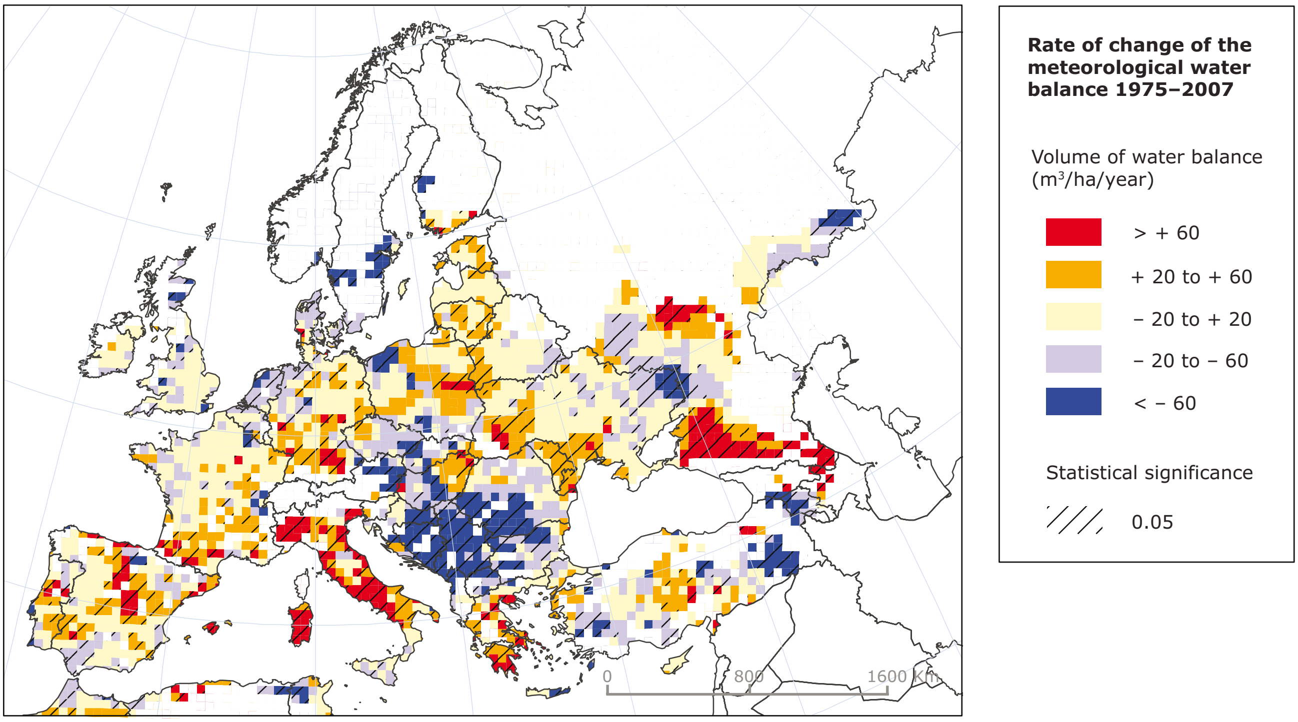
Source: Eastering *et al.*, 2007. Published with permission of the Intergovernmental Panel on Climate Change.

5.9.5 *Water requirement*

Key messages

- Between 1975 and 2006 clear trends, both positive and negative, were evident in water requirement across Europe, with marked spatial variability. A significant increase in water demand (50–70 %) occurred mainly in Mediterranean areas; large decreases were recorded mainly in northern and central European regions.
- Current trends and future scenarios depict an increase in the demand for water in agriculture, potentially increasing competition for water between sectors and uses.

Map 5.42 Rate of change of the meteorological water balance 1975–2007



Note: The rate of change of the 'meteorological water balance', expressed in m^3 ha^{-1} y^{-1} The map provides an estimate of the increase (red in the map) or decrease (blue in the map) of the volume of water required from irrigation in order to ensure that crop growth is not limited by water stress.

Source: MARS/STAT database (Genovese, 2004a, 2004b).

Relevance

Climate change may affect agriculture primarily through increasing atmospheric CO_2, rising temperatures and changing rainfall. Where rainfall does not limit crop growth, these conditions allow for earlier sowing dates and enhanced crop growth and yield (see previous indicators). Where reduced rainfall is predicted, however, the increased requirement for irrigation water can have an overall negative impact in economic and environmental terms. In these areas, increased water shortages are expected to increase competition for water between sectors (tourism, agriculture, energy, etc.), particularly in southern Europe where the agricultural demand for water is greatest. Several adaptation options are available to mitigate the risks of water shortage. Increased irrigation can further burden surface and groundwater resources and increase greenhouse gas emissions, adding to the mitigation challenge.

Past trends

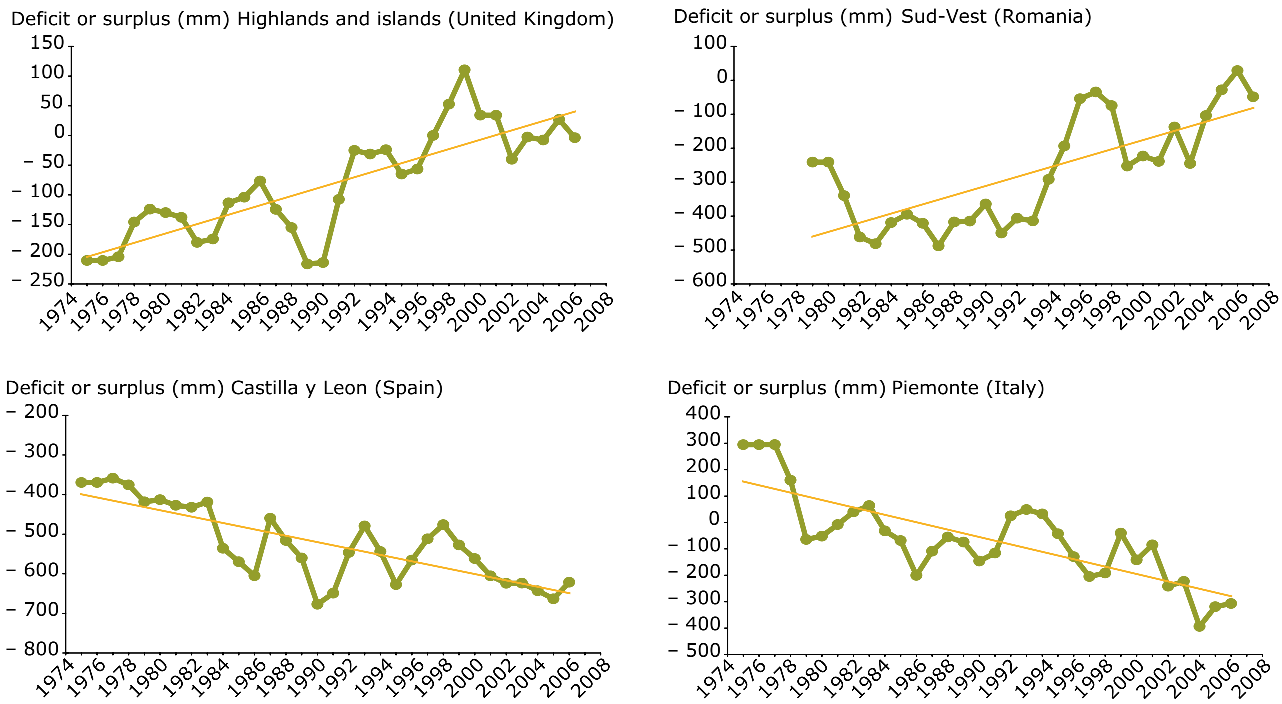
Systematic observations of water demand for agriculture do not exist at the European scale, however local trends can be reconstructed by using meteorological data. On average, the rate of increase in water demand is around 50 m³/ha/year, but in some cases (Italy, Greece, Maghreb, central Spain, southern France and Germany) it is more than 150–200 m³/ha/year. Areas with upward trends in the water balance (due mainly to an increase in rainfall), have been observed in the Balkan Peninsula, the Alpine region, Scandinavia, Scotland, Benelux, the Czech Republic, Slovakia, Poland and Hungary, as well as in many Turkish areas. In the Mediterranean area, a worsening meteorological water deficit (declining water balance) has been observed over the past 32 years.

Projections

No quantitative projections of irrigation demand are available. Many climatic projections for Europe (IPCC, 2007) foresee a very likely precipitation increase in the north and a decrease in the south, especially during the summer. Also the extremes of daily precipitation are projected to increase in the north and the annual number of rainy days to decrease in the Mediterranean (see Section 5.5.4). The risk of summer drought is therefore likely to increase in central Europe and in the Mediterranean area. Agricultural crops will be affected, among other factors, in positive and negative ways by changes in the length and timing of the vegetative cycle. Crop management will have to be adapted in order to try to avoid crucial development stages sensitive to water-stress (flowering, grain filling, etc.) occurring during generally dry periods.

Photo: © Jörg Rechenberg

Figure 5.40 Meteorological water balance in selected parts of Europe 1975–2007



Note: Surplus means positive values of meteorological water balance.

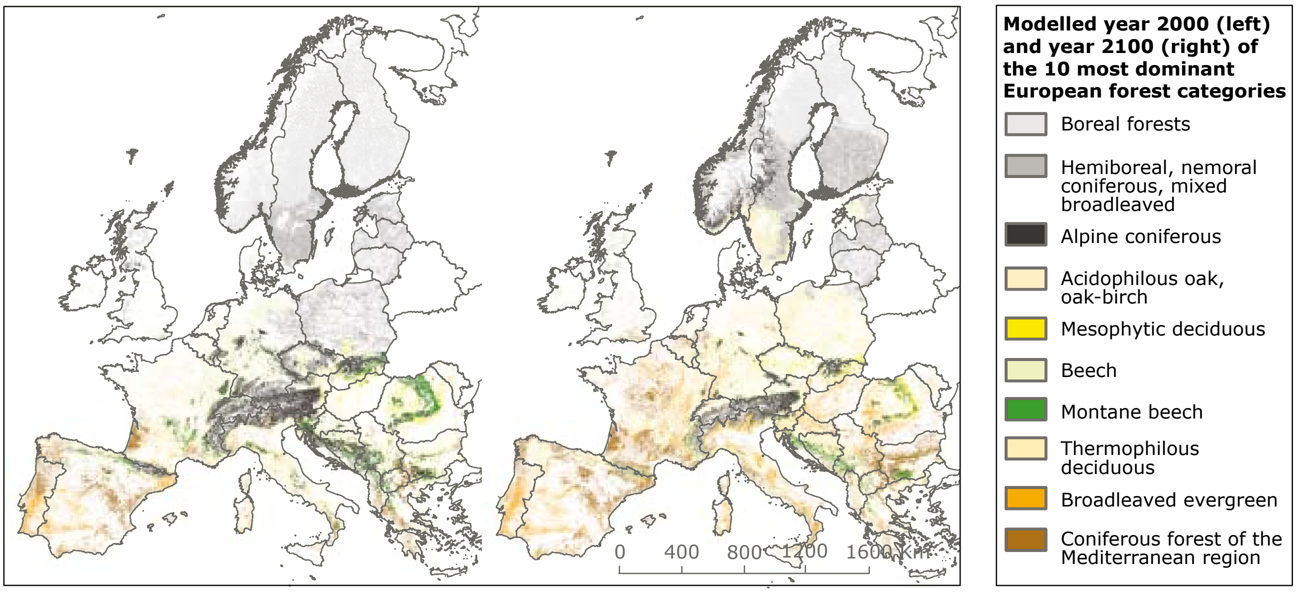
Source: MARS/STAT database (Genovese, 2004a, 2004b).

5.9.6 *Forest growth*

Key messages

- In much of continental Europe, the majority of forests are now growing faster than in the early 20th century.
- A changing climate will favour certain species in some forest locations, while making conditions worse for others, leading to substantial shifts in vegetation distribution.
- The distribution and phenology of other plant and animal species (both pests and pollinators) are likely to change, leading to further alterations in competitive dynamics in forests that will be difficult to predict.
- Periods of drought and warm winters are increasing pest populations and further weakening forests.

Map 5.43 Current (2000) and projected (2100) forest coverage in Europe



Note: Modelled to evaluate the change of habitat suitability coverage of the ten most dominant European Forest Categories (EEA, 2006), used IPCC SRES A1B scenario and NCAR CCM3 model.

Source: Casalegno *et al.,* 2007.

Relevance

Forests contain 77 % of the global carbon pool in vegetation biomass and hence play an important role in the global carbon cycle (Dixon *et al.*, 1994; IPCC, 2007). Forests and woodlands provide many things that society values, including food, marketable products, medicines, biodiversity, carbon reservoirs and opportunities for recreation. In addition, they regulate biogeochemical cycles and contribute to soil and water conservation. Changes in global climate and atmospheric composition are likely to have an impact on most of these goods and services, with significant impacts on socioeconomic systems (Winnett, 1998).

Management has a significant influence on the development of the growing stock and forest productivity. Adaptation measures include changes to plantation practices and forest management, the planting of different species mixtures, better matching of the species to the specific site, planting of similar species from their places of origin and non-native species in anticipation of climate change

(Broadmeadow *et al.*, 2003), and the restoration of forest typologies that could offer greater flexibility to climate change (Kölling, 2008).

Photo: © Pawel Kazmierczyk

Past trends

For many centuries, most European forests were overexploited. Growth rates were reduced and biomass stocks were depleted until the middle of the 20th century, when growth rates started to recover (Spieker *et al.*, 1996). Much of this increase can be attributed to advances in forest management practices, genetic improvement and, in central Europe, the cessation of site-degrading practices such as litter collection for fuel. It is also very likely that increasing temperatures and CO_2 concentrations, nitrogen deposition, and reduction of air pollution (SO_2) have had a positive effect on forest growth. Trees have long been known to respond to changes in climate: variations in tree-ring widths from one year to the next are recognised as an important source of climatic information (see Chapter 2).

Several studies have already noted changes in dates of budburst and therefore longer growing seasons in several species (see Section 5.7.3), shifts in tree-line, and changes in species distribution (see Section 5.7.2). A north-east shift of forest categories has already been observed for European forest species (Bakkenes *et al.*, 2002; Harrison *et al.*, 2006).

Projections

Tree growth is controlled by complex interactions between climate- and non-climate-related factors, with forest management also having a significant effect. Possible future responses of forests to climate change include increased growth rates, tree-line movements, changes to forest growth, phenology, species composition, increased fire incidence (see Section 5.9.7), more severe droughts in some areas, increased storm damage, and increased insect and pathogen damage (Eastaugh, 2008). Taken together this is likely to lead to a changed pattern of forest cover. Simulation of the IPCC SRES A1B scenario for the period 2070–2100 shows a general trend of a south-west to north-east shift in suitable forest category habitat (Casalegno *et al.*, 2007).

Although climate change is projected to have an overall positive effect on growing stocks in northern Europe, negative effects are also projected in some regions (e.g. drought and fire pose an increasing risk to Mediterranean forests), making overall projections difficult.

Figure 5.41 Impacts of climate change on forest growth and forest conditions

Warmer winter weather is likely to increase productivity by extending the length of the growing season (Cannell *et al.*, 1998).

Elevated atmospheric CO_2 concentrations can have a fertilising effect.

Cold and snow-related damage are likely to become less common.

Reduced summer rainfall may reduce tree growth and severe droughts may kill increasing numbers of trees.

Elevated atmospheric ozone concentrations may have a negative impact on growth (Sitch *et al.*, 2007; Karnosky *et al.*, 2005).

Violent storms may occur more often, and more trees are likely to be damaged or blown down.

Possible increase in spring frost damage as trees become more susceptible through earlier leafing.

Damage by forest fires and insect pests is projected to increase.

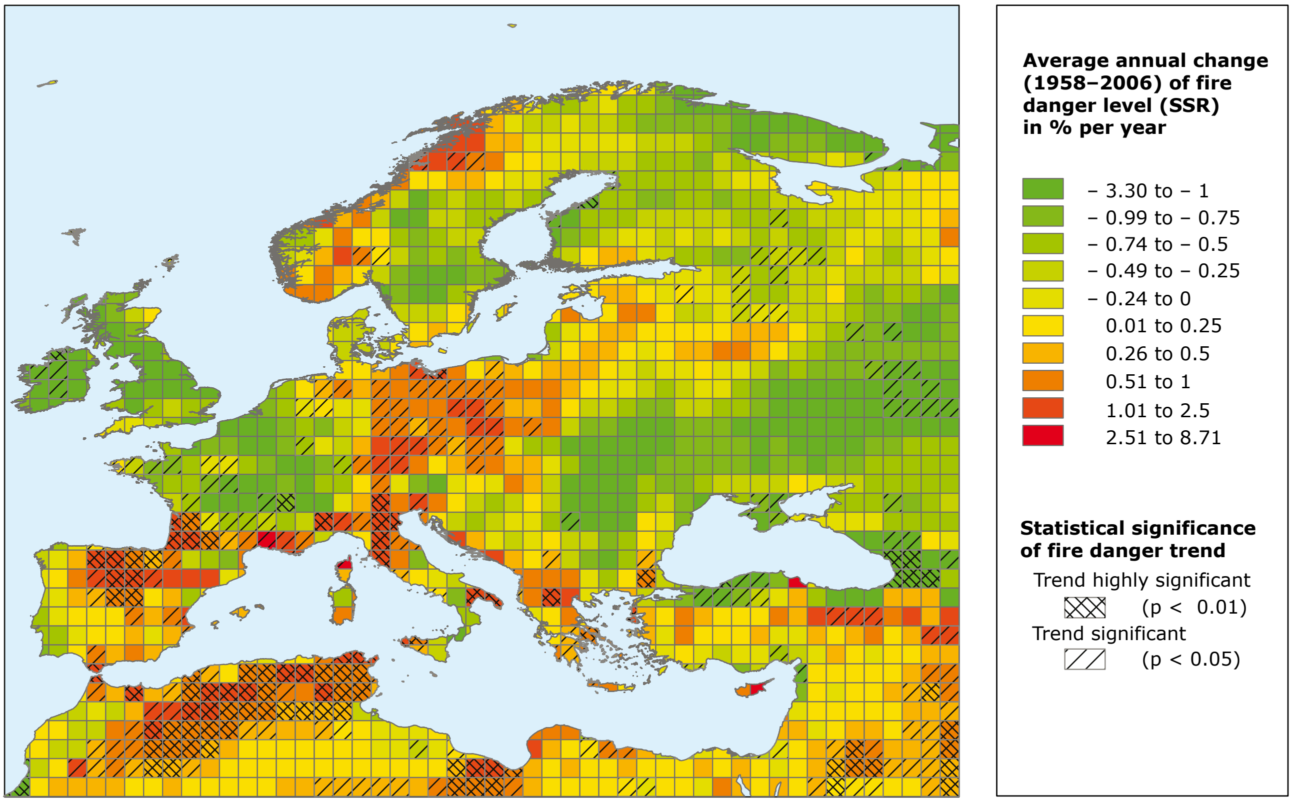
Source: Produced by Tracy Houston Durrant (Joint Research Centre (JRC)) for this report.

5.9.7 *Forest fire danger*

Key messages

- In a warmer climate, more severe fire weather is expected and, as a consequence, more area burned, more ignitions and longer fire seasons.
- Climate change will increase the fire potential during summer months, especially in southern and central Europe.
- The period during which fire danger exists will become longer as a result of climate change, with a probable increase in the frequency of extreme fire danger days in spring and autumn.

Map 5.44 Average annual changes in fire danger level 1958–2006



Note: Based on use of Seasonal Severity Rating (SSR). The map indicates the increase in fire danger in as a percentage of a historic absolute value which is not shown in the figure.

Source: Camia *et al.*, 2008.

Relevance

Wildfires are a serious threat to forests and ecosystems in Europe and climate is the most important driving force affecting fire potential changes over time (Flannigan *et al.*, 2000). Although it is generally recognised that the occurrence of forest fires in Europe is due mainly to causes of an anthropogenic nature, the total burned area changes significantly from year to year largely because of weather conditions. Changes in fire regimes may have strong impacts on natural resources and ecosystem stability, with consequent direct and indirect economic losses. On other hand active forest and fire management practices can counteract the impacts of a changing climate to some extent.

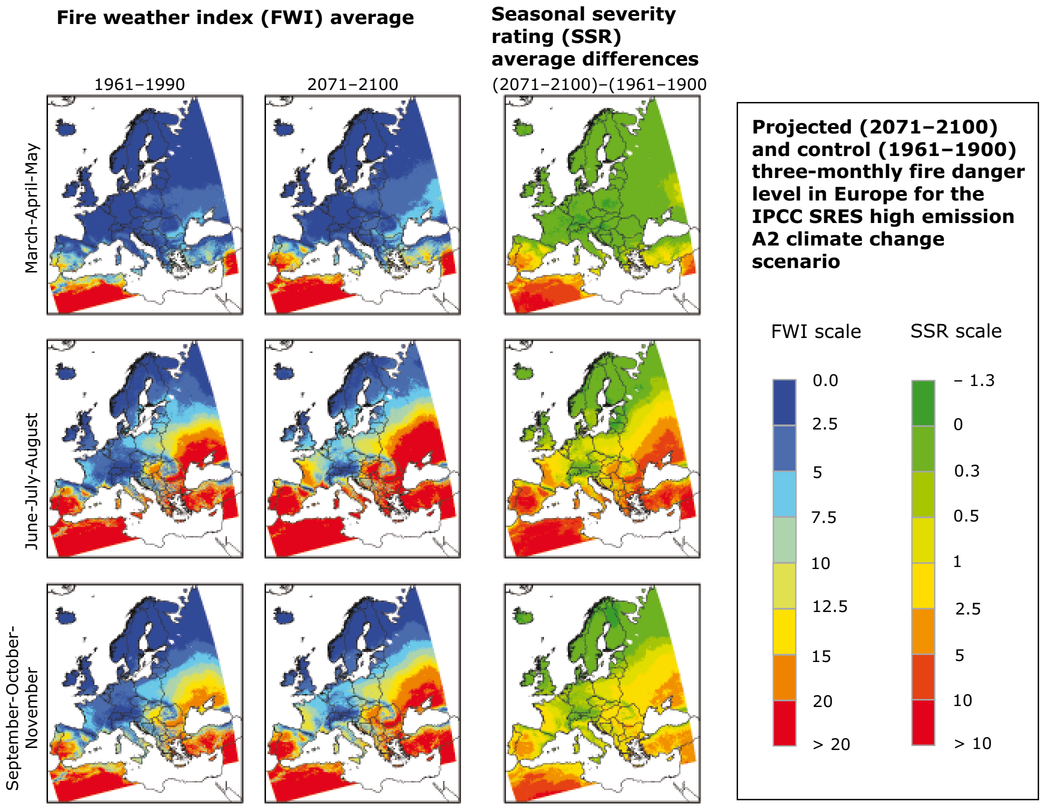
Past trends

Fire risk depends on many factors of a different nature that change over time (e.g. weather, fuel load, fuel type and condition, forest management practices, socio-economic context). Historic fire series can be used to support statements on trends but, unfortunately, long and consistent time series of fire events are rarely available in Europe. In addition, by looking at the historic fire series alone, it is difficult to get a clear picture and recognise the effect of climate on fire potential. In contrast, meteorological fire danger indices, which are designed to rate the component of fire risk that depends on weather conditions, can be usefully employed to analyse fire trends in a consistent way over longer periods. These indices, normally applied on a daily basis, can be summarised on a seasonal basis to rate the overall fire potential of a given year (seasonal fire severity) due to meteorological conditions. The index of Seasonal Severity Rating (SSR) has been derived from daily values of Van Wagner's Fire Weather Index (FWI), Van Wagner (1987), the fire danger assessment method most widely applied throughout the world (San Miguel-Ayanz *et al.*, 2003). Results of a recent study on SSR development are shown in Map 5.44. The average trend for 1958–2006 was computed for all the grid cells, but it was statistically significant for only 21 % of the cases (15 % positive and 6 % negative), which appear to be concentrated in specific geographical areas.

Projections

Projections were derived for the IPCC SRES scenario A2, processing data from the PRUDENCE data archive, namely the daily-high resolution data (12 km) from the HIRHAM model run by DMI, for the time periods 1960–1990 (control) and 2070–2100 (projections) (see Map 5.45). In agreement with a similar assessment performed for North America (Flannigan *et al.*, 2005), the results for Europe confirm a significant increase of fire potential, an enlargement of the fire-prone area and a lengthening of the fire season.

Map 5.45 Modelled three-monthly fire danger levels in Europe for 1961–1990 and 2071–2100 and change between these periods



Note: Based on the IPCC SRES high emissions A2 scenario and the HIRAM model. Fire danger in winter months (DJF) is not shown because it is negligible.

Source: Camia *et al.*, 2008.

5.10 Human health

5.10.1 Introduction

Climate change is already contributing to the global burden of disease and premature deaths. Human beings are exposed to climate change through changing weather patterns (temperature, precipitation, sea-level rise and more frequent extreme events) and indirectly through changes in the quality of water, air and food, and changes in ecosystems, agriculture, industry, settlements, and the economy. At this early stage the effects are small but they are projected to increase progressively in all countries and regions (Confalonieri *et al.*, 2007).

There is emerging evidence of climate-change effects on human health. For example, climate warming in recent decades has altered the distribution of some infectious disease vectors, altered the seasonal distribution of some allergenic pollen species and increased the frequency and intensity of heat waves. In the longer term, many serious impacts on health may occur, including an increase in the number of people suffering from death, disease and injury from heat waves, floods, storms, fires and droughts, a change in the range of some infectious disease vectors, and an increase in the burden of diarrhoeal diseases from changes in water quality and quantity (IPCC, 2007b). In parts of Europe, there may be some benefits to health, including fewer deaths from cold. It is however expected that the benefits will be outweighed by the negative effects of rising temperatures worldwide.

Photo: © Pawel Kazmierczyk

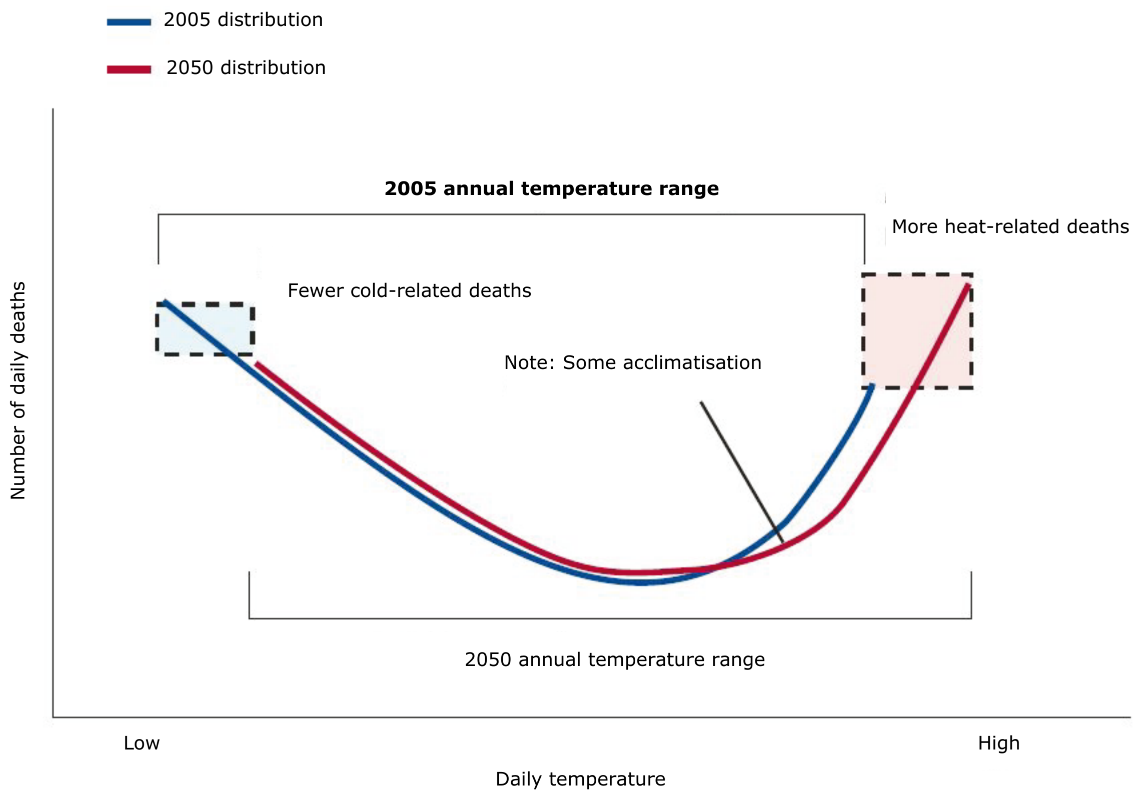
This chapter describes some of the climate-sensitive health outcomes in Europe. The information contained in this chapter is not merely indicator based but a collection of information from scientific publications. Epidemiological studies have been undertaken on the health impacts of individual extreme events (e.g. heat waves, floods), spatial studies where climate is an explanatory variable in the distribution of the disease or the disease vector, and temporal studies assessing the health effects of climate variability, including daily changes in temperature or rainfall. A very limited number of studies has been undertaken to investigate the effectiveness of public-health measures to protect people from future climate change.

5.10.2 *Heat and health*

Key messages

- Increasing temperatures are likely to increase the number of heat-related deaths. Mortality risk increases by between 0.2 and 5.5 % for every 1 °C increase in temperature above a location-specific threshold.
- Heat-wave events can have detrimental effects on human health. More than 70 000 excess deaths were reported from 12 European countries in the hot summer of 2003 (June to September). Long heat waves (more than 5 days) have an impact 1.5 to 5 times greater than shorter events.
- 86 000 net extra deaths per year are projected for the EU Member States for a high-emissions scenario with a global mean temperature increase of 3 °C in 2071–2100 relative to 1961–1990.

Figure 5.42 Relationship between number of temperature-related daily deaths and daily temperature



Note: Schematic representation of how an increase in average annual temperature would affect the annual total of temperature-related deaths, by shifting the distribution of daily temperatures to the right. Additional heat-related deaths in summer would outweigh the extra winter deaths averted (as may happen in some northern European countries). The average daily temperature range in temperate countries would be about 5–30 °C (McMichael, 2006).

Source: McMichael, 2006.

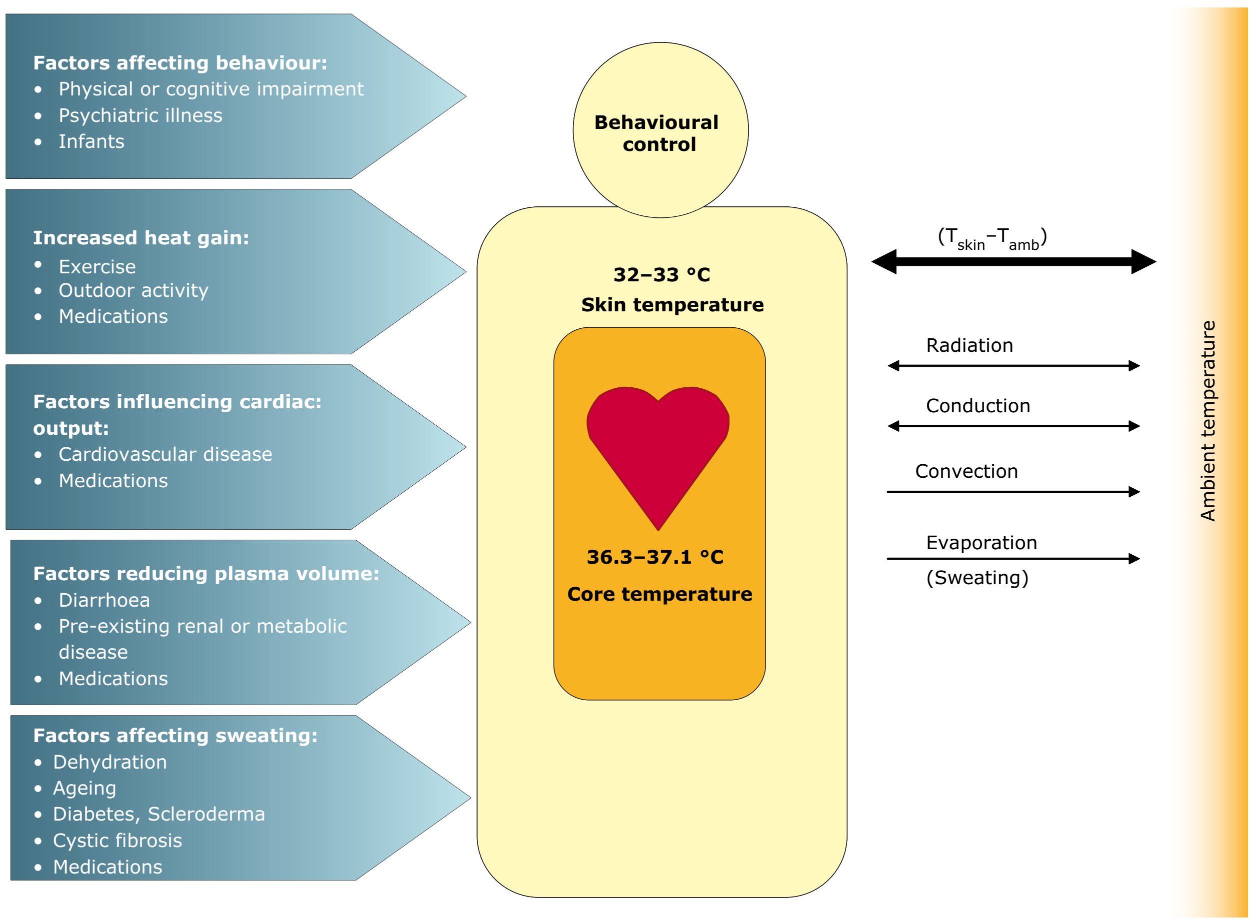
Relevance

Populations typically have an optimum temperature at which the (daily or weekly) death rate is lowest. Mortality rates rise at temperatures outside this comfort zone. Figure 5.42 shows a typical U/J-shaped relation theoretically, as well as in six European cities assessed in the PHEWE project. The trough represents the comfort zone; the steeper (right) arm of each line shows the mortality increase at high temperatures, and the left arm of each line shows the increase at low temperatures. Overall, the impact of hot weather and heat waves depends on the level of exposure, the size and structure of the exposed population, the population sensitivity, the preparedness of health systems, and the prevention measures in place. In temperate countries, there is a seasonal variation of mortality, with higher mortality in winter than in summer. There is uncertainty on whether some current observed reductions in winter mortality can be attributed to climate change (Confalonieri *et al.*, 2007). People with cardiovascular diseases are more at risk in winter, because of the cold-induced tendency of blood to clot.

Heat waves have caused significant mortality in Europe in recent decades. However it is difficult to compare the heat-wave effects across Europe and over time. Heat directly affects the human physiology: thermoregulation during heat stress requires a healthy cardiovascular system. When environmental heat overwhelms the heat-coping mechanism, the body's core temperature increases. This can lead to heat illness, or death from heat stroke, heart failure and many other causes (Figure 5.43).

Several medical factors can increase the risk of heat-wave mortality, including dehydration, drugs, ageing, and having a chronic disease that affects cardiac output and skin blood flow, as well as being confined to bed. Social factors, such as social isolation, may also be important, although there has been little research in Europe (see Figure 5.43; Bouchama, 2007). Many housing and urban factors have also been assessed, in particular for their role in high indoor temperatures (Kovats and Hajat, 2008). One special concern relates to indoor temperatures in health-care facilities and nursing homes. Increasing numbers of older adults in the population will increase the proportion of the population at risk (Confalonieri *et al.*, 2007). Health-system action will be needed to ensure adequate planning of locations for health care and nursing institutions, as well as for the thermal protection of their facilities.

Figure 5.43 Factors affecting human thermoregulation and the risk of heat illness



Source: Matthies *et al.*, 2008 (adapted from Bouchama, 2007).

The EuroHEAT project concluded that heat-related illnesses and deaths are largely preventable. In the long term, the most important measure is improving urban planning and architecture, and energy and transport policies. Such improvements should begin now, as the lead time for policy development is very long. Heat-wave effects can be reduced by keeping indoor temperatures low, keeping out of the heat, keeping the body cool and hydrated, and helping others. Health-system preparedness planning is essential, by collaborating with weather services in providing accurate, timely weather-related health alerts and developing strategies to reduce individual and community exposures to heat, especially among vulnerable populations, planning health and social services and infrastructure, and providing timely information to the population (Matthies *et al.*, 2008).

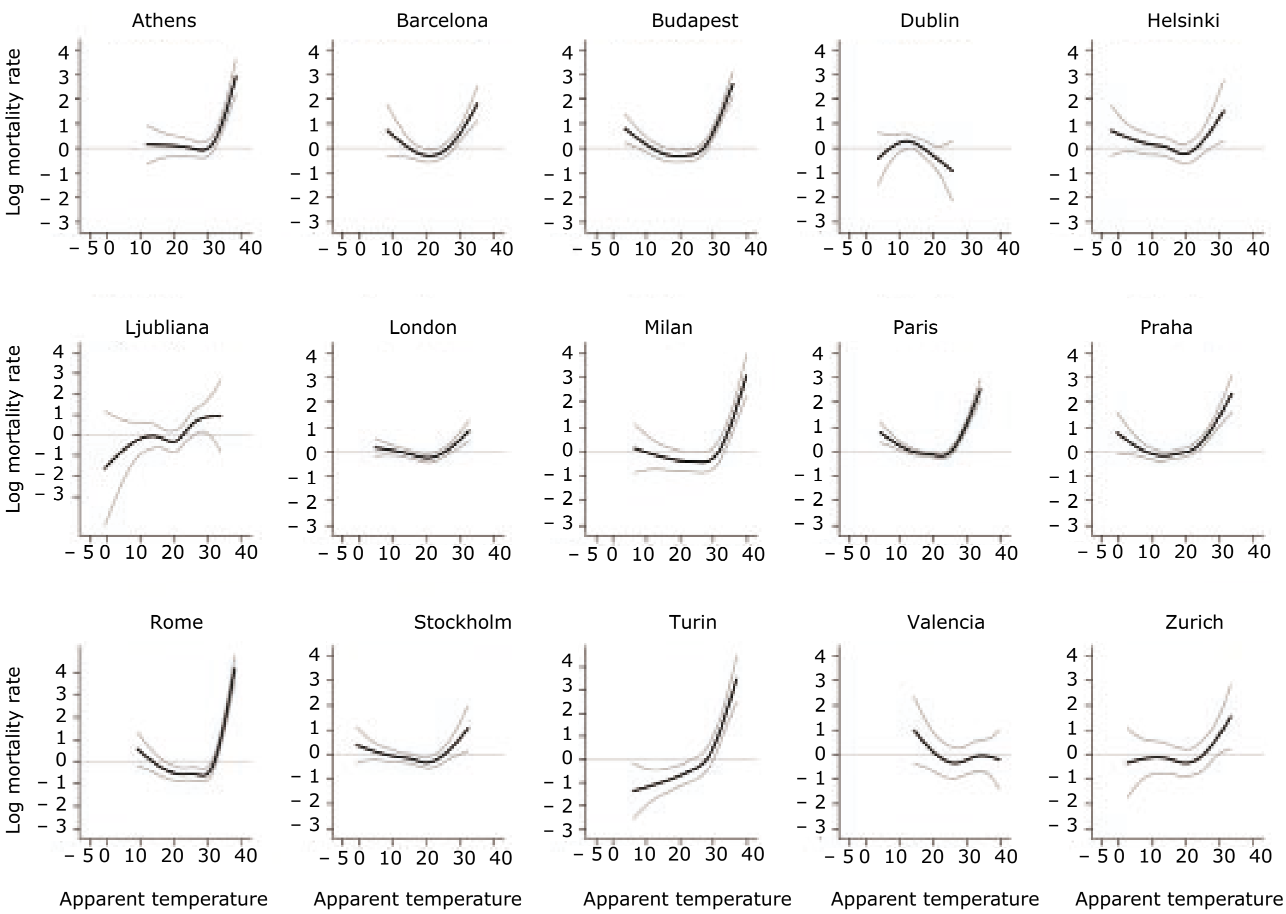
Past trends

Many epidemiological studies have quantified the impact of temperature on daily mortality. In all cities in Europe mortality increases over a certain threshold of temperature. This threshold is location-specific (see Figure 5.44).

The estimated change in mortality risk per degree temperature increase over the location-specific threshold ranges from 0.2 to 5.5 % (Kovats *et al.*, 2006; Baccini *et al.*, 2008).

Most European countries have between 5 and 30 % higher death rates in winter than in summer. Winter-related mortality in many European populations has declined since the 1950s (Kunst *et al.*, 1991; Lerchl, 1998; Carson *et al.*, 2006). Cold

Figure 5.44 Daily mortality rates in 15 European cities by apparent temperature in summer time



Note: City-specific estimates of the relevant parameters were obtained from 15 years (1990–2004) of data by specifying a marginal Poisson model for the daily count of deaths. Bayesian random effects meta-analysis models were used to combine the city-specific results.

Source: Baccini *et al.*, 2008.

days, cold nights and frost days have become rarer, but explain only a small part of this reduction: improved home heating, better general health and improved prevention and treatment of winter infections have played a more significant role (Carson *et al.*, 2006).

More than 70 000 excess deaths were recorded in 12 European countries from June to September 2003, compared with the 1998 to 2002 average (Robine *et al.*, 2007). Although this increase cannot be entirely attributed to the heat waves in 2003, in the absence of any other explanatory factors, most of these deaths are likely to have been caused by the several heat waves in that year. The timing, intensity and duration of heat waves have been shown to influence the amount of mortality. Impacts of heat waves characterised by longer duration were from 1.5 to 5 times higher than for short heat waves (Matthies *et al.*, 2008).

Major heat-wave events are also associated with other health hazards such as air pollution, wild fires, water, food and electricity supply failures, which also have implications for public health action. The combined effect of heat waves and peaks of air pollution due to ozone or particulate matter with a diameter under 10 μm (PM_{10}) increases mortality. There is growing evidence that the effects of heat-wave days on mortality are larger when ozone or PM_{10} levels are high, particularly among the elderly (75–84 years). In nine European cities the total daily number of deaths in the age group 75–84 years increased by 10.6 % during heat-waves when ozone levels were low but by 16.2 % when ozone levels were high; corresponding figures for PM_{10} were 10.5 % and 14.3 % (Analitis and Katsouyanni, in press). The mortality increase due to the combined effect of heat and air pollution can be reduced by decreasing exposure to ozone and PM_{10} on hot days.

Cold waves continue to be a problem if very low temperatures are reached in a few hours and extend over long periods. Accidental cold exposure in temperate and cold climates occurs mainly outdoors, among the socially deprived (alcoholics, the homeless), workers, and the elderly (Ranhoff, 2000). Living in cold environments in polar regions is associated with a range of chronic conditions in the non-indigenous population as well as acute risk from frostbite and hypothermia (Hassi *et al.*, 2005). In countries with populations well adapted to cold conditions, cold waves can still cause increases in mortality if electricity or heating systems fail.

Photo: © Waltraud Grubitzsch, dpa, 2003

Projections

Heat-related morbidity and mortality is projected to increase. Estimates of heat mortality have been made in several national assessments, using different climate scenarios and population and adaptation assumptions. In the United Kingdom, annual heat-related deaths are expected to increase from about 800 in the 1990s to about 2 800 in the 2050s and about 3 500 in the 2080s in the medium-high scenario. Annual cold-related deaths decrease from about 80 300 in the 1990s to about 60 000 in the 2050s and 51 200 in the 2080s in the same scenario (Donaldson *et al.*, 2001). In Germany, a 20 % increase in heat-related mortality is projected. This increase is not likely to be compensated by reductions in cold-related mortality (Koppe *et al.*, 2003). In Portugal, an increase in heat-related mortality from a baseline of 5.4 to 6 per 100 000 to a range of 19.5 to 248 per 100 000 by the 2080s is projected (Dessai, 2003).

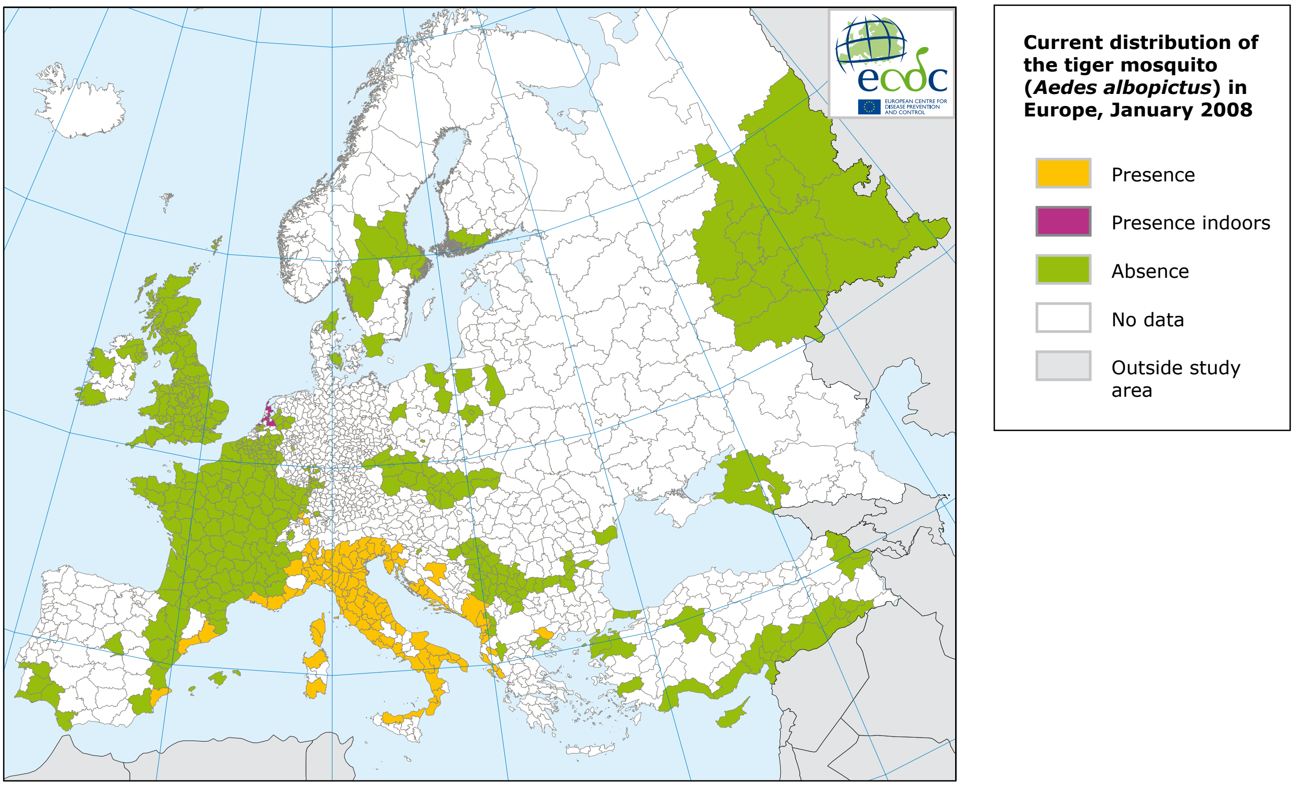
For the EU-27 Member States, the PESETA study projected almost 86 000 net extra deaths per year in 2071–2100, compared with the 1961–1990 EU-25 average, for a high emissions scenario (IPCC SRES A2, see Chapter 4) with a global mean temperature increase of 3 °C (EC, 2007). These results are preliminary, assume no physiological adjustment, and do not separate out the impact of non-climate changes (socio-economic changes in age structure or population movements). The study is based on assumptions of a mortality-temperature relationship that does not take into account the differences between the Mediterranean and northern European countries.

5.10.3 Vector-borne diseases

Key messages

- The tiger mosquito, a transmitter of a number of viruses, has extended its range in Europe substantially over the past 15 years and is projected to extend even further. There is a risk of additional outbreaks of Chikungunya and a potential for localised dengue to re-appear.
- Ticks and the associated Lyme disease and tick-borne encephalitis are moving into higher altitudes and latitudes.
- Changes in the geographical distribution of the sandfly vector are occurring in several European countries (high confidence) and there is a risk of human Leishmania cases further north.
- Projected temperature increases in the United Kingdom could increase the risk of local malaria transmission by 8 to 15 %; in Portugal a significant increase in the number of days suitable for the survival of malaria vectors is projected. However, the risk of localised malaria transmission is low.

Map 5.46 Presence of *Aedes albopictus* (the tiger mosquito) in Europe in January 2008



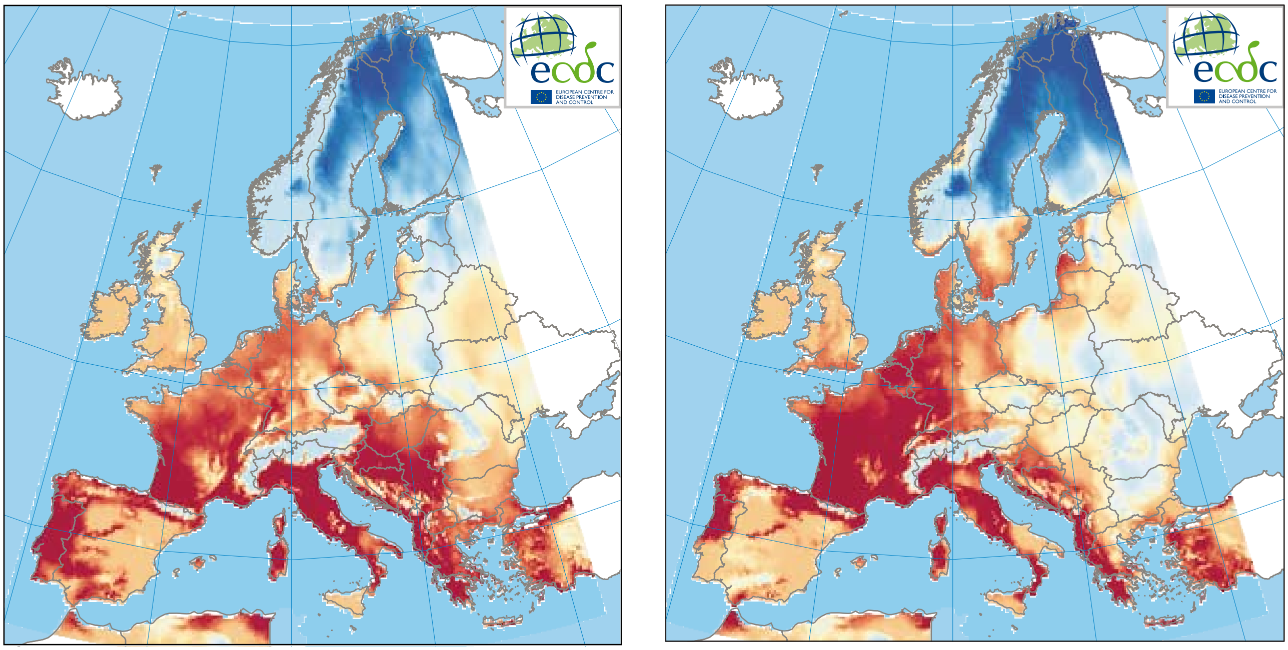
Note: Developed by Francis Schaffner (BioSys Consultancy, Zurich), in partnership with Guy Hendrickx/Ernst-Jan Scholte (Avia-GIS, Zoersel, Belgium) and Jolyon M Medlock (Health Protection Agency, UK) for the ECDC TigerMaps project. © European Centre for Disease Prevention and Control 2008.

Source: Based on Schaffner *et al.*, 2008.

Relevance

Climate change is likely to cause changes in ecological systems that will affect the risk of infectious diseases in Europe, including the seasonal activity of local vectors, and the establishment of tropical and semi-tropical species. Shifts in the global and regional distribution and behaviour

Map 5.47 Areas of possible establishment of *Aedes albopictus* (the tiger mosquito) in Europe for 2010 and 2030



Areas of possible establishment of *Aedes albopictus* (the tiger mosquito) in Europe for 2010 and 2030

Left: maximum-change scenario for 2010; right: minimal-change scenario for 2030

Less suitable areas — Most suitable areas

0 | 25.5 | 51 | 76.5 | 102 | 127.5 | 153 | 178.5 | 204 | 229.5 | 255

Note: Developed by Francis Schaffner (BioSys Consultancy, Zurich), in partnership with Guy Hendrickx/Ernst-Jan Scholte (Avia-GIS, Zoersel, Belgium) and Jolyon M Medlock (Health Protection Agency, United Kingdom) for the ECDC TigerMaps project. © European Centre for Disease Prevention and Control 2008.

Source: Based on Schaffner *et al.*, 2008.

of insect and bird species are early signs that biological systems are already responding to climate change (see also Section 5.7.5). The IPCC (2007a) projects that climate change will lead to significant changes in infectious disease transmission by vectors (such as mosquitoes and ticks) as a result of changes in geographic range, seasonality, disease transmission and absolute number of cases.

Patterns of infectious disease in Europe are and will be affected by the movement of people and goods, changes in hosts and pathogens, land use and other environmental factors. Personal risk factors such as the status of the immune system also play an important role. There are fears in Europe that new infectious diseases could be triggering population health problems, and that previously-existing diseases could re-emerge. Whether this happens will depend very much on the international, European and national surveillance systems in place for early detection and response, vector- and host-control measures, awareness of people and health professionals, and preventive measures such as vaccination and treatment. In many cases it will be necessary to revise integrated vector-control measures, increase international surveillance, strengthen collaboration between veterinary and public health services, and inform people on how to avoid potential risks.

Information is available, mainly from the climate change and adaptation strategies for human health (cCASHh) study, national assessments and global scenarios. The ongoing EDEN project and the ECDC expert consultation on magnitude and importance of vector-borne diseases in Europe (V-borne assessment) will further provide clarification and additional risk considerations in the next few years.

Vector-borne diseases in this report are grouped into mosquito-borne, tick-borne and sandfly-borne. Bacteria and parasites can be transmitted through these vector viruses.

Past trends

Mosquito-borne

Higher temperatures can contribute to higher virus replication rates in mosquitoes, increased mosquito populations, expansion of the mosquito distribution, and easier establishment and replication of vectors.

Chikungunya: *Aedes albopictus* (the tiger mosquito) has extended its range in Europe substantially over the past 15 years (Scholte and Schaeffner, 2007) and is now present in 12 European countries (see Map 5.46).

This mosquito can transmit a variety of diseases. The risk of local transmission of mosquito-borne viruses is the result of the simultaneous presence of the virus, competent mosquitoes, susceptible human hosts, and contacts between these three entities. In 2007, a cluster of cases of Chikungunya (a virus that is highly infective and disabling but not transmissible between people) was observed in the Emilia-Romagna Region of Italy. This is the first example in continental Europe of an imported human disease case being followed by sustained local mosquito transmission (ECDC, WHO, 2007; Menne *et al.*, 2008).

Dengue: *Aedes aegypti*, one of the many vectors that transmit dengue, closely follows the 10 °C winter isotherm and is extending its range. Currently, *Ae. aegypti* is absent in Europe, but was well-established until after World War II. Dengue is only one of a variety of diseases transmitted by *Ae. aegypti*. Today, dengue is frequently introduced into Europe by travelers returning from dengue-endemic countries. No locally-transmitted dengue cases have been reported; one can thus assume that the risk of locally-transmitted dengue is currently low, and any increase would depend on the re-introduction of *Ae. aegypti* into Europe. In addition, local transmission could occur if the dengue virus were introduced into the *Ae. albopictus* population (Semenza and Menne, 2008).

Malaria: Anopheles mosquitoes, the malaria vectors, are and have long been present in all European countries. In recent decades, conditions for the transmission of malaria in Europe have remained favorable, as documented by repeated rare autochthonous transmission of a tropical malaria strain by local vectors to a susceptible person. Currently, autochthonous malaria continues to pose a challenge in Turkey. However, the risk of local transmission depends on the simultaneous presence in a given area of anthropophilic, high-longevity and genetically-competent vectors, and human parasite carriers (Menne *et al.*, 2008; Ebi and Menne, 2006).

West Nile Virus (WNV): is primarily transmitted through bird-feeding mosquitoes (particularly *Culex* spp.). Climate change has been implicated in changes in the migratory and reproductive phenology (advances in breeding and migration dates) of several bird species, their abundance and population dynamics, as well as a northward expansion of their geographical range in Europe. There are two potential consequences: a) shifts in the geographic distribution of the vectors and pathogens due to altered distributions or changed migratory patterns of bird populations; b) changes in the life cycles of bird-associated pathogens due to a mistiming between bird breeding and the breeding of vectors, such as mosquitoes. Higher transmissions of WNV have been observed along major bird flyways. However human cases of WNV are rare in Europe and occur mainly in wetland and urban areas (Hubálek *et al.*, 2006).

Tick-borne

Climate change can increase tick survival and thus tick density, prolong the season of tick activity, prolong host activities, and shift ticks toward higher altitudes and northern latitude. Under climate change, a shift towards milder winter temperatures may enable expansion of the range of Lyme disease and tick-borne encephalitis into higher latitudes and altitudes. In contrast, droughts and severe floods will negatively affect the distribution, at

Aedes albopictus (the tiger mosquito)

Photo: © ECDC, www.world-television.se/world_television.se/mnr_stat/mnr/ECDC/431/index.php least temporarily. There is some observational evidence of northern or altitudinal shifts in tick distribution from Sweden and the Czech Republic. However, climate change alone is unlikely to explain recent increases in the incidence of tick-borne diseases in Europe, as there is considerable spatial heterogeneity in the degree of increase of tick-borne encephalitis (Daniel *et al.*, 2006).

Sandfly-borne

While there is no current compelling evidence that sandfly and visceral leishmaniasis distributions in Europe have altered in response to recent climate change, cCASHh analysis points to a considerable potential for climate-driven changes in leishmaniasis distribution. Sandfly vectors already have a wider range than the pathogen (*L. infantum*), and imported dogs infected with it are common in central and northern Europe. Once conditions make transmission possible in northern latitudes, the imported dog cases could act as a source of new endemic foci. Climate-induced changes in sandfly abundance may thus increase the risk of emergence of new diseases in the region (Lindgren and Naucke, 2006).

Projections

Projections of climate-change-related vector-borne diseases use different approaches to classify the risk of climate-sensitive health determinants and outcomes. For malaria and dengue, results from projections are commonly presented as maps of potential shifts in distribution (see Map 5.47). Health-impact models are based typically on climatic constraints on the development of the vector and/or parasite, and include limited population projections and non-climate assumptions. Models with incomplete parameterisation of biological relationships between temperature, vector and parasite often over-emphasise relative changes in risk, even when the absolute risk is small. Several modelling studies used the IPCC SRES climate scenarios, a few applied population scenarios, and none incorporated economic scenarios. Few studies incorporate adequate assumptions about adaptive capacity. The main approaches used are inclusion of current 'control capacity' in the observed climate–health function and categorisation of the model output by adaptive capacity, thereby separating the effects of climate change from those of improvements in public health (Confalonieri *et al.*, 2007).

The range of *Aedes albopictus* is projected to be further extended. Schaffner *et al.*, 2008 estimated areas of further *A. albopictus* extension for 2010 and 2030 (see Map 5.47). However, whether or not there will be outbreaks of Chikungunya in the next years will depend very much on the global circulation of the virus and global travel.

An empirical model estimated that, in the 2080s, 5–6 billion people would be at risk of dengue as a result of climate change and population increase, compared with 3.5 billion people if the climate remains unchanged (Hales, 2002). This projection includes an extension of the risk of dengue for Mediterranean countries.

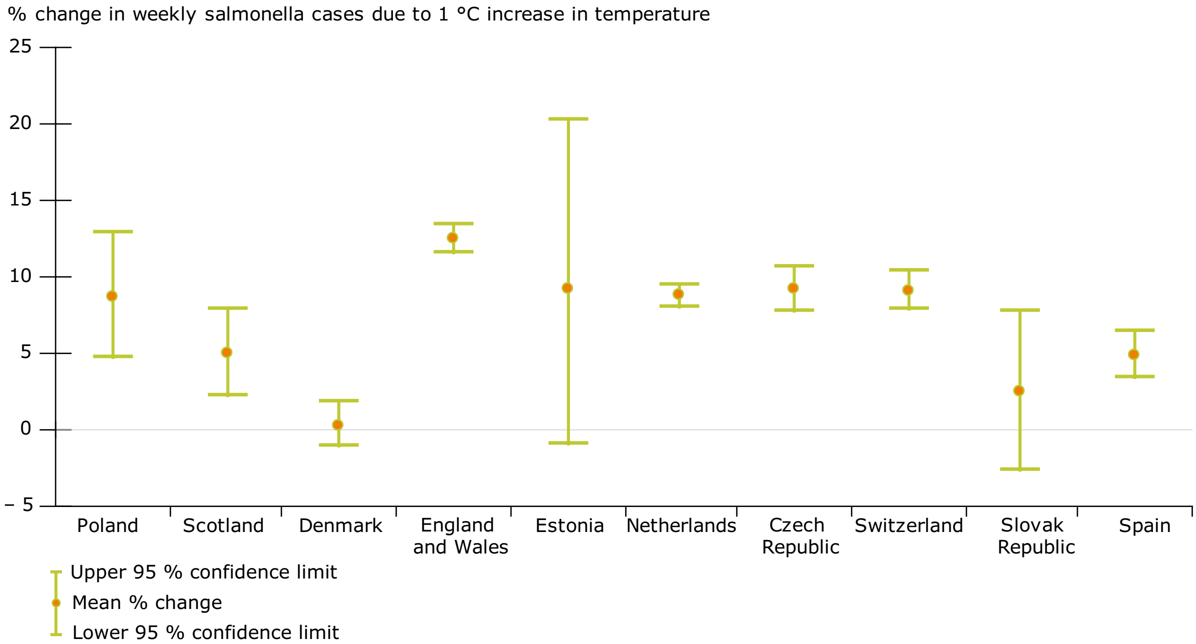
Several climate-change-related models project an increase in malaria risk: For example, in the United Kingdom it was estimated that, with temperature increases, the risk of local malaria transmission could increase by 8–15 % by 2050. In Portugal, the number of days suitable for survival of malaria vectors is projected to increase. Nevertheless, there is agreement that the risk of transmission of malaria related to localised climate change is very small. Risks are greater in countries where importation of malaria coincides with socioeconomic degradation, disintegration of health and social services, uncontrolled cross-border migration and lack of environmental management for mosquito control.

5.10.4 *Water- and food-borne diseases*

Key messages

- There has been a linear increase in reported cases of some food-borne diseases for each degree increase in weekly or monthly temperature over a certain location-specific threshold (medium confidence). Several thousand cases of salmonella are expected in future years, particularly in countries where food safety standards are poor.
- Changing frequency and intensity of precipitation events (and temperature) from climate change may result in outbreaks of water-borne diseases (high confidence) and could mobilise pathogens.
- In the Mediterranean additional salmonella problems from bathing water quality are projected, which would require proper monitoring and surveillance.

Figure 5.45 Percentage change of weekly salmonella cases by 1 °C temperature increase



Source: Kovats *et al.*, 2004.

Relevance

Four main issues should be considered when evaluating the relationship between health outcomes and exposure to changes in rainfall and water availability and quality: (1) links between water availability, household access to improved water and the health burden due to diarrhoeal diseases; (2) the role of extreme rainfall (intense rainfall or drought) in facilitating water-borne outbreaks; (3) effects of temperature and runoff on microbiological and chemical contamination of coastal, recreational and surface waters; (4) direct effects of temperature on the incidence of diarrhoeal and other diseases. Climate variability and change also change the risks of fires and pest and pathogen outbreaks, with negative consequences for food, fibre and forestry (Menne *et al.*, 2008).

Access to safe water remains an extremely important global health issue. The risk of outbreaks of water-borne diseases increases where standards of water, sanitation and personal hygiene are low.

Extreme precipitation events leading to floods or droughts can have direct and indirect health effects. Flooding can cause drowning, injuries (cuts, sprains, laceration, punctures, electric injuries, etc.), diarrhoeal diseases, vector-borne diseases (including those borne by rodents), respiratory infections, skin and eye infections, and mental health problems. Floods also have other effects with health consequences: damage to infrastructure for health care and water and sanitation, crops (and/or disruption of food supply) and property (lack of shelter), and disruption of livelihood and displacement of populations. Droughts or extended dry spells can impair provision of safe water leading to water-related health problems, for example through reducing the volumes of river flow, which may increase the concentration of effluent pathogens, posing a problem for the clearance capacity of treatment plants.

Climate change is also likely to affect the quality of coastal waters, by changing natural ecosystems or the quality of the waters draining into the coastal zone. This poses specific risks for the recreational use of bathing waters, particularly for transient tourist populations that may not have built-in resistance to endemic water-related diseases or may be faced with water quality that does not meet the stringent conditions imposed in the home country. The quality and safety of seafood is directly linked to the quality of the water in the coastal zone.

Intestinal infectious diseases that are transmitted through food or water are sensitive to climate and weather factors. Such diseases are the main causes of infectious diarrhoea and cause significant amounts of illness each year in Europe. Approximately 20 % of the population in western Europe is affected by episodes of diarrhoea each year (van Pelt *et al.*, 2003). Such infections have a significant economic impact in terms of treatment costs and loss of working time (Roberts *et al.*, 2003).

Various adaptation options are available, which include ensuring access to safe drinking water, providing sanitation services, and establishing common standards for surveillance systems and contingency plans for detecting and preventing water-borne disease outbreaks. Water-safety plans may need to be revised for changing climate conditions. Such plans will need to include ways of ensuring safe drinking water from source to tap through better risk assessment and management. Improved management of water demand in the context of fully-integrated planning for river-basin management will become imperative as a first coping mechanism, but is unlikely to satisfy all the needs created by demographic growth, rising living standards and economic development. Alternative strategies will need to be explored, including reusing treated wastewater, using grey water, harvesting rainwater and, where economically viable, desalination. Contamination of food products usually arises from improper practices at some point during the journey from farm to fork. Providing education and timely information on the best ways to handle food and avoid food-borne diseases to producers, food handlers and consumers is essential. Food-borne disease outbreaks can be prevented by using safe water and raw materials, keeping food clean and at safe temperatures, cooking food thoroughly, and keeping raw and cooked food separate.

Past trends

Access to public sources of drinking water in EU Member States is high. Heavy precipitation has been linked to a number of drinking-water outbreaks of Cryptosporidium (a pathogen causing a diarrhoeal illness) in Europe, due to spores infiltrating drinking water reservoirs from springs and lakes and persisting in the water distribution system (Lake *et al.*, 2005; Semenza and Nichols, 2007). In Germany, bacteriological and parasitic parameters spiked considerably during extreme runoff events (Kistemann *et al.*, 2002). New pathogens have also emerged in recent years. In Europe the risk of infectious disease outbreaks is relatively small due to the standard of water treatment and distribution infrastructure. While water-borne outbreaks have a rather large potential, the actual disease burden in Europe is difficult to estimate and is most probably underestimated. Examples of an increased risk of infectious disease outbreaks have been found in the United Kingdom (Reacher *et al.*, 2004), Finland (Miettinen *et al.*, 2001), Czech Republic (Kříž *et al.*, 1998) and Sweden (Lindgren, 2006).

Key food- and water-borne infections in Europe are monitored. The incidence of salmonella has been declining in many countries, but that of other pathogens is increasing. Several studies have confirmed and quantified the effects of high temperatures on common forms of food poisoning, such as salmonellosis (D'Souza *et al.*, 2004; Kovats *et al.*, 2004; Fleury *et al.*, 2006) (see Figure 5.45). These found an approximately linear increase in reported cases with each degree increase in weekly or monthly temperature over a certain threshold. Temperature is much less important for the transmission of Campylobacter (Kovats *et al.*, 2005; Louis *et al.*, 2005; Tam *et al.*, 2006). Contact between food and pest species, especially flies, rodents and cockroaches, is also temperature-sensitive. Fly activity is largely driven by temperature rather than by biotic factors (Goulson *et al.*, 2005).

Harmful algal blooms (HABs) produce toxins that can cause human diseases, mainly via consumption of contaminated shellfish. Warmer seas may thus contribute to more cases of human shellfish and reef-fish poisoning (ciguatera) and poleward expansions of these disease distributions (Lehane and Lewis, 2000; Hall *et al.*, 2002; Hunter, 2003; Korenberg, 2004).

Projections

Infections with *Salmonella* spp. increase by 5–10 % for each degree increase in weekly temperature, at ambient temperatures above 5 °C (Kovats *et al.*, 2004). Some emerging studies show that the disease burden in Europe could be significant (all else being constant) with potentially an extra 20 000 cases per year by 2030 and 25 000–40 000 by 2080 (EC, 2007).

Water stress over central and southern Europe is projected to increase. In the EU, the percentage of land area under high water stress is likely to increase from 19 % today to 35 % by the 2070s, by when the number of additional people affected is expected to be between 16 and 44 million. Furthermore, in southern Europe and some parts of central and eastern Europe, summer water flows may be reduced by up to 80 %. By 2025 it is projected that an additional 31 million people will be living in the coastal zone of the Mediterranean, and that 130 million more will visit the region each year.

6 Adaptation to climate change

Key messages

- Adaptation aims at increasing the resilience of natural and human systems to current and future impacts of climate change. Adaptation occurs mainly at sub-national and local levels but involves all levels of decision-making from municipalities to international organisations.
- Adaptation is a cross-sectoral and transboundary issue which requires comprehensive integrated approaches. Integration of adaptation into sectoral policies at European and national levels is key to a long-term reduction in the vulnerability of ecosystems, economic sectors, landscapes and communities to climate change impacts. Integrating climate change into all main policy actions and measures would benefit from an enhanced sharing of information on current and planned adaptation activities in Europe.
- Good adaptation practices should be appropriate, proportionate and cost-effective in the long term, and links between adaptation and mitigation need to be considered when they are being developed. Substantial work is needed to better assess adaptation costs in order to support further integrated policy-making.

6.1 Europe needs to adapt

The previous chapters presented an overview of European impacts, showing that many regions are vulnerable to climate change and that impacts have already been observed in many vulnerable systems. Most of the impacts are adverse and are generally projected to worsen, certainly beyond a few decades. There is therefore a need for all countries, developing and developed, to adapt to climate change ([5]). Adaptation offers opportunities to make Europe more resilient to climate change.

The EU has agreed to limit the increase in the long term of global mean temperature to 2 °C above pre-industrial levels. Even if this goal is achieved through stringent world-wide mitigation actions to stabilise global GHG concentrations, some impacts will remain, at least in the short- and medium-term, making adaptation imperative to reduce vulnerability and enhance resilience. Europe has to adapt to climate change and also has a moral obligation to assist developing countries as they are most vulnerable in terms of communities, economic sectors and ecosystems. This should be done in the context of the Nairobi Five-year programme of work on impacts, vulnerability and adaptation to climate change (UNFCCC, 2006), the National Adaptation Plans of Actions (NAPAs) and the Bali Action Plan (UNFCCC, 2007c). A number of developing countries have prepared NAPAs using the UNDP Adaptation Policy Framework (UNDP, 2004). Furthermore, the Bali Action plan, resulting from the most recent COP/MOP meetings (Conference and Meeting of the Parties, December 2007), recognises that adaptation will need to be explicitly included in a global post-2012 climate change agreement, currently being negotiated with the aim of reaching an agreement in Copenhagen by the end of 2009 (UNFCCC COP15).

Climate change does not pose a threat at all levels of change and for all sectors or regions. In some areas in the world, agriculture, for example,

([5]) Adaptation to climate change is defined by the IPCC as 'Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation' (IPCC, 2007). Climate change is one driver of global change, to which adaptation is needed. Adaptation includes pro-active and reactive measures, which relate mainly to planned adaptation, as well as autonomous actions. Mitigation aims at avoiding the unmanageable impacts, while adaptation aims at managing the unavoidable impacts.

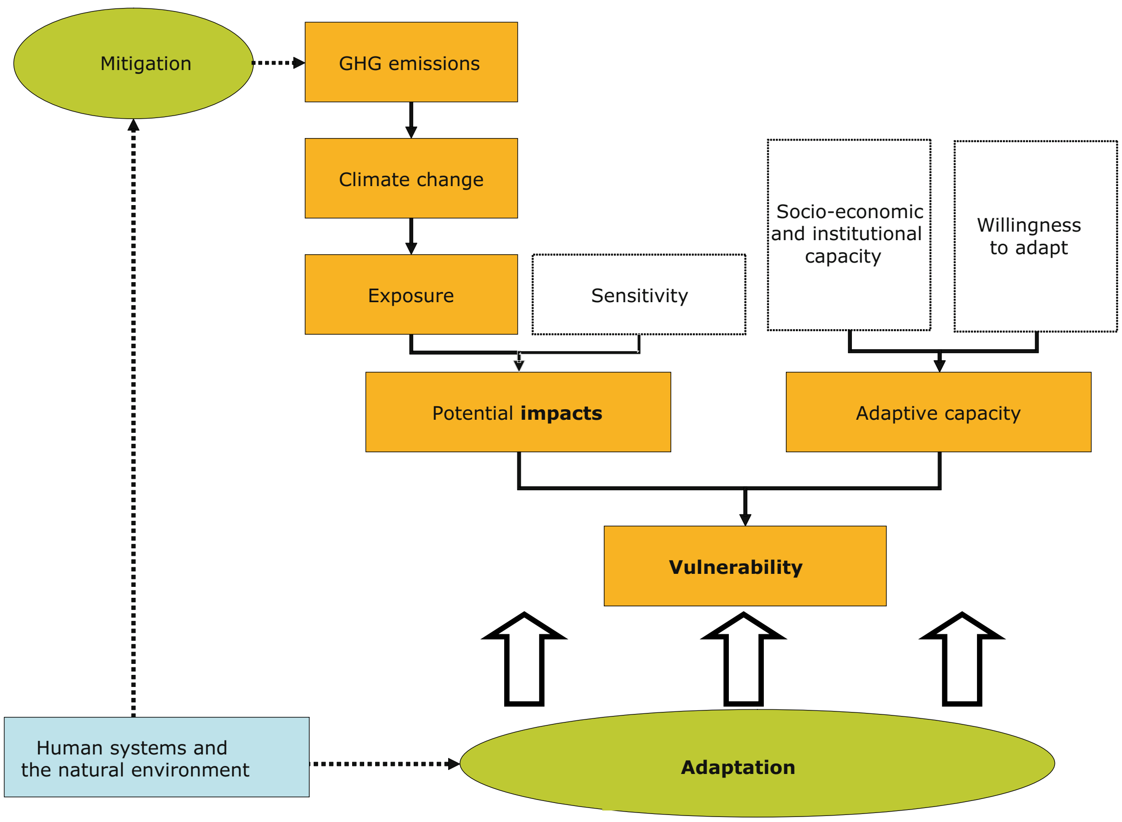
can benefit from small temperature increases and related CO_2 fertilisation, at least in places without reduced precipitation. Climate change may also provide opportunities for innovation in technology and governance in other sectors (e.g. tourism, energy supply, water management, health, construction and shipping). Reducing vulnerability and capturing opportunities both require pro-active adaptation actions, for which integrated analysis and tools such as spatial planning are essential (Uhel and Isoard, 2008). There is now significantly improved understanding of the relationship between impacts, which forms the basis for the 'reasons for concern', and of vulnerability, including an ability and willingness to adapt to impacts (see Figure 6.1 and Grothmann and Patt, 2005).

Recognising the necessity for Europe to adapt to climate change impacts, the European Commission in June 2007 adopted a Green Paper 'Adapting to climate change in Europe — options for EU action' which sketches four pillars of actions (EC, 2007). These are:

- 'Early action in the EU' (integrate adaptation when implementing existing and future legislation and policies, integrate adaptation into existing Community funding programmes, develop new policy responses);
- 'Integrating adaptation into EU external actions';
- 'Reducing uncertainty by expanding the knowledge base through integrated climate research';
- 'Involving European society, business and the public sector in the preparation of coordinated and comprehensive adaptation strategies'.

The publication of the Green Paper included an extensive regional stakeholders consultation process. The European Commission is planning to adopt, in late 2008, a White Paper framing a European adaptation strategy and options for adaptation, accompanied by an Impact Assessment of policy proposals.

Figure 6.1 Conceptual model for climate change impacts, vulnerability and adaptation



Source: Isoard, Grothmann and Zebisch, 2008.

Many adaptation options are already available, which are usually location- and sector-specific. Nowadays, adaptation is seldom undertaken for the sake of climate change alone, and is generally integrated into other cross-cutting and precautionary policy actions, such as disaster preparedness, coastal zone management, rural development, health services, spatial planning and regional development, ecosystems and water management. An increasing consideration of adaptation issues in decision-making is expected to lead to the development of new assessment tools and more integrated adaptation measures.

However, there are limits to adaptation. Natural systems often have a lower adaptive capacity than human systems, especially when certain thresholds — which are poorly but increasingly understood — are exceeded. More diverse systems are likely to adapt to climate change better. But even for human systems (i.e. all economic sectors) there will be limits, influenced by social, technological, economic, environmental, political and institutional constraints. With increasing impacts of climate change, adaptation costs will increase and response options may decrease. The costs of adaptation are estimated to be significant (although only orders of magnitude are known so far), but we can assume that the longer we wait before taking action the higher the costs will be. The range of estimated global costs for adaptation is 30–90 billion USD/year ([6]), and this is calculated as additional to Official Development Assistance (ODA) ([7]), which averaged 80 billion USD/year over recent years (EEA (2007), UNFCCC (2007a, 2007b), UNDP (2007), Oxfam (2007), World Bank (2007) and OECD (2008)).

6.2 Adaptation occurs at transboundary, sub-national and local levels

Adaptation is a crosscutting issue since it aims at enhancing resilience to climate change impacts which affect virtually all economic sectors in Europe, such as water management; agriculture; forestry; health; energy; transport; tourism; nature and soil protection, biodiversity and ecosystems goods and services; fisheries. Integrating climate change adaptation into sectoral policies is therefore one of the key approaches in Europe together with mainstreaming into EU funding mechanisms. Integration of climate change into other policy areas aims at protecting citizens and nature, and making economic activities less vulnerable by appropriate and proportionate adaptation measures. Examples of such measures include: health/heat action plans, vaccination, health system planning, flood risk planning (early warning systems), drought and water scarcity risk management, water demand management, coastal and flood defences, economic diversification, natural hazard monitoring, reinforcing the built environment (e.g. roads, bridges, electric wires), land-use management, and greening of cities.

Economic sectors that are particularly concerned with adaptation include energy supply, health, water management, agriculture, tourism and transport. Adaptation is very much about managing the risks associated with future climate change impacts. In many cases a link with disaster management will also be appropriate. Adaptation occurs primarily at transboundary (e.g. river catchments), sub-national and local levels, and therefore involves many levels of decision-making. The choice of the level of intervention will be different for different regions, landscape types and sectors. The transboundary nature of climate change and associated adaptation responses, together with the subsidiarity principle, are important factors to consider when implementing strategies.

In addition, linkages between adaptation and mitigation also have to be considered (Swart and Raes, 2007), particularly when one looks forward towards mainstreaming and coordinating future actions. Some adaptation options can be developed in synergy with mitigation, for example in the land and water management sectors. The development of mitigation measures also needs to consider vulnerabilities and adaptation options. Identifying possible conflicts between mitigation and adaptation is key for avoiding mal-adaptation such as, in some cases, artificial snow making, transfer of water, air conditioning or desalination. However, there is a need to develop criteria for clearly defining and avoiding mal-adaptation, since

([6]) UNDP (2007) reports estimates of costs needed for investing in adaptation of about USD 86 billion annually by 2015. UNFCCC (2007a, 2007b) estimated that the overall additional investment and financial flows needed for adaptation in 2030 amount to several tens of billion US dollars (e.g. USD 14 billion for agriculture, forestry and fisheries, USD 11 billion for water supply, USD 5 billion for diarrhoeal disease, malnutrition and malaria, USD 11 billion for beach nourishment and dykes, and USD 8–130 billion for adapting new infrastructure). The World Bank (2007) reported an estimate of USD 30 billion for adaptation costs.

([7]) The long-standing development assistance target is 0.7 % of the Gross National Income for rich countries. The EU and G8 commitment of 2005 included a pledge to double aid flows by 2010, representing a USD 50 billion increase.

it can lead to additional greenhouse gas emissions which can offset mitigation efforts.

Consequently, adaptation options have to be tailor-made to the specifics of the geographic area considered in terms of vulnerable landscape types (e.g. coastal areas, wetlands and rivers, mountains and glaciers, the Mediterranean, the semi-Arctic) and sectors involved, with a view to implementing measures at the appropriate level of decision-making (EU, national, regional, local). Different vulnerable systems at different geographic levels will require different approaches.

6.3 From European and national strategies to regional and local implementation

EU Member States are at different stages of preparing, developing and implementing national adaptation strategies, depending on the magnitude and nature of the observed impacts, assessment of current and future vulnerability, and capacity to adapt (see details in Table 6.1). All countries have also submitted information on their adaptation plans in their 4th National Communication to the UNFCCC in 2005. In addition, some actions and measures are increasingly also being taken at regional and local levels.

National strategies provide the framework for adaptation actions, many of which have to be implemented at sub-national and local levels (regions, provinces or municipalities). Various regionally-oriented initiatives are underway in Europe, particularly under the European Commission INTERREG programme that links research and policy development ([8]). National and European action can provide and strengthen the enabling circumstances for regional and local adaptation by focusing on specific regions that are particularly vulnerable to climate change (e.g. the Alps). National and European information sources, such as this report, contribute to enhancing the knowledge base for identifying vulnerable areas and setting the context for implementing regional and local adaptation action. Specific impact indicators can be directly linked to the economic sectors that have to prioritise, develop and implement adaptation strategies.

European countries emphasise different types of adaptation measure. It is important to consider an analytical framework that could help to assess these activities within countries and provide an overview of actions. Massey (2007) has developed a draft framework for this purpose ([9]), which categorises adaptation measures from three main angles, (1) the level or stage of adaptation measures (i.e. whether a programme is in place or whether a country is contemplating a specific action), (2) the objective of the actions (i.e. why adaptation is taking place, e.g. building adaptation capacity, reducing risk and sensitivity) and (3) the issue or problem that adaptation aims to address (e.g. coastal zone management, health and disease management). The PEER network ([10]) has also recently started a research project on a comparative analysis of national adaptation strategies and sectoral policies for adaptation in various European countries, including a few national and regional case-studies.

However, there is a lack of information across Europe on impacts and vulnerability assessment at regional and local levels, and on adaptation activities and measures planned or currently being implemented by countries. There is therefore a need to enhance information-sharing on impacts, vulnerability and adaptation to climate change, which requires overall coordination. This is re-inforced by the need to inform the many levels of decision-making involved in practical adaptation responses. Ensuring a wider access to and understanding of impacts and vulnerability, for example with climate and socio-economic scenarios and databases on good practice adaptation policies in the various vulnerable sectors (with a focus on regional specificities), would certainly help expanding the knowledge base across Europe.

The relevance of adaptation at the EU level is primarily concerned with coordinating information sharing, and encouraging an appropriate, proportionate and integrated implementation of adaptation measures at national, regional and local levels. The integration of adaptation into EU sectoral policies, and in addition into structural/cohesion

([8]) INTERREG and other relevant projects include: ASTRA (Developing Policies & Adaptation Strategies to Climate Change in the Baltic Sea Region), AMICA (Adaptation and Mitigation — an Integrated Climate Policy Approach), ADAGIO (Adaptation of Agriculture in European Regions at Environmental Risk under Climate Change), BRANCH (Biodiversity Requires Adaption in Northwest Europe under a CHanging climate), CIRCLE (Climate Impact Research for a Larger Europe), ClimChAlp (Climate Change, Impacts and Adaptation Strategies in the Alpine Space) and ESPACE (European Spatial Planning — Adapting to Climate Events).

([9]) See also Füssel and Klein (2004).

([10]) Partnership for European Environmental Research (PEER), http://peer-initiative.org.

funds and external relations, are key instruments in this respect, together with fostering research and involving stakeholders.

Only an integrated approach to addressing the cross-cutting nature of adaptation will deliver long-lasting measures that will enhance resilience in Europe. The issues to be considered are not only sectoral, but very importantly also cover regional and local specifics in terms, for example, of landscape types, land use and biodiversity.

Table 6.1 EU Member States progress towards National Adaptation Strategies (NAS)

Countries	Impacts, vulnerability and adaptation assessments	NAS under preparation	NAS adopted	Web links
Austria	Anpassungsstudie			www.klimaanpassung.lebensministerium.at/
Belgium	SSD	X (2012)		
Bulgaria	X			www2.moew.government.bg/recent_doc/international/climate/NAPCC_Final_English.doc
Czech Republic		X (end 2008)		www.env.cz/AIS/web-en.nsf/pages/Climate_Change
Cyprus				
Denmark	Ministry of Climate and Energy		2008	www.kemin.dk/NR/rdonlyres/1247B5C0-0BAD-464A-9997-2EAB952D9494/56490/klimatilpasningsstrategi.pdf www.klimatilpasning.dk
Estonia	ASTRA	X (2009)		www.astra-project.org
Finland	FINADAPT		2004	www.mmm.fi/attachments/5eWDKveQh/5h0aZ7Iid/Files/CurrentFile/Finlands_national_adaptation_srtrategy_julkaisu.pdf www.ymparisto.fi/default.asp?contentid=227544&lan=EN
France	GICC		2006	www.ecologie.gouv.fr/Adaptation-au-changement.html
Germany	KomPass; Klimazwei; KLIMZUG	X (1st draft end of 2008)		www.anpassung.net www.klimazwei.de
Greece	Ministry of Environment & Athens Academy			
Hungary	VAHAVA		2008	http://klima.kvvm.hu/documents/14/nes_080219.pdf
Iceland	VO			http://eng.umhverfisraduneyti.is/media/PDF_skrar/Stefnumorkun_i_loftslagsmalum_enlokagerd.pdf
Ireland	ERTDI; CCRP			www.environ.ie/en/PublicationsDocuments/FileDownLoad,1861,en.pdf www.epa.ie
Italy	X			www.conferenzacambiamenticlimatici2007.it www.apat.gov.it/site/en-GB
Latvia	ASTRA	X (2009)		www.vidm.gov.lv/eng www.astra-project.org
Liechtenstein	X			www.energie.zh.ch/internet/bd/awel/energie/de/themen/energieplanung.html
Lithuania	ASTRA			www.astra-project.org
Luxembourg				
Malta				www.mepa.org.mt/environment/index.htm?climate_change/mainpage.htm&1
Netherlands	National Programme for Spatial Adaptation to Climate Change (ARK), CcSP, Knowledge for Climate		2008	www.vrom.nl/pagina.html?id=2706&sp=2&dn=7222 www.vrom.nl/pagina.html?id=2706&sp=2&dn=7502 www.climatechangesspatialplanning.nl http://international.vrom.nl/pagina.html?id=10918
Norway	NORADAPT, NORKLIMA	X (end 2008)		www.regjeringen.no/en/dep/md/Whats-new/News/2008/ber-om-innspill-til-redegjorelse-om-klim.html?id=51146 www.cicero.uio.no/projects/detail.aspx?id=30182&lang=EN www.forskningsradet.no/servlet/Satellite?pagename=norklima/Page/HovedSide&c=Page&cid=1088796719022
Poland	X			

Table 6.1 EU Member States progress towards National Adaptation Strategies (NAS) (cont.)

Countries	Impacts, vulnerability and adaptation assessments	NAS under preparation	NAS adopted	Web links
Portugal	SIAM			www.siam.fc.ul.pt/siam.html
Romania	X	X (end 2008)		www.mmediu.ro
Slovakia	X			
Slovenia	X			
Spain	ECCE + Impacts on coastlines		2006	www.mma.es/portal/secciones/cambio_climatico/areas_tematicas/impactos_cc/eval_impactos.htm www.mma.es/portal/secciones/cambio_climatico/areas_tematicas/impactos_cc/imp_cost_esp_efec_cc.htm www.mma.es/portal/secciones/cambio_climatico/areas_tematicas/impactos_cc/pnacc.htm
Sweden	SWECLIM; SWECIA; CLIMATOOLS			http://mistras.internetborder.se/mistra/english/researchresults/researchprogrammes/completedprogrammes/sweclimswedishregionalclimatemodellingprogramme.4.1eeb37210182cfc0d680007760.html www.mistra.org/mistra/english/researchresults/researchprogrammes/activeprogrammes/mistrasweciaclimateimpactsandadaptation.4.a791285116833497ab800017356.html www.foi.se/FOI/Templates/ProjectPage____5846.aspx www.sweden.gov.se/sb/d/574/a/96002 www.regeringen.se/sb/d/8756/a/91682
Switzerland	OcCC			www.bafu.admin.ch/klima/00469/00810/index.html?lang=fr www.occc.ch/index_e.html
Turkey				
United Kingdom	UK National Risk Assessment + UKCIP studies		2008	www.ukcip.org.uk www.defra.gov.uk/adaptation www.defra.gov.uk/Environment/climatechange/uk/legislation/index.htm

7 Economic consequences of climate change

7.1 Introduction

A wide range of economic effects will result from climate change in Europe. These include effects on services associated with the natural environment (including forests and fisheries), coastal zones, agriculture, tourism, energy, human health and the built environment.

The observed and projected effects of climate change in Europe differ across regions and sectors. Many of the impacts are projected to be adverse and to lead to economic costs or losses, though there will also be economic benefits (gains). There is a strong distributional pattern for the economic effects predicted across Europe, with a significant trend towards more potentially adverse impacts in south-eastern Europe and the Mediterranean (e.g. in relation to energy demand, agricultural productivity, water availability, health effects, summer tourism, ecosystems). In northern and western Europe a more complex balance between negative and positive impacts is projected for moderate levels of climate change in the coming decades, with potential benefits derived from new farming and tourism opportunities. As climate change continues, eventually the negative impacts are projected to dominate.

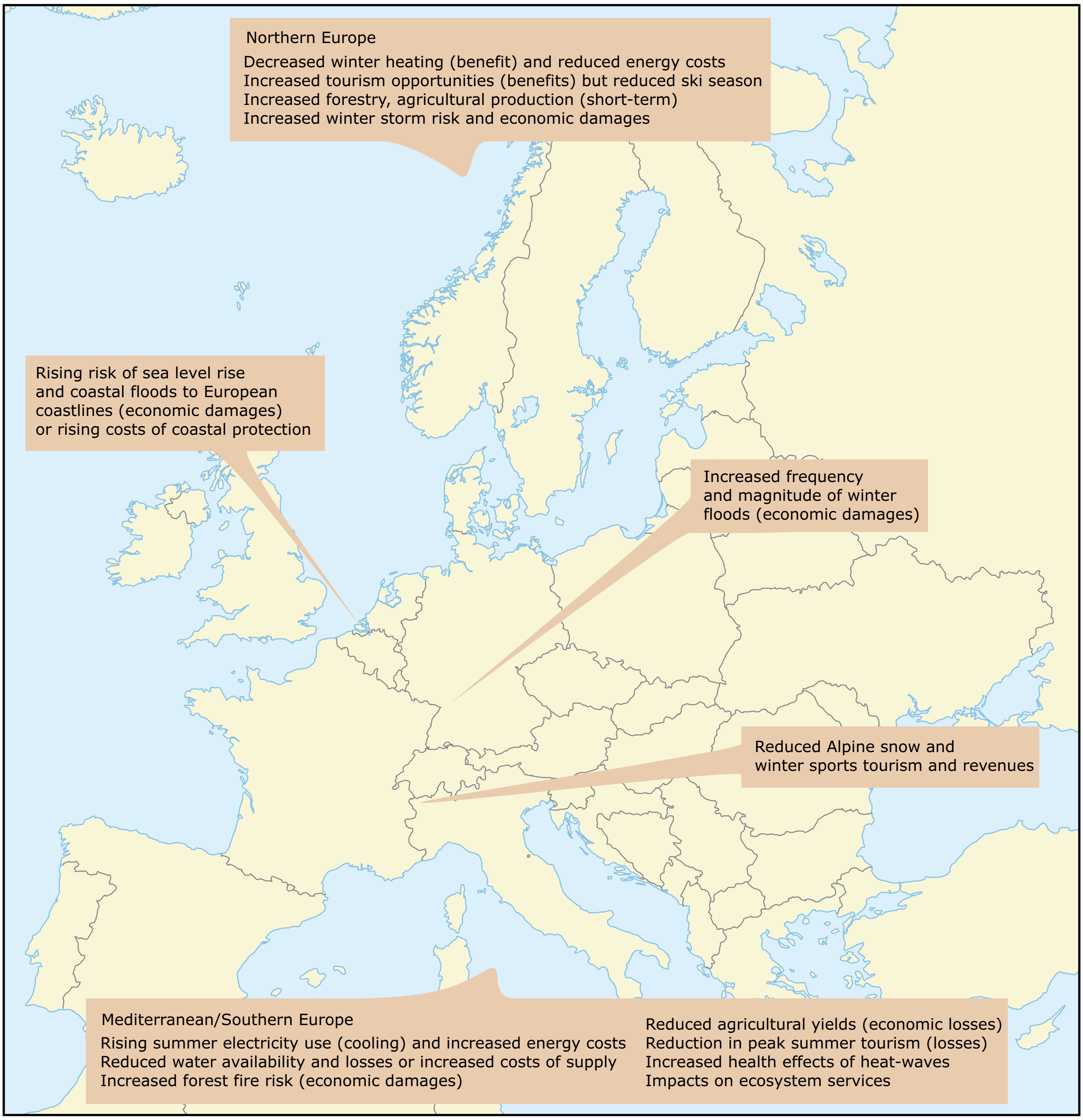
It is also evident that even if emissions of greenhouse gases were to stop today, changes in climate will continue for many decades. Therefore, in addition to mitigation, it is essential to develop proportionate adaptive responses (adaptation) as a means of moderating damages or realising opportunities associated with climate change. There is therefore also a need to consider the economic aspects of adaptation. However there has so far been more research on the physical impacts of climate change than on the costs of these impacts (their economic valuation) and of adaptation actions.

The economic costs of climate change impacts if no adaptation were to take place are known as the 'costs of inaction'. They relate to both direct and indirect impacts, including the associated socio-economic developments. Estimates of these costs and the costs of adaptation are increasingly helping to inform the policy debate, in particular in discussing the level of mitigation effort that is needed globally.

As a first indicator, direct losses from weather-related natural disasters are analysed. Past trends indicate that economic losses due to such disasters have increased considerably, particularly in recent years. Since no statistically significant increase in the frequency of events like floods has yet been observed, the increase in economic losses is probably determined mainly by other factors, such as a possible increase in the intensity of flood events, the overall increase in wealth and possibilities for insurance, and the increased amount and distribution of infrastructure vulnerable to such disasters. We have therefore also included a separate indicator on economic losses from floods (which comprise the largest share of weather-related natural disasters in Europe) for which such socio-economic effects have been removed or 'normalised' in order to assess the actual weather/climate-related trend better. It is shown that by using such a normalisation method the losses are simulated to be generally lower. Additional information and analysis are presented in subsequent sections for coastal areas, public water supply, agriculture and forestry, biodiversity loss and ecosystem goods and services, energy, tourism and recreation, health and the society as a whole. These sections should be read in connection to the indicator information presented in Chapter 5 which is not repeated here.

A brief overview of the economic effects of projected climate change across Europe is presented in the map below.

Map 7.1 Examples of potential economic effects across Europe



Source: Based on Watkiss, 2006.

7.2 Direct losses from weather disasters ([11])

Key messages

- About 90 % of all natural disasters in Europe that have occurred since 1980 are directly or indirectly attributable to weather and climate. About 95 % of economic losses caused by catastrophic events ([12]) have resulted from these weather and climate-related disasters.
- The average number of annual disastrous weather and climate-related events in Europe increased by about 65 % over 1998–2007 compared with the annual average for the 1980s, while non-weather events (e.g. earthquakes) remained stable. An unknown share of this increase can be attributed to climate change, the rest to changes in the sensitivity of human/societal systems.
- Overall losses resulting from weather- and climate-related events have increased clearly during the past 25 years. Even though social change and economic development are the main factors responsible for this increase, there is evidence that changing patterns of weather disasters are also drivers. However, it is still not possible to determine the proportion of the increase in damages that might be attributed to anthropogenic climate change.
- While in the immediate future disaster losses are projected to increase mainly as a result of societal change and economic development, the most severe effects of anthropogenic climate change on economic assets are expected in the second half of the century.

Relevance

Changes in the frequency and intensity of storms, floods and extreme temperatures affect the financial sector, including the insurance sector, through the amount of compensation payments. Examining insurance claims related to weather disasters can help to identify the sectors (e.g. agriculture, forestry, infrastructure, industry or private households) that are most affected by damage and/or could be most affected in future.

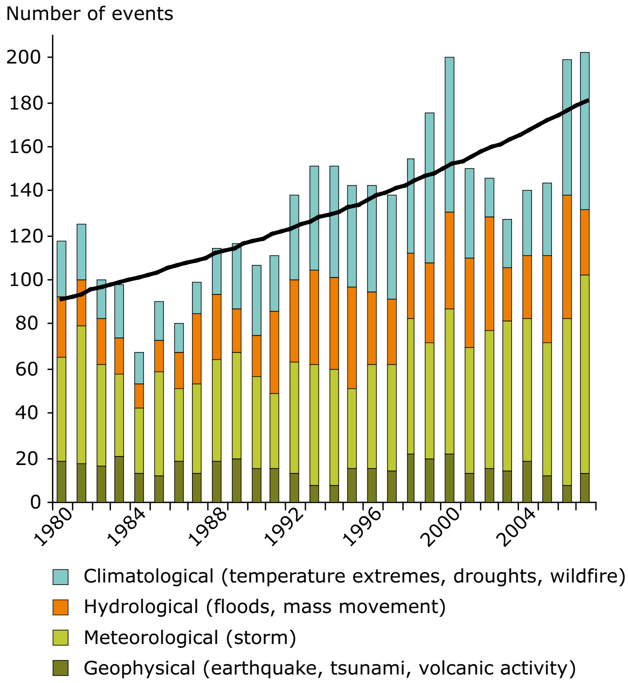
A recently published report from the United Nation Environment Programme's Finance Initiative (UNEP FI, 2006) estimated that losses from weather events are doubling globally every 12 years. Even though the observed increase in losses is dominated by socio-economic factors (such as population growth, increased number of habitations in vulnerable areas, increased wealth, increased amount and value of vulnerable infrastructure), there is evidence that changing patterns of natural disasters are also drivers (Figure 7.1). It is however not known how much of this increase in losses can be attributed to anthropogenic climate change (Höppe *et al.*, 2006).

Insurance mechanisms are key in risk management and hence can play an important role in adapting to climate change by covering the residual risks and providing incentives for risk reduction. Through their underwriting policy, the (re)insurance companies can indeed increase risk awareness and provide incentives for risk reduction. Insurance companies have inherent interests in minimising the impacts of climate change in order to maintain residual risks insurable. Through their investment policy and asset management, the financial sector as a whole (savings, loans and insurance companies as well as other institutional investors) has great influence on companies' investment decisions. They can therefore ensure that any investments made are more climate-resilient and channel money into projects related to adaptation and mitigation of climate change. On the other hand the industries with greatest exposures will have to respond increasingly with innovative products, e.g. catastrophe bonds (Bouwer *et al.*, 2007).

([11]) The most recent Munich Re dataset, which is not normalised, has been used for presenting past trends in losses due to all weather-related natural disasters (i.e. this section). This is different from the normalized indicator on losses from river flood disasters presented in Section 7.3.

([12]) The following definitions apply (Munich Re): (1) A 'major catastrophe' is defined as a 100+ fatalities event with overall losses in excess of USD 200 m; (2) A 'devastating catastrophe' is defined as a 500+ fatalities event with overall losses in excess of USD 500 m; (3) A 'great natural catastrophe' or 'GREAT disaster' is defined as leading to thousands of fatalities with the economy being severely affected and extreme insured losses (UN definition); interregional or international assistance is necessary, hundreds of thousands are made homeless.

Figure 7.1 Natural disasters in Europe 1980–2007



Source: Münchener Rückversicherungs-Gesellschaft (Munich Re), Geo Risks Research, NatCatSERVICE, 2008.

Past trends

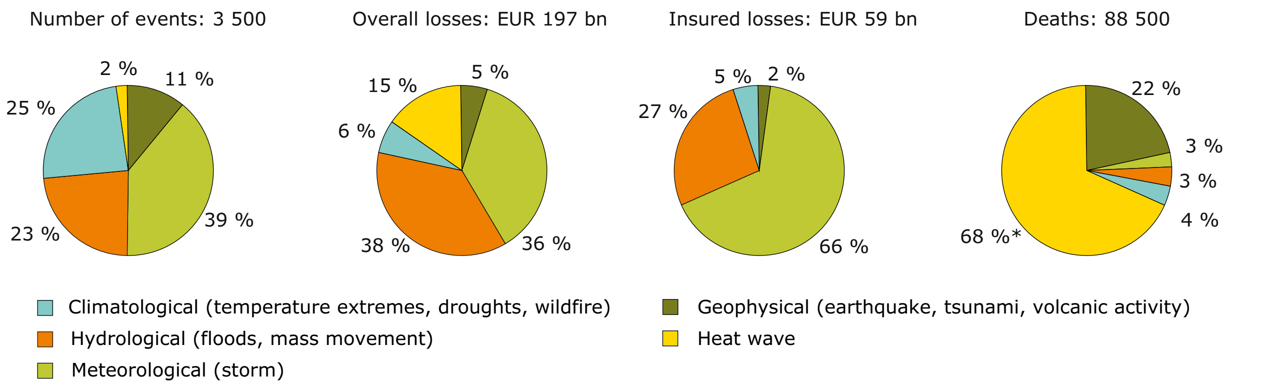
In Europe, 64 % of all loss events since 1980 are directly attributable to weather and climate events (storms, floods and heat-waves) and 25 % to wild fires, cold spells, landslides and avalanches, which are also linked to weather and climate. 95 % of the overall losses and 78 % of all deaths caused by disastrous events result from such weather and climate-related events (Figure 7.2).

The annual average number of these weather- and climate-related events in Europe increased during the period 1998–2007 by about 65 % compared with the 1980s, while non-climatic events, such as earthquakes, remained stable (Figure 7.1). An unknown share of this increase can be attributed to climate change, the rest to changes in the sensitivity of human/societal systems.

In Europe, overall losses caused by weather- and climate-related events increased during the period 1980–2007 from a decadal average of less than EUR 7.2 billion (1980–1989) to about EUR 13.7 billion (1998–2007). Six of the nine years with the largest overall losses in this period have occurred since 1999 (Figure 7.3). The insured portion of the losses generally rose, although with great year-to-year variability.

Particularly disastrous extreme events in Europe in recent years include the severe flooding in central Europe in August 2002 and the extended heat wave in 2003. The 2002 flooding in Austria, the Czech Republic, Germany, Slovakia and Hungary resulted in overall losses of about EUR 16.8 billion and insured losses of about EUR 3.4 billion (Munich Re, 2008). The 2003 heat wave (Schär *et al.*, 2004) resulted in many more deaths in north-western Europe and the Mediterranean over and above the normal numbers (Kovats and Jendritzky, 2006; Robine *at al.*, 2007) and caused significant losses in the agricultural and energy-producing sectors. As an example, the total loss from the 2003 hot summer in France (including the stress on power generation, the transport system, forests and other ecosystems, including fires, reduced wine production and decreased agricultural productivity) has been estimated at 0.1/0.2 % of

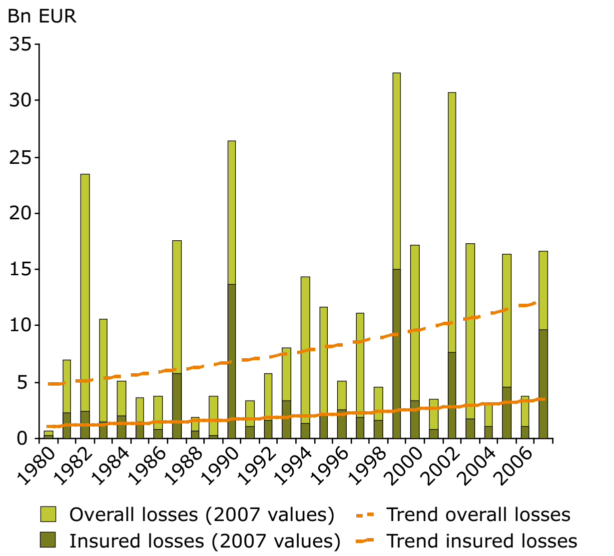
Figure 7.2 Natural disasters in Europe 1980–2007



Note: * Most of the casualties were elderly people who died in the 2003 summer heat wave (surmortality).

Source: Münchener Rückversicherungs-Gesellschaft (Munich Re), Geo Risks Research, NatCatSERVICE, 2008.

Figure 7.3 Overall and insured losses from weather disasters in Europe 1980–2007



Source: Münchener Rückversicherungs-Gesellschaft (Munich Re), Geo Risks Research, NatCatSERVICE, 2008.

GDP, equivalent to EUR 15–30 billion. The 2003 summer was also estimated to have increased building subsidence claims in the United Kingdom by 20 %, with estimated impacts of GBP 30 to GBP 120 million and damage to transport infrastructure (rail buckling and road subsidence) of £40 million (Watkiss *et al.*, 2006).

Projections

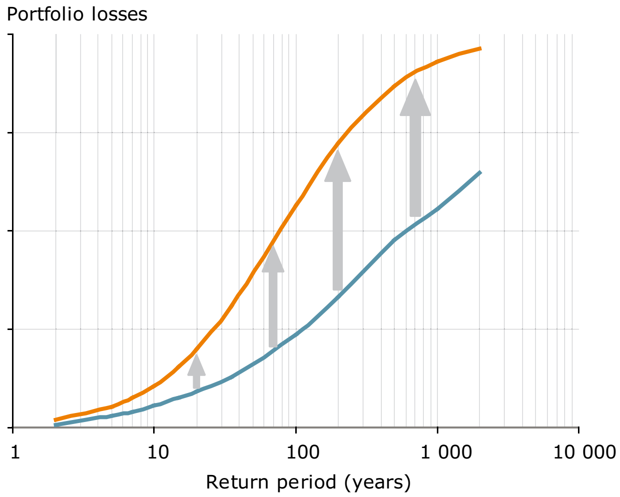
Extreme weather events such as heat waves, droughts and heavy precipitation are projected to increase in frequency and intensity in Europe, and the number of people at risk is also projected to grow (IPCC, 2007a). However, the associated time scale and hazard over the next 20 years remains uncertain. The most severe effects of anthropogenic climate change are expected in the second half of the century.

Predicting the future effects of extreme events also remains difficult because of increasing exposure caused by changes in economic development, which increases the value and density of human and physical capital. Disaster losses are expected to rise more rapidly than average economic growth, stressing the importance of risk reduction (Bouwer *et al.*, 2007).

Nonetheless, Swiss Re has estimated that in Europe the costs of a 100-year ([13]) storm event could double by the 2080s with climate change (to EUR 40 billion compared with EUR 20 billion today), while average storm losses are estimated to increase by 16–68 % over the same period. The Association of British Insurers (ABI, 2005, 2007) reports an estimated increase in worldwide annual losses from hurricanes, typhoons and windstorms by two-thirds by the 2080s, to EUR 18 billion; in addition, they indicate that subsidence costs in the United Kingdom could increase by 50 % on average clay-soil areas over the next 50 years due to climate change, and that by the 2040s, more than half of all European summers are projected to be warmer than that of 2003 which resulted in huge increases in hospital admissions and premature deaths. Finally, they report that by 2050 around a quarter of working hours will be hotter than 'comfort levels' in London.

The possible future increases in damage will enhance the vulnerability of the insurance sector (see Figure 7.4) and have important implications for the role of financial services under climate change (IPCC, 2007b). In high-risk areas people will experience increasing difficulty or costs in getting adequate insurance. This is likely

Figure 7.4 Example of the adjustment of loss distribution as a consequence of changing risk



Note: Models can produce a probable maximum loss (PML) curve, a chart that is a function of the highest amount an insurer is set to lose at a range of return periods (years).

Source: Munich Re, 2007.

([13]) In average happening once in 100 years only.

Photo: © Münchener Rück Stiftung, München

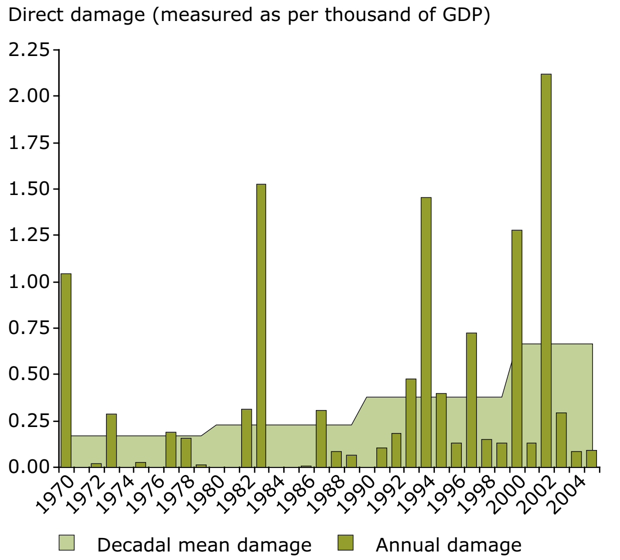
to lead to greater levels of uninsured assets, particularly to socially-deprived groups, hence exacerbating inequalities. Thus governments may need to consider new ways of ensuring that especially poorer and more vulnerable people will still be able to have insurance and/or may be compensated for possibly increasing losses in future (e.g. through public-private insurance schemes such as those introduced in Belgium and proposed in the Netherlands (Bouwer *et al.*, 2007)). Nevertheless, the noticeable differences in the climate predictions across Europe show that there is no one-size-fits-all solution and suggest, more specifically, that European countries might need to implement different insurance schemes to secure sustainable and flexible loss-compensation systems.

7.3 Normalised losses from river flood disasters

Key messages

- Economic losses as a consequence of extreme flood events in recent years have been dramatic. Flood disasters ([14]) increased significantly in Europe during the 1990s and the 2000s. The estimated losses in central Europe in 2002 were EUR 17.4 billion. This is more than the GDP of Bulgaria in that year. The cost of floods in the United Kingdom in summer 2007 is estimated at around EUR 4.3 billion.
- Although there is scientific evidence for a continuing intensification of the water cycle there is no homogeneous trend in extreme river flows/discharge in Europe.
- Analyses of long-term records of flood losses indicate that societal, environmental and economic factors clearly play an important role in the observed upward trends.

Figure 7.5 Flood losses per thousand of GDP in the EU 1970–2005



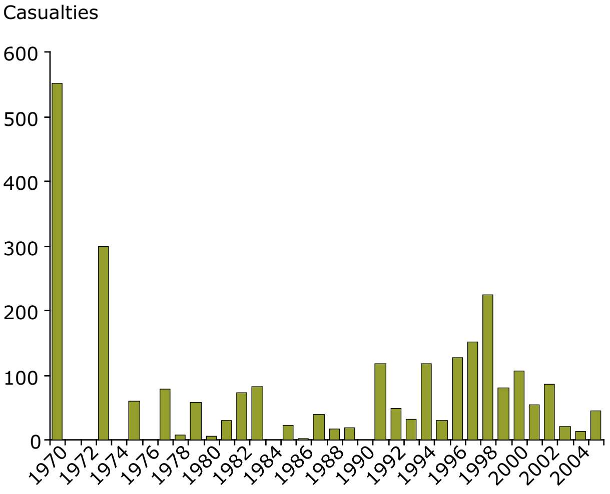
Source: Barredo, 2007.

Relevance

There is good reason to be concerned about the growth of flood losses in Europe even without taking climate change into account. Economic losses from flood disasters in Europe increased from the 1970s to the 2000s (Barredo, 2007). In addition to the rising trend in flood damage, the effects of unusually severe floods during the 1990s and 2000s increased awareness of the economic consequences of flooding. The 1997 floods in Poland and Czech Republic were responsible for losses of about EUR 5.2 billion. In 2000, Italy, France and Switzerland experienced losses of EUR 9.2 billion. In 2002 the material flood damage of EUR 17.4 billion recorded in Germany, the Czech Republic and Austria was higher than in any single previous year (Kundzewicz *et al.*, 2005). And the cost of floods in the United Kingdom in summer 2007 has been estimated at around EUR 4.3 billion.

There is no clear evidence of a climate-related trend for floods during recent decades in Europe (Mudelsee *et al.*, 2003; Kundzewicz, 2005). Even

Figure 7.6 Number of casualties caused by flood disasters in the EU 1970–2005



Source: Barredo, 2007.

([14]) Flood disasters are defined here as extreme flood events associated with actual damage (i.e. an extreme flood event in an unpopulated area may create no damage).

if there is scientific evidence of a continuing intensification of the global water cycle (Huntington, 2006) there is no homogeneous trend in extreme river flows on the European or regional scale. Analyses of long-term records of flood losses indicate that societal and economic factors have played an important role in the observed upward trends (Pielke Jr and Downton, 2000; Mills, 2005; Barredo, 2007).

Past trends

Flood disasters in Europe increased in number and amount of loss from the 1970s to the 2000s. The number of major flood disasters during the last 16 years (between 1990 and 2005) is more than twice that between 1970 and 1989 (Barredo, 2007, see also Section 5.5.3). When assessing flood losses it is important to compensate for changes in asset values and exposure over time. Failure to adjust for economic factors results in loss amounts that are not directly comparable over time and a pronounced ever-increasing trend for purely economic reasons (Höppe and Pielke Jr, 2006; Muir Wood *et al.*, 2006). Figure 7.5 therefore shows the costs of flood losses in Europe as a percentage of GDP ([15]). A continuous increase is observed in the decadal average of flood damage expressed in this way.

In fact in the period 1970–1999 the trend in EU flood losses was not statistically significant, and the increase registered in the last sub-period is a consequence of one single event, the floods in central Europe in the summer of 2002. However, even though evidence indicates that the growth of flood losses in recent decades is related to both societal and climatic factors, the shares are unclear (Pielke Jr and Downton, 2000; Barredo, 2007). It is therefore still not possible to determine the proportion of the increase in damage that might be attributed either to climate change or to societal change and economic development (Höppe and Pielke Jr, 2006). There is agreement that climate change cannot be regarded as the dominant factor for increasing flood losses. In addition there are no conclusive studies that confirm the hypothesis of changes in the occurrence of extreme river flows in Europe. In a hypothetical scenario without climate change, total flood losses will continue to increase as consequence of societal and economic factors such as increase in exposure and vulnerability (Pielke Jr and Downton, 2000).

Figure 7.6 shows the yearly number of deaths resulting from floods in Europe for the period 1970–2005. There is no clear trend. The number of deaths is very dependent on single events, as for the events of 1970 in Romania and Hungary, 1973 in Spain, and 1998 in Italy. In recent decades, early warning systems and prevention measures have improved evacuation mechanisms in the many areas exposed to floods.

The issue of extreme precipitation and surface water flooding (heavy rainfall and insufficient capacity of drainage systems) is also worth further investigation since this is already causing problems while not being well enough understood in terms of risk mapping. It has been estimated that the 2007 summer floods in the United Kingdom were caused mainly by surface water flooding and inadequate drainage (roughly 60 % of the losses) while the rest was caused by river flooding.

Projections

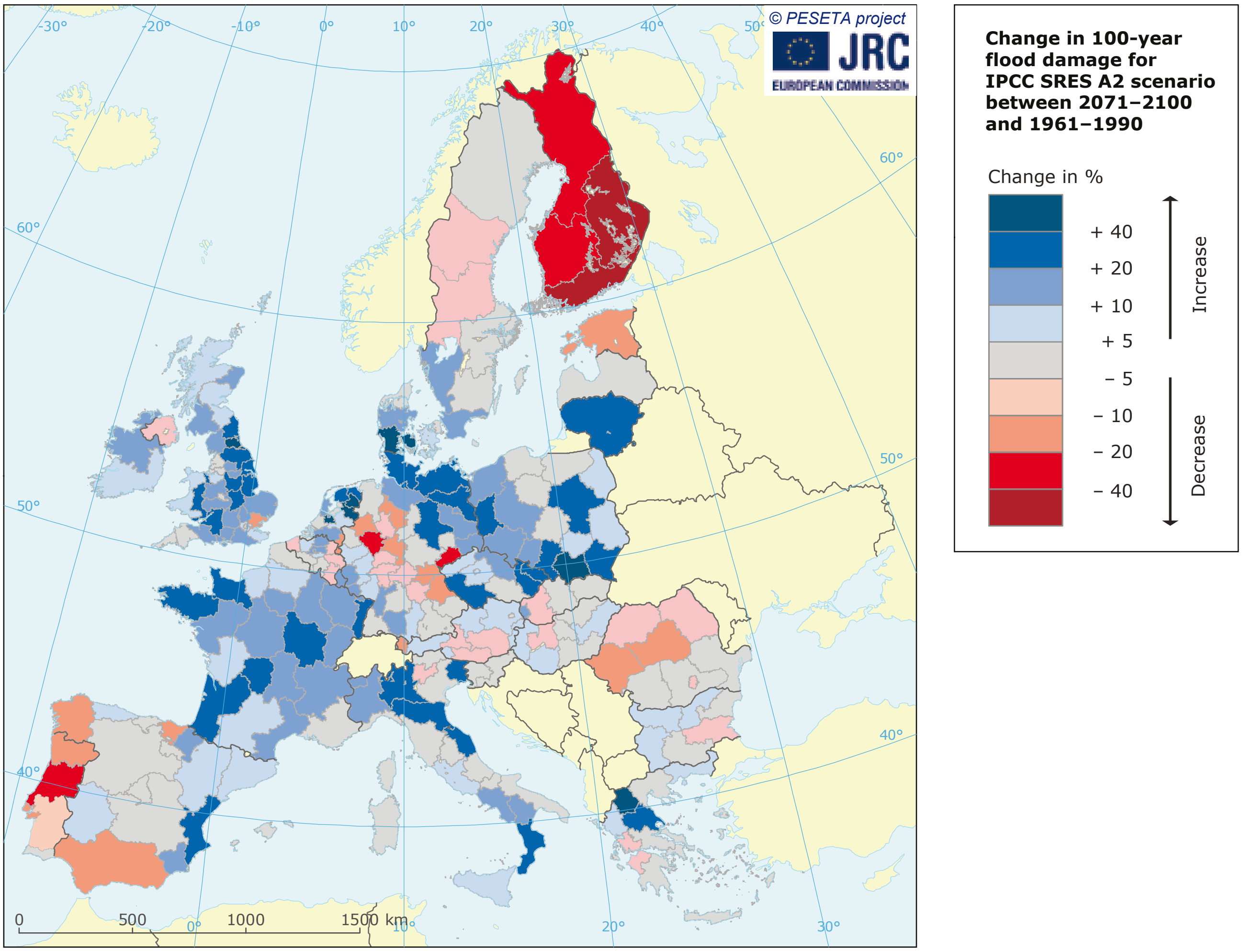
Some preliminary estimates (ABI, 2005) indicate that annual flood losses in Europe could rise to EUR 100–120 billion (tenfold) by the end of the century under high emissions scenarios. Hall *et al.* (2005) presented a national-scale assessment for England and Wales, and predicted an up to 20-fold increase in losses by the 2080s in the scenario with the highest economic growth and no adaptation. These results include changes in sea-level rise, increasing precipitation and increasing economic vulnerability. More detailed disaggregated work under the PESETA project ([16]) has modelled changes in river flows in a changing climate in Europe, studying two river catchments in detail.

- For the Upper Danube the estimated total damage of a 100-year flood is projected to increase by 2100 by around 40 % of the current damage estimate (an increase of EUR 18.5 billion) for the high emission scenario (A2) and around 19 % for the intermediate emission scenario (B2). The number of people affected is projected to increase by 242 000 (around 11 %) for the A2, and 135 000 (around 6 %) for the B2 scenario.

- For the Meuse, the potential damage of a 100-year flood is projected to increase by about 14 % for the A2 scenario and about 11 % for the B2 scenario.

([15]) GDP has been used as surrogate measure of exposure since other direct measures are not available for all the assessed countries.
([16]) In the rest of this chapter some of the preliminary results of the PESETA project on the effects of climate change in Europe will be presented. PESETA is a JRC-funded project, coordinated by IPTS, and benefitting from past DG Research projects. All results relate to the same scenario (unless otherwise stated): A2 SRES socio-economic driver, HadAM3H Global Circulation model, HIRHAM Regional Climate Model. The PESETA project also considers other scenarios derived from different socio-economic drivers and different climate models (see http://peseta.jrc.ec.europa.eu/). For river floods, see http://peseta.jrc.ec.europa.eu/docs/Riverfloods.html.

Map 7.2 Projected change in damage of river floods with a 100-year return period between 2071–2100 and 1961–1990



Note: Model calculation using the IPCC SRES scenario A2 and NUTS2 level.

Source: JRC PESETA project (http://peseta.jrc.ec.europa.eu/docs/Riverfloods.html).

These regional studies have been expanded for river flooding EU-wide. Map 7.2 shows the percentage change in economic damage for floods with 100-year return period for the SRES A2 scenario.

A number of uncertainties in these river catchment and Europe-wide results should, however, be highlighted. First, the numbers are the combined effect of the climate and socio-economic effects, and second, they do not include existing or any future flood protection and management measures ([17]), so strictly speaking they are a measure of potential exposure, not impacts (though they may underestimate potential losses by not incorporating changes in exposure). This highlights a broad issue with climate and socio-economic analysis of future flood risks. Research into flood risks in the Netherlands indicates that potential economic losses from flooding (river and sea) as a result of socio-economic change could increase by 22–45 % in 2040 (WL Delft Hydraulics, 2007). The particular role of climate change was not taken into account, because of unknown effects on flood severity and frequency. Moreover, socio-economic factors are expected to dominate future loss records, and will continue to complicate normalisation studies, because of the large inaccuracies associated with actual loss estimates, compared with geophysical data on extreme weather itself (Pielke Jr, 2007).

([17]) There are no datasets available for existing measures for the whole of Europe, so these are not considered in the assessment.

7.4 Coastal areas

Key messages

- Coastal flooding can lead to important losses. By 2100, the population in the main coastal European cities exposed to sea-level rise and associated impacts on coastal systems is expected to be about 4 million and the exposed assets more than EUR 2 trillion (without adaptation).
- Future projections of sea-level rise and associated impacts on coastal systems show potentially large increases in the risk of coastal flooding. These could have signficant economic costs (without adaptation), with recent estimates in the range of 12 to 18 billion EUR/year for Europe in 2080 under the IPCC SRES A2 scenario. The same estimates indicate that adaptation could significantly reduce this risk to around EUR 1 billion.

Climate change is an additional pressure and, as shown by the PESETA project on the effects of climate change on European coastal systems, is likely to have significant impacts on coastal zones, particularly through sea-level rise and changes in the frequency and/or intensity of extreme weather events, such as storms and associated surges. Coastal zones in Europe contain large human populations and significant socio-economic activities. They also support diverse ecosystems that provide important habitats and sources of food. One third of the EU population is estimated to live within 50 km of the coast, and some 140 000 km^2 of land is currently within 1 m of sea level. Significantly inhabited coastal areas in countries such as the Netherlands, England, Denmark, Germany and Italy are already below normal high-tide levels, and more extensive areas are prone to flooding from storm surges.

There are estimates of the physical impacts and economic costs to coasts in Europe from sea-level rise and flooding storm events. Results using the DIVA database and model produced from the DINAS-COASTS DG research project (DINAS-COAST Consortium) have been developed for Europe in the PESETA project ([18]). They show impacts increasing significantly without adaptation: in the 2080s under the A2 SRES scenario, it is estimated that around 2 000 to 17 000 km^2 of land in Europe could be permanently lost, leading to 0.1 to 1.3 million people in Europe experiencing coastal flooding each year, depending on the climate sensitivity. The economic costs of these events are estimated in the range of 12 to 18 billion euro/year for Europe in 2080 (current prices) ([19]). Large areas of coastal wetlands are also threatened, with the highest relative losses on the Mediterranean and Baltic coasts.

ABI (2006) estimates that a 40 cm rise in sea levels will put an extra 130 000 properties at risk of flooding in the United Kingdom. In total 400 000 properties will be at risk, up nearly 50 % on the current number. Without improvements to existing flood defences, the costs of a major coastal flood could soar by 400 % to as much as GBP 16 billion. Essential services and lives will also be at risk, e.g. 15 % of fire and ambulance stations and 12 % of hospitals and schools are in flood-risk areas. The elderly will be particularly affected as the number living on, or moving to, the coast is well above the national average.

Using the same climate and sea-level projection as above (A2 scenario in the 2080s), with hard adaptation measures (dike building and beach nourishment) included, the DINAS-COAST Consortium and the PESETA project suggest that the land loss falls to less than 1 000 km^2 and the economic costs to around 1 billion euro/year. The adapation costs (mainly coast protection with dikes) are estimated at some 1 billion euro/year, but these achieve considerable reductions in the residual damage.

ABI (2006) also estimates that spending around GBP 6–8.5 billion on improving coastal defences would have a substantial impact on damages, both now and in the future. In other words, they would virtually pay for themselves in a single incident, ignoring the wider social and economic costs that arise from regional damage. But of course sea

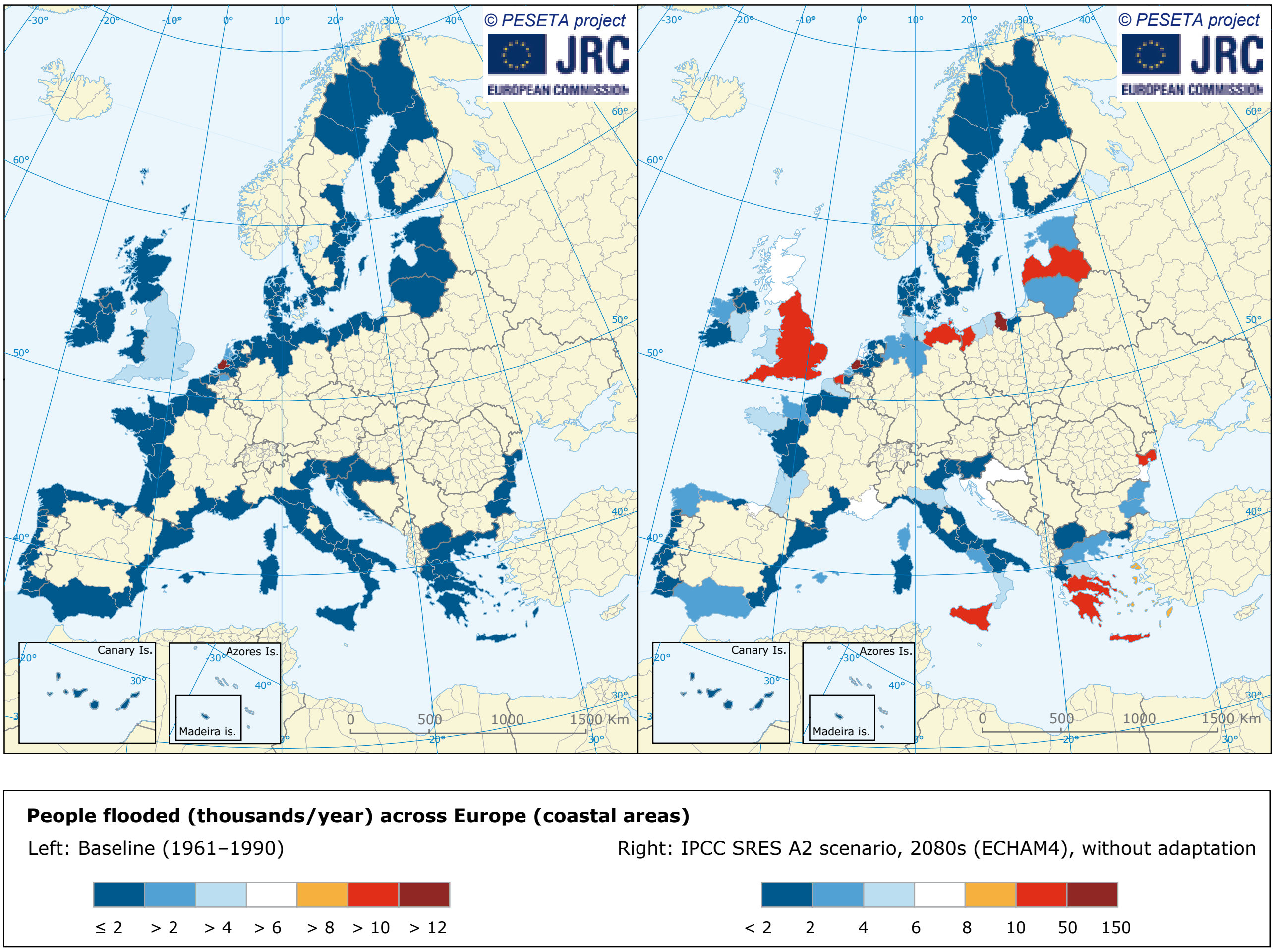
([18]) See http://peseta.jrc.ec.europa.eu/docs/Costalareas.html.
([19]) This includes the combined effect of climate and future socio-economic developments.

defences do not simply operate on a single occasion: in reality defences would prevent many less severe storm surges from causing damage. Typically this type of capital investment may deliver benefits over its lifetime worth seven times the cost. The benefits from this investment will be even greater if the frequency of storms increases in line with predictions.

However, there are many possible adapation measures that can minimise the impacts of sea-level rise and would have significant benefits (including soft measures) such as: coastal defences (e.g. physical barriers to flooding and coastal erosion such as dikes and flood barriers); realignment of coastal defences landwards; abandonment (managed or unmanaged); measures to reduce the energy of near-shore waves and currents; coastal morphological management; and resilience-building strategies. Despite some difficulties in estimation, there is an increasing literature reporting the direct costs of adaptation to sea-level rise and estimating optimal levels of protection based on cost-benefit analysis.

Recent work (OECD, 2008) has also looked at threats to current and future major coastal cities from sea-level rise (0.5 metres global average) and storm surges. It assessed exposure to a 1 in 100 year flood event, looking at population and asset value exposed now and with sea-level rise in 2100 for the following cities: Amsterdam, Rotterdam, Hamburg, London, Copenhagen, Helsinki, Marseille-Aix-en-Provence, Athens, Napoli, Lisbon, Porto, Barcelona, Stockholm, and Glasgow. For these cities, the exposed population increases from 2.3 million to 4.0 million, and the exposed assets from EUR 240 to EUR 1 400 billion (the values are dominated by London, Amsterdam, and Rotterdam).

Map 7.3 Modelled number of people flooded across Europe's coastal areas in 1961–1990 and in the 2080s



Source: JRC PESETA project (http://peseta.jrc.ec.europa.eu/docs/Costalareas.html).

7.5 Public water supply and drinking water management

Key messages

- Economic consequences of climate change impacts will be particularly pronounced in areas where increases in water stress are projected. Evaluation studies of the economic consequences of increasing water stress are now emerging. They indicate that adaptation costs are generally significantly lower than the losses that would be incurred without adaptation.

Changes in water demand depend strongly on economic and sectoral growth and societal developments. Household water demand is likely to increase with climate change, with more water used for garden watering and personal hygiene, although a clear separation exists between components that are sensitive to climate change (showering, gardening, lawn sprinkling, golf courses, swimming pools and aqua parks), from those that are non-sensitive (e.g. dish washing, clothes washing). Changes in the quantity and quality of river flows and groundwater recharge may affect drinking water supply systems and alter the reliability of raw water sources (see Chapter 5 for details).

Problems of water supply in islands and tourist resorts are becoming increasingly common, e.g. Cyprus is exploring the possibilities of transporting water in tankers from Lebanon. Hot summers such as 2003 and 2007 may provide an indication of future climate impacts on peak water demand (e.g. 15 % increase in public demand in the Netherlands in August 2003; state of emergency declared on the Cyclades islands in Greece in summer 2007 and reservoirs down to less than 5 % full in Turkey's capital (Ankara, home to 4 million´people)). Other studies, however, indicate that the increase in household water demand may be rather small. Downing *et al.* (2003) concluded that per capita domestic demand in England could rise by an extra 2 to 5 % during the next 20 to 50 years as a result of climate change.

High water temperatures, low water flows and therefore less dilution of pollutants may have severe consequences on the quality of drinking water and recreation activities related to water. Saline intrusion in coastal aquifers making the water unsuitable for drinking water may be exacerbated by future sea-level rise.

These effects have economic consequences, especially in areas where there are predicted increases in water stress. Alcamo *et al.* (2007) project that the percentage of land area under high water stress in Europe is likely to increase from 19 % today to 35 % by the 2070s, and the additional number of people affected is expected to be between 16 and 44 million. Some studies on the economic consequences of increasing water stress are emerging. Work in the United Kingdom has estimated the economic losses to households of foregone water use due to the anticipated water deficit by 2100 in south-east England at between GBP 41 and GBP 388 million per year (depending on the scenario). However, the costs of adaptation to largely (but not entirely) eliminate these deficits would be only GBP 6 to GBP 39 million per year.

7.6 Agriculture and forestry

Key messages

- The hot summer of 2003 in Europe is estimated to have led to EUR 10 billion in economic losses to farming, livestock and forestry from the combined effects of drought, heat stress and fire.
- Climate-related increases in crop yields are expected mainly in northern Europe (by about 10 %) with reductions (of 10 % or more) in the Mediterranean and the south-west Balkans.
- There are likely to be changes in forest growth with climate change, and related economic consequences, though projections of future net changes in Europe are uncertain.

Agriculture

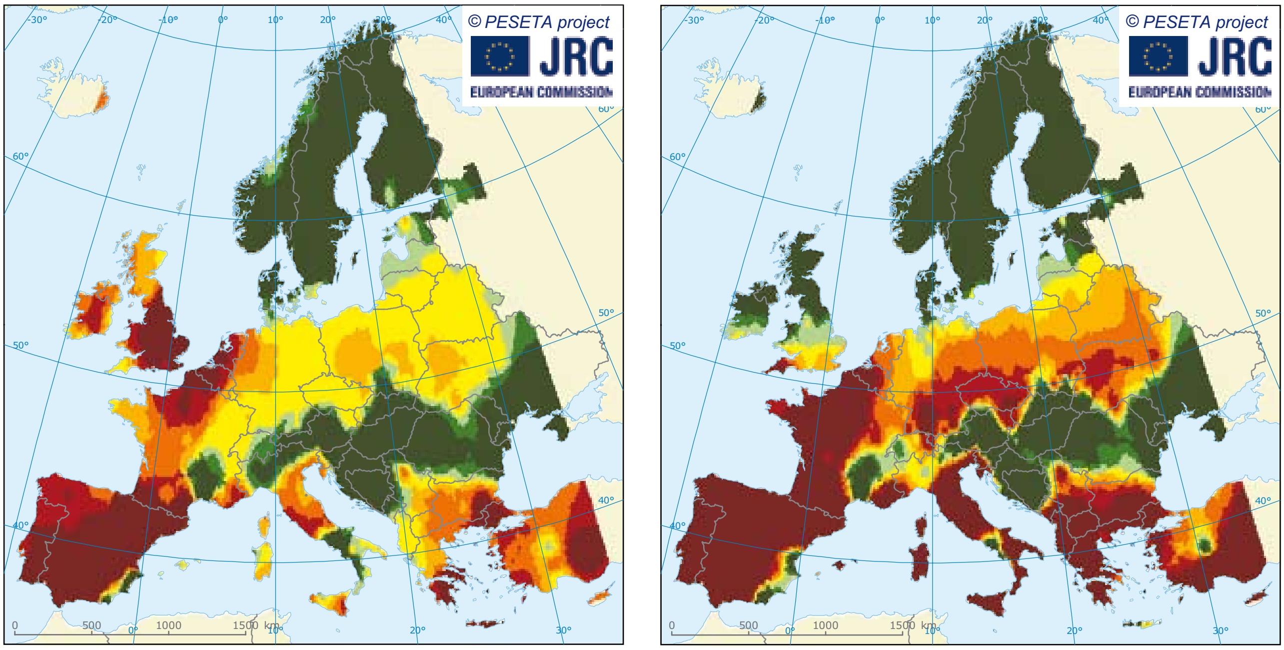
Agriculture accounts for only a small part of gross domestic production (GDP) in Europe, and it is considered that the overall vulnerability of the European economy to changes that affect agriculture is low (EEA, 2006). However, agriculture is much more important in terms of area occupied (farmland and forest land cover approximately 90 % of the EU's land surface), and rural population and income. The agriculture sector has a strong influence on other sectors, and, moreover, the effects of climate change may still be substantial at the European level because of the spatial distribution of changes. The overall economic indicators are related partly to total yield and market prices, as well as to many other factors (e.g. subsidies, labour and production costs, global price changes, efficiency and productivity, technological development, consumer demand, socio-economic development) ([20]). Hence climate change is only one driver among many that will shape agriculture and rural areas in future decades. Socio-economic factors and technological developments will need to be considered alongside agro-climatic changes to determine future trends in the sector. In this respect, most projections of long-term impacts on yields do not fully consider technological progress and adaptation.

Agriculture is a more significant sector in southern European (Mediterranean) and southerly eastern European countries in terms of employment and GDP, and these countries will face greater stresses due to climate change that will lead to lower yields. A loss in agricultural potential would therefore impose a larger income loss in these regions than over the rest Europe. In contrast, the agricultural systems in western Europe are considered to have lower sensitivity to climate change, and modelling predictions show likely opportunities in terms of yield increases and wider agricultural crops for northern Europe. The recent IPCC 4th assessment report (2007b) concludes that in northern Europe, climate change is initially projected to bring mixed effects, including some benefits such as increased crop yields and increased forest growth. However, as climate change continues, its negative impacts are likely to outweigh its benefits.

Most of the analyses now build in (autonomous) adaptation, reflecting a likely trend of producers to alter practices and crop types by region as the climate changes. Several studies show the likely spatial patterns outlined above, with a strong distribution of yield changes across Europe, as found in the recent PESETA project ([21]), which has projections for regional yield changes for the 2080s. It shows that south and west Europe could experience a decrease in yields of 10 % or more (due among others to shortening of the growing season), though there are also improvements of yields in Nordic countries (increase in growing season, but also higher minimum temperatures in winter). The general decreases in yields in southern Europe will be combined with increases in water demand. Recent valuation studies in the United Kingdom predict increases in yields and also revenue in the 2020s, but with these declining by the 2050s and expected economic losses of up to GBP 24 million/year by the 2080s, particularly in more southern areas where water becomes increasingly limited.

([20]) There are currently no detailed data available on subsidy distribution by crop and region.
([21]) See http://peseta.jrc.ec.europa.eu/docs/Agriculture.html.

Map 7.4 Projected crop yield changes between the 2080s and the reference period 1961–1990 by two different models



Simulated crop yield changes by 2080s relative to the period 1961–1990 under the HadCM3/HIRHAM (left) and ECHAM4/RCA3 (right) A2 scenario

Change in %

– 30 – 15 – 10 – 5 0 5 10 15 30

Note: Model calculations using a high emission scenario (IPCC A2) and two different climate models: HadCM3/HIRHAM (left), ECHAM4/RCA3 (right).

Source: JRC PESETA project (http://peseta.jrc.ec.europa.eu/docs/Agriculture.html).

However, while these models generally consider the effects of projected changes in temperature and CO_2 fertilisation, they do not fully consider issues of water availability, and rarely consider extreme events. The latter could be important for Europe in relation to heat extremes and floods. As an example, the droughts of 1999 caused losses of more than EUR 3 billion in Spain (EEA, 2004) and the hot summer of 2003 in Europe is estimated to have led to EUR 10 billion in economic losses to farming, livestock and forestry from the combined effects of drought, heat stress and fire (Munich Re, 2008) ([22]). A proactive risk management and insurance scheme will therefore be vital to European agriculture in the near future. A major paradigm shift will also be required in order to incentivise autonomous and planned adaptation.

Finally, the role of autonomous and planned adaptation is extremely important for agriculture, and this has been studied intensively. While most analyses consider short-term autonomous adaptation, there are also potential long-term adaptations in the form of major structural changes and technological progress to overcome adversity caused by climate change, which are usually the result of a planned strategy. There are a number of studies that show the benefits of adaptation to farmers in reducing negative impacts, although the costs of adaptation are rarely made explicit.

A recent study commissioned by the EC (DG AGRI) on 'Adaptation to Climate Change in the Agricultural Sector' and undertaken by AEA-T and the Universidad de Politécnica de Madrid,

([22]) Overall net positive effects on the UK agricultural, fruit and viticulture industries are also estimated to have occurred with estimated economic benefits of GBP 64 million. However, the authors note that it is not possible to conclude with any confidence that these gains/losses are wholly attributable to the weather conditions that prevailed in the summer of 2003.

analysed potential impacts, risks and opportunities as well as adaptation options for EU agriculture (EC, 2007). It indicates for example that the prolonged drought in Finland in 2002/2003 caused estimated losses of EUR 100 million compared with normal years. Water had to be transported by tanker to more than 1 100 farms (Martilla *et al.*, 2005). In addition, it reports recent research activities such as that undertaken by the Latvian State Institute of Agrarian Economics on an agricultural insurance system.

Potential economic effects on agriculture beyond cereals yields are also key issues. The expected increase in climate variability (extreme events) could trigger variability in agricultural production, food prices and farm income as the frequency of crop failures increases. Year–to-year weather variability is the main determinant of yield levels, which determine prices and the inherent risks of farming.

Forestry

Forestry is also a small part of European GDP, although in a large part of Europe it represents an important economic sector and also provides potential for carbon sequestration and environmental services. Forests in Europe are likely to be affected by climate change, in terms of distribution (forest area will expand in the north, but contract in the south), species composition, forest yield, windstorm damage and forest fires (Alcamo *et al.*, 2007, Eurostat Pocketbooks — Forestry statistics 2007 edition). Potential economic consequences of forest fires (i.e. enlargement of the fire-prone area and a lengthening of the fire season) include lost production and direct costs of fire fighting. In the summer 2003 heat wave in France, the costs of fighting forest fires for the Ministry of Interior increased from EUR 83 million in a normal year to EUR 179 million.

An on-going study commissioned by the EC (DG AGRI) on the 'Impacts of climate change on European forests and options for adaptation' led by the European Forest Institute (EFI), analyses in depth exposure, sensitivity, potential impacts, adaptive capacity and vulnerability in relation to European forests as well adaptation options (EC, 2008a). It indicates that forest damage by wind and snow is a continuing cause of economic loss in forestry throughout Europe. The economic cost of the damage corresponds approximately to hundreds of millions of US dollars each year. The economic impact of wind damage is particularly severe in managed forests because of the reduction in the yield of recoverable timber, the increased costs of unscheduled thinning and clear-cutting, and resulting problems in forestry planning. For example, in Sweden, approximately 4 million m^3 of timber is damaged annually by snow and wind, roughly corresponding to EUR 100 million.

While the economic effects of timber production can be captured using market prices, forests (natural and managed) play a much greater role than timber alone, and there is a need to progress towards a total economic valuation of forestry including full ecosystem goods and services.

7.7 Biodiversity and ecosystem goods and services

Key messages

- Work undertaken under Phase I of the joint initiative 'The Economics of Ecosystems and Biodiversity' tentatively indicates that the cumulative welfare losses due to loss of ecosystem services could be equivalent to 7 % of annual consumption by 2050. This damage calculation captures a number of causes for biodiversity loss, including climate change as one of the pressures. However, little is currently known either ecologically or economically about the impacts of future biodiversity loss, and further assessment and methodological work is needed.
- Methods for the valuation of ecosystems are improving, but it is not yet possible to cover a wide range of ecosystem productivity, goods and services, or the economic benefits to direct and indirect users.

The functioning of ecosystem service provision by many natural and semi-natural ecosystems in Europe is under threat from land use change and other pressures, including climate change. Such services include food and water supply, climate regulation and species preservation. Particularly sensitive areas include the Arctic region, mountains, and various coastal zones, especially in the Baltic and parts of the Mediterranean. The ecosystem services can be divided into supporting, provisioning, regulating and cultural. Most functions attributed to provisioning services have a direct market value e.g. food, fish, timber and fresh water. Other functions, such as regulating and cultural services and the ability of an ecosystem to provide natural habitat for flora and fauna, and biodiversity have, however, no direct market price, though it is possible in some cases to approximate the value of these.

Past and ongoing research tries to value ecosystem loss, reflecting ecosystem productivity, goods and services, but also the wider use of ecosystems, increasingly using the Millennium Ecosystem Assessment framework (MEA, 2005). This uses the rate of extinction (per thousand species per millennium) to illustrate some of the changes in ecosystem services. There is also a growing body of more general economic studies on ecosystems and biodiversity, and of work studying places where biodiversity loss has led to the loss/degradation of ecosystem services and consequently to economic costs. However, while methods for valuation of ecosystems are improving, as yet they fail to cover the full range of ecosystem productivity, goods and services, and direct and indirect economic benefits to users. Nonetheless, there are some illustrative values showing potentially very high estimates (e.g. IPCC, 2007b). Hence, at this stage it is extremely difficult to put forward indicators for the economic effects on ecosystems associated with climate change.

Following commitments made at the G8+5 meeting of Environment Ministers in Potsdam in March 2007, a joint initiative has been launched to draw attention to the global economic benefits of biodiversity and the costs of biodiversity loss and ecosystem degradation, entitled 'The Economics of Ecosystems and Biodiversity' (TEEB). The initiative will evaluate the costs of the loss of biodiversity and the associated decline in ecosystem services worldwide. It will consider the failure to take protective measures vs. the costs of effective conservation and sustainable use, and provide a better understanding of how action to halt the loss of biodiversity makes economic sense. The interim report (EC, 2008b), which gives the results of Phase I of the initiative, was presented at the high-level segment of the 9th Conference of the Parties (COP9; May 2008) to the UN Convention on Biological Diversity (CBD) whose aim is to significantly reduce the loss of biodiversity by 2010. Work undertaken under Phase I of TEEB tentatively indicates that the cumulative welfare losses ([23]) due to loss of ecosystem services could be equivalent to 7 % of annual consumption by 2050 ([24]). This damage calculation captures a number of causes for biodiversity loss, including climate change as one of the pressures.

The study therefore showed that the problem is potentially severe and economically significant, but that we know relatively little both ecologically and economically about the impacts of future biodiversity loss. Further work is envisaged in Phase II of the joint initiative, also to further elaborate the assessment framework and the methodology.

([23]) This is calculated as a welfare loss and not a GDP loss since a large part of ecosystem services is currently not included in GDP.
([24]) This is a conservative estimate. For details see EC, 2008b.

7.8 Energy

Key messages

- Historic data on heating degree days shows a fall in recent years in Europe, indicating a benefit from reduced space heating. Actual energy demand from these changes is also determined by technical and socio-economic factors, including behavioural changes. At present, no data are available on cooling degree days across Europe, although country-specific data show some increases in cooling degree days over the same period, consistent with greater space-cooling demand.
- Future projections of climate change suggest reductions in heating degree days in Europe, but increases in cooling degree days. The net change in energy demand is difficult to predict, but there will be strong distributional patterns, with significantly reduced space-heating demand in northern Europe and increased space-cooling demand in southern Europe, with associated costs and benefits. There may also be increases in energy demand associated with adaptation to climate change, e.g. for water supply.
- The projected change in river runoff due to climate change will result in an increase in hydropower production by about 5 % and more in northern Europe and a decrease by about 25 % or more in the south. Dam safety may be affected under changed climatic conditions with more frequent extreme flows and possibly natural hazards.
- Climate change could have an adverse impact on thermal power production as most studies show that summer droughts will be more severe, hence limiting the availability of cooling water in terms of quantity, appropriate temperature and power plant efficiency.

Heating and cooling demand

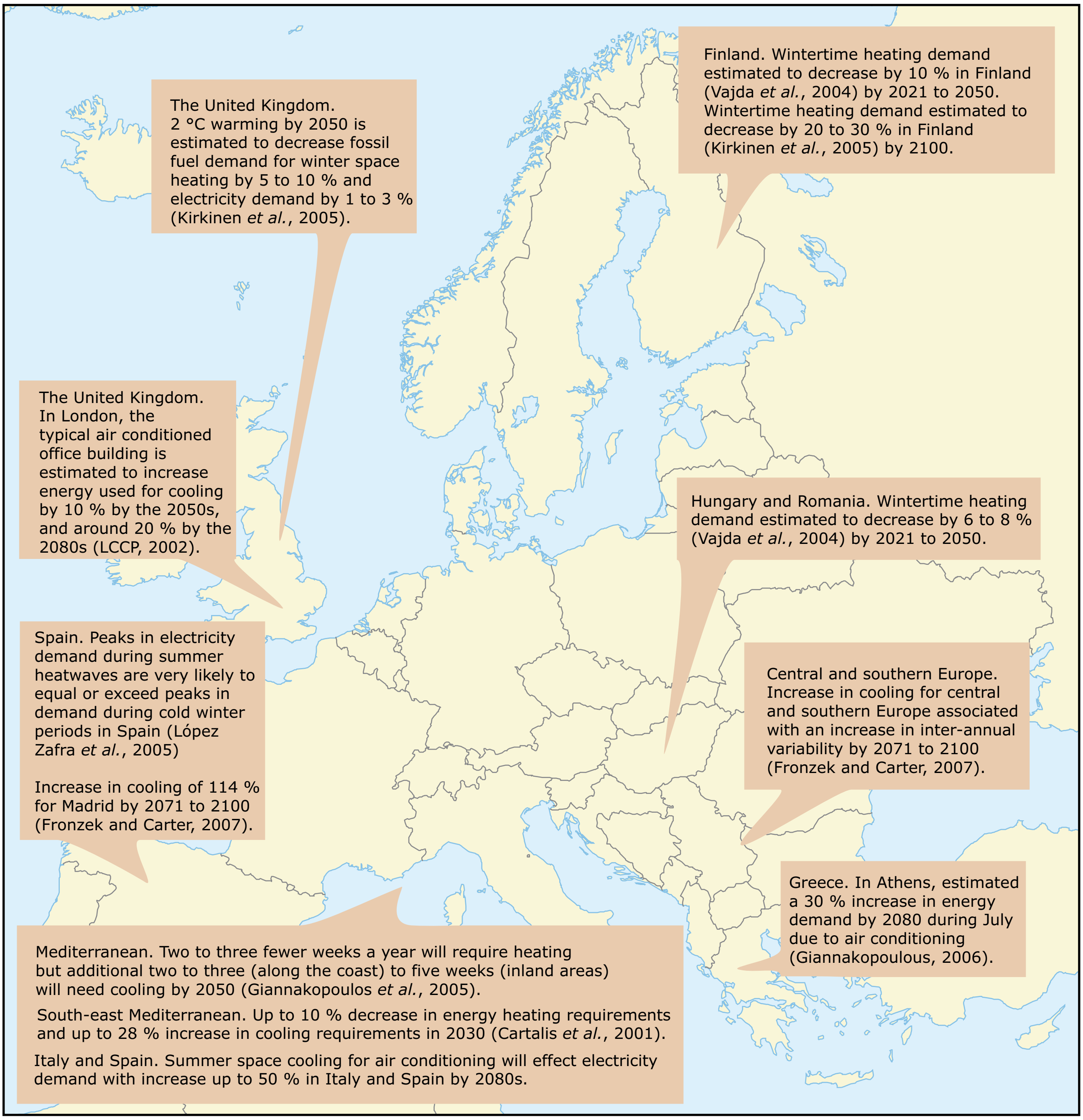
Energy industries are the single most important source of greenhouse gas emissions in Europe and will also be affected by climate change. Numerous studies have demonstrated that energy demand is linked to climatic conditions (e.g. outside temperature), particularly in the domestic sector, but also in the service and industry sectors (Eurostat, 2007). The changing climate in Europe is likely to lead to a decrease in demand for winter heating, but an increase in summer cooling, which can be described as either an impact or an adaptation measure that in some cases can offset mitigation efforts. There are also other factors that affect the apparent temperature and the related energy demand such as wind chill, illumination and cloud cover, and precipitation.

Energy demand has risen very strongly in Europe over recent years, due to technical, behavioural and socio-economic factors (Eurostat, 2007). Actual final energy consumption for heating since 1997 has been persistently below the projected temperature-corrected consumption. This suggests warmer-than-average years at the European level, which is confirmed by the information on heating degree-days. The heating degree days (HDD) data show that recent years (since 1996) are all lower than the long-term average ([25]). Note that at present, net energy demand in Europe is dominated by space heating rather than cooling. However, it is difficult to separate (or 'normalise') the specific effect of outside temperature from these data from technical, behavioural and socio-economic factors ([26]). The heating degree day indicator above shows a falling trend reflecting the recent warmer years, translating into a lower winter heating burden (a benefit). There is currently less data available on space cooling demand at the European level, which relates to human comfort levels, but also cooling for appliances.

Projections for Europe suggest further reductions in heating degree days, and further increases in cooling degree days, due to mean average temperature

([25]) The relative degree days are weighted by population or area. The HDD figures for individual European countries vary considerably, with much higher HDD values for Scandinavian countries, and much lower ones for southern European countries, though there is a downward trend across both regions.
([26]) For example the effects of population, housing density, housing stock, insulation levels, technology, equipment penetration level, efficiency of heating or cooling units, behaviour, perceived comfort levels, energy prices, income.

Map 7.5 Projections of energy demand for several time horizons in Europe

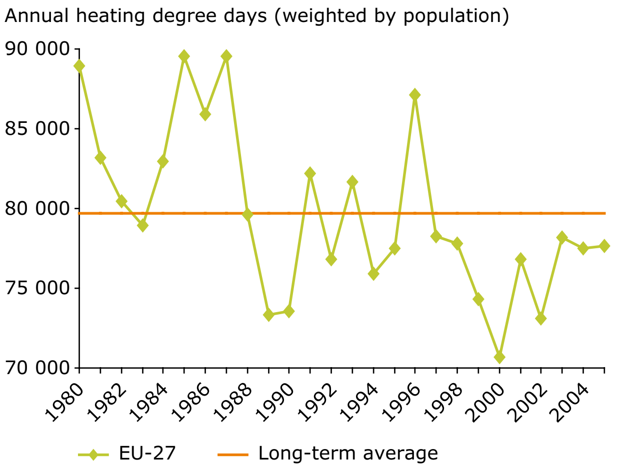


Source: Alcamo *et al.*, 2007.

increases. For cooling, there may be additional peaks associated with heat waves. The overall changes in energy and economic costs (at a net level) are predicted to be modest in the short-medium term, due to the aggregated effects of decreased winter heating demand vs. increased summer cooling demand. However, strong distributional patterns are expected across Europe — with rising cooling (electricity) demand in summer in southern Europe, compared with reduced heating (energy) demand in winter in northern Europe (Alcamo *et al.*, 2007; see Map 7.5). This translates into a likely net benefit to northern Europe and net losses for southern Europe.

The actual net economic costs are more complex to estimate, due to interactions between energy sources, technology, socio-economic trends and future mitigation scenarios. Winter heating demand is primarily from fossil-fuel use, and summer cooling from electricity, and there may be additional issues

Figure 7.7 Heating degree days in Europe 1980–2005



Source: Eurostat (http://epp.eurostat.ec.europa.eu/cache/ITY_SDDS/EN/nrg_esdgr_sm1.htm) and JRC (JRC IPSC/Agrifish Unit/MARS-STAT Action).

of peak demand levels in southern Europe in the summer ([27]). Adaptation has a role to play here, particularly through alternatives to mechanical air conditioning, e.g. through passive ventilation, building design and planning; synergies between mitigation and adaptation are important to consider in this context. Finally, there may also be an emerging issue of energy use for water supply increasing (pumping, desalinisation, recycling, irrigation, water transfers). Again, these are likely to be greater in southern Europe where overall precipitation levels are projected to fall. There is also the potential for extreme weather events (e.g. storms) to increase the risk of energy infrastructure failure.

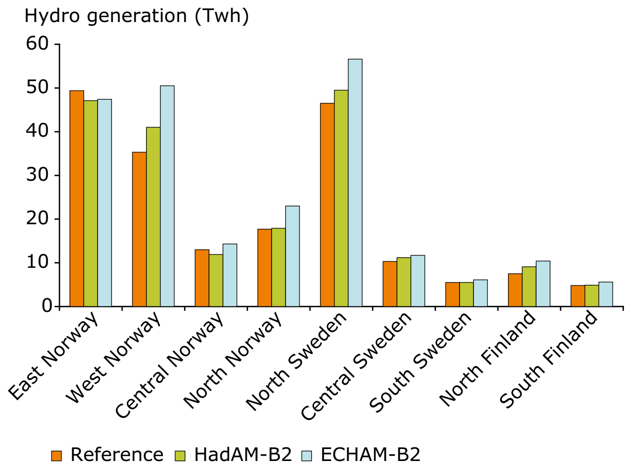
Hydropower and cooling water for thermal plants

The production of electricity is strongly dependent on water, both for cooling in power plants and for hydropower ([28]). In some areas, hydropower may benefit from increased river runoff, while in others this potential will decrease (see Section 5.5 for details). The generation of electric power in thermal (in particular coal-fired and nuclear) power stations often relies on large volumes of water for cooling. During heat waves and drought periods the use of cooling water may be restricted if limit values for temperature are exceeded, which may force plant operators to work at reduced capacity or even temporarily close down, with potentially serious consequences.

Since the 1970s, annual energy production of some existing hydropower stations in Europe has decreased, in particular in Portugal, Spain and other southern European countries (UCTE, 1999). This has been attributed to changes in average discharge, but whether this is due to temporary fluctuations or are already the consequences of long-term changing climate conditions is not yet known (Lehner *et al.*, 2001). Dam and reservoir safety may be affected under changed climatic conditions by more frequent extreme flows. However, evaluating changes in reservoir safety is complex (Veijalainen and Vehviläinen 2006; Andréasson *et al.*, 2006).

The EuroWasser study (Lehner *et al.* 2001, 2005) demonstrates a clear north-south gradient. Although there are large local differences between the outcomes for the two models used (ECHAM4 and HadCM3), especially in the Alps and part of the Mediterranean region, both show increases in hydropower production up to 25 % or more in north Europe, and reductions by 25 % or more in southern parts by 2070.

Figure 7.8 Projected changes in hydropower production in Scandinavia



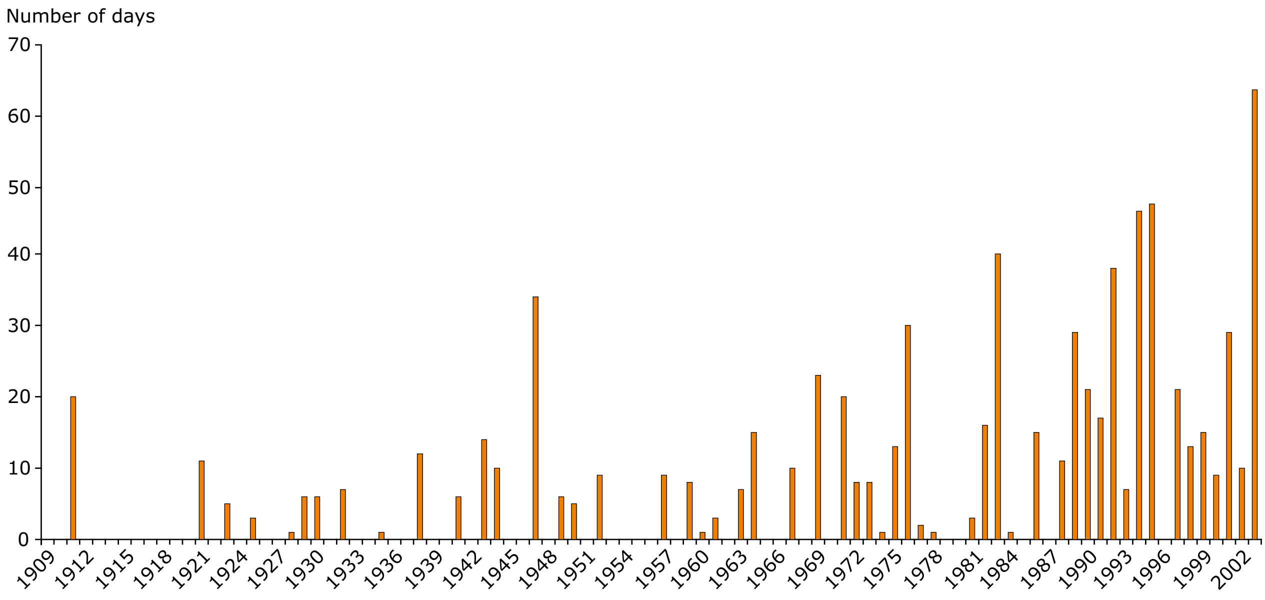
Note: Reference period 1961–1990, projections for 2071–2100 for two models (HadAM and ECHAM) and IPCC SRES scenario B2.

Source: Mo *et al.*, 2006.

([27]) While the overall energy balance may not change that greatly in Europe as a result of climate change, there could still be important economic effects. Winter space heating is provided by fuels (coal, oil, gas) that can be stored. Summer cooling is provided by electricity, which cannot be stored easily. A rise in peak summer electricity demand, associated with cooling and heat waves in southern Europe, could increase the plant peak capacity needed, which would be expected to lead to higher marginal costs.

([28]) In 2005 hydropower contributed 9.25 % of the electricity consumption in the EU-27 (Eurostat energy balances). The share of hydropower in the electricity production is usually high in the northern countries and countries in the Alps. In 2001, the EU agreed that 21 % of the total electricity consumption in 2010 should come from renewable resources (EU, 2006). In 2005, the share of renewable energy sources in gross electricity consumption was 14 %, of which hydropower represented 66 % (Eurostat energy balances).

Figure 7.9 Number of days with water temperature higher than 23 °C in the river Rhine (Lobith, the Netherlands) 1909–2003



Source: Bresser *et al.*, 2006.

The Nordic Climate and Energy study (covering Scandinavia, Iceland and the Baltic states; Bergström *et al.*, 2007) also projects increases in hydropower production in Scandinavia in more detail due to the use of RCMs (Regional Circulation Models) for downscaling. Generally the increase is largest in the western coastal regions. Figure 7.8 shows the hydropower production by regions for the reference period 1961–1990 and for 2070–2100 for two models. Decreased precipitation is expected to have an adverse impact on the electricity generation sector where rivers provide the cooling water. Power stations have to be shut down when water temperatures exceed ([29]) or river levels fall below certain thresholds (see Figure 7.8). Electricity production has already been significantly reduced in various locations in Europe during very warm summers, such as in 2003, 2005 and 2006 (BMU, 2007; Lehner *et al.*, 2005). It is highly likely that electricity companies will experience greater problems with their cooling water systems due to the rise in temperature and more frequent low discharges.

([29]) Cooling water discharge must be no warmer than 30 °C; a water temperature of 23 °C applies as the critical limit for the intake of cooling water.

7.9 Tourism and recreation

Key messages

- Changes in climate are starting to impact upon the attractiveness of many of the Mediterranean's major resorts, while improving it in other regions.
- Future projections of climate change suggest that the suitability of the Mediterranean for tourism will decline during the key summer months, though there will be an increase during other seasons (spring and autumn). This can produce shifts in the major flows of tourism within the EU, which will be very important in regions where tourism is a dominant economic sector, though adaptation responses such as economic diversification will be critical to limit economic losses. The tourism industry will therefore face significant adaptation costs.
- Adaptation measures will be driven by climate change and socio-economic factors, and their sustainability (e.g. associated environmental impacts) will have to be assessed. Mal-adaptation should be avoided and adaptation measures will also have to be developed in synergy with mitigation actions.

As shown by the PESETA project, which studied the effects of climate change on European tourism, mass tourism is closely associated with climate, for both the source of tourists and their destination. At present, the predominant summer tourist flows are from north to south, to the coastal zone. However, coastal and mountain tourism are the segments that are most vulnerable to climate change, and the Mediterranean region is the world's most popular holiday region: it attracts some 120 million visitors from northern Europe each year, the largest international flow of tourists on the globe, and their spending is in excess of EUR 100 billion. There are large differences within Europe and between seasons as to attractiveness for tourism. During the key summer months the Mediterranean has a 'close-to-ideal' climate for tourism, with very high values of the Tourism Comfort Index (TCI) ([30]). This drives the current holiday market, next after cultural, social, landscape and other factors.

With growing incomes and increasing leisure time, the tourism industry in Europe is expected to continue to grow. However, temperature rise is likely to have some influence in summer (and other season) destination preferences in Europe, seasonality being a key issue in tourism. The effect of climate change might also make outdoor activities in northern Europe more attractive, while summer temperatures and heat waves in the Mediterranean, potentially exacerbated by water supply problems due to maximum demand coinciding with minimum resources availability, could lead to a redistribution or a seasonal shift in tourism away from the current summer peak.

Results from climate change models point towards a possible shift northward of tourism during the 21st century and an increasing bi-modal distribution of tourism over the seasons in the Mediterranean (i.e. either side of a significant dip in summer). At the same time northern European locations show increasing attractiveness for tourism. The PESETA maps indicate significant potential shifts in the climatic suitability for tourism, with the belt of excellent summer conditions moving from the Mediterranean towards northern Europe. The reduction in attractiveness of current summer resorts is likely to be at least partially offset by increased opportunities for tourism in northern Europe. In the shoulder seasons (spring and autumn, not shown here), TCI scores are generally projected to increase throughout Europe and particularly in southern Mediterranean countries, which could compensate for some losses experienced in summer.

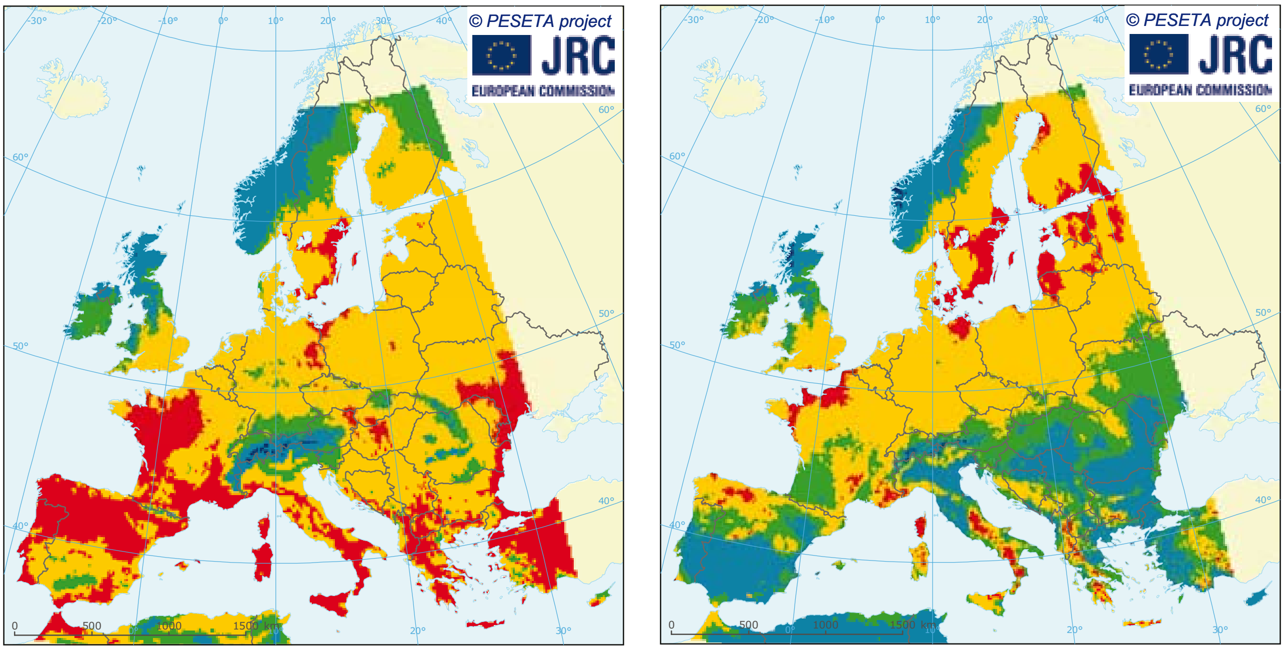
The above assessments reflect the theoretical (modelled) suitability of future tourism. Projections of the actual changes in tourism movements that are likely to occur, and their economic implications,

([30]) The Tourism Comfort Index is based upon a range of climate variables that reflects the suitability of regions related to an individual's bioclimatic comfort.

are much harder to assess. Much will depend on the flexibility of tourists and institutions such as schools (holidays). If summer remains the predominant season for tourism in Europe, major shifts of tourist flows may eventually occur. Shifts in the holiday season may however be the dominant form of adaptation. If these, as well as other societal changes (e.g. ageing population), allow for a more flexible timing of holidays among a large proportion of the population, some of these effects may be offset. Climate change may even be beneficial for the Mediterranean tourist industry if it levels-out demand, reducing the summer peak, while increasing occupancy in the shoulder seasons. In the absence of such adjustments, the Mediterranean tourist industry will be among the main losers. Some studies have investigated the potential economic effects of climate change on tourism and show an increase in the number of inbound tourists due to population and economic growth in the rest of the world; they also indicate that the influence of climate change may be rather to change the rate of relative growth in northern regions of Europe compared with the Mediterranean. The study also shows a potential shift towards a greater level of domestic tourism in regions with increasing attractiveness (e.g. within the United Kingdom).

There is also a major winter sports tourism industry in Europe, with the ski industry in the European Alps and Pyrenees attracting millions of tourists each year. This industry is a significant contributor to the economy (OECD, 2007), generating nearly EUR 50 billion in annual turnover. Studies project widespread reductions in snow-cover over the 21st century (IPCC, 2007b), which will affect the winter sports industry in Europe and its financial viability. Abegg *et al.* (2007) report that the numbers of snow-reliable ski areas in Austria, France, Germany, Italy, and Switzerland are projected to drop from approximately 600 to 500 if temperatures rise by 1.2 °C, to 400 if temperatures rise by 2 °C, and to 200 in a + 4 °C scenario.

Map 7.6 Modelled conditions for summer tourism in Europe for 1961–1990 and 2071–2100



Simulated conditions for summer tourism in Europe for 1961–1990 (left) and 2071–2100 (right) according to a High-Emissions Scenario (IPCC SRES A2)

Tourism Comfort Index (TCI)

- Unfavourable (TCI: 0–40)
- Acceptable (TCI: 40–60)
- Good (TCI: 60–70)
- Very good (TCI: 70–80)
- Excellent (TCI: 80–100)

Source: JRC PESETA project (http://peseta.jrc.ec.europa.eu/docs/Tourism.html).

There are already responses in place (e.g. artificial snow-making) and these have increased in recent years. For example, in France almost half a billion Euros were spent between 1990 and 2004 on artificial snow-making installations, while in Austria, approximately EUR 800 millions were spent between 1995 and 2003. The introduction of these machines is also driven by other socio-economic factors (increasing the reliability of resorts to increase revenues and expand their ski areas beyond previous natural limits). These measures have limits and their costs are likely to rise non-linearly as temperatures increases.

Adaptation options also pose sustainability and environmental problems (e.g. water use of snow-machines negatively affects current water resources, which could be exacerbated in the future, energy use and associated greenhouse gas emissions) that will need to be assessed. There is also a need to develop criteria for clearly defining and avoiding mal-adaptation. Finally, adaptation measures will have to be developed in synergy with mitigation actions. Sustainable adaptation measures exist, including economic diversification within or outside the tourism sector, e.g. from winter sports to other recreational or seasonal activities.

7.10 Health

Key messages

- Human beings are affected by climate change through direct or indirect exposures. These changes will have economic consequences. Few studies are available measuring the direct costs, such as treatment, hospitalisation, lost time at work, and additional medical costs.

- Health adaptation involves revising and strengthening a number of current measures, policies and strategies. Current levels of risk have already led to the introduction of new measures. As long as the increase in global warming is moderate, many of the projected effects on health are likely to be controllable by strengthening well-known public health interventions. Nevertheless, the cost-effectiveness of these actions will need to be further evaluated under a changing climate.

- Current actions, policies and measures might become insufficient at higher levels of risk or in the face of more frequent and intense events, or more rapid climate changes — which will have significant economic costs.

Globally, studies focused mainly on the welfare costs (and benefits) of climate-change impacts and aggregated the 'damage' costs of climate change (Tol, 2002a, 2002b) or estimate the costs and benefits of measures to reduce climate change (Cline, 2004). Those studies have shortcomings, such as: (a) a limited number of health outcomes is considered, mainly heat and malaria; (b) economists traditionally assign a lower value to life in lower income countries. Limited studies are available on the direct costs through e.g. work absenteeism, hospital admission, treatment costs, or work productivity.

In Europe PESETA estimated that the economic effects of climate change in Europe could be significant, with potentially large economic costs (billions of euro/year) from summer mortality by the 2080s, though these will be offset to a great extend by economic benefits from the reduction in winter mortality. Confalonieri *et al.* (2007) agree that projections of cold-related deaths, and the potential for decreasing their numbers due to warmer winters, can be overestimated unless they take into account the effects of better housing, influenza vaccination and season (Armstrong *et al.*, 2004). Alberini and Chiabai (2005) estimated that 286 million Euro can be saved in the city of Rome alone in 2020 if early action to prevent health illness is taken now.

Climate change also raises the issue of food safety. PESETA ([31]) estimated an extra 20 000 cases per year by 2030 and 25 to 40 000 extra cases by 2080, costing several billion euro a year in terms of medical expenses, lost time at work, expenses to avoid pain and suffering, and a small number of cases of fatal food poisoning. Adaptation is however found to offer a low-cost way to reduce these.

Coastal flooding is likely to threaten up to 1.6 million more people every year in the EU (EEA, 2007a). Direct health effects are caused by flood waters, and include drowning, heart attacks

Photo: © Waldemar Jarosinski

([31]) In PESETA only mean temperature-related mortality effects have been addressed, and not heat waves. For further details, see http://peseta.jrc.ec.europa.eu/docs/Humanhealth.html.

and injuries. Indirect health effects follow damage to infrastructure, and include infectious diseases, rodent-borne diseases, poisoning and post-traumatic stress disorder (sleeplessness, difficulties in concentration and psychosocial disturbances). The PESETA study estimated that coastal floods, in the absence of adaptation, could lead to economic costs of 0.8–1.4 billion euro by 2080 (B2 and A2 emissions scenario).

There is a number of emerging health issues from climate change in Europe, where quantification and valuation have not yet been explored. A warmer climate may have important effects on air quality in Europe (for ozone formation). The seasonality of allergic disorders may change with implications for direct costs in terms of over-the-counter medications for allergic rhinitis, and wider economic costs to individuals.

Data on adaptation costs, such as those related to surveillance and outbreak control, are starting to emerge, and adaptation strategies that can be implemented by health sectors (cCASHh project) are most likely to be built on well-established public health approaches, though further work is needed to fully assess the costs. Most adaptation measures appear to be low cost (e.g. provision of information), but large-scale vaccination or other prevention programmes against vector-borne disease are potentially very costly. They also highlight that there are likely to be strong distributional implications for climate change and health, with poorer countries being either more exposed or more vulnerable.

7.11 Costs of climate change for society

Key messages

- The total projected economic losses of the impacts of climate change are difficult to assess, and the literature shows a very wide range of results. Due to the many uncertainties involved, there is no one single 'true' cost but rather a range of costs that is relevant.
- Macro-economic and micro/sectoral economic assessments rely on different methodologies for different levels of analysis and purposes. They provide complementary estimates to better inform policy makers.

The costs of climate change will accrue to different individuals, in different sectors, in different places, and at different times. Due to this complexity, the total projected economic consequences of the impacts of climate change (globally or in Europe alone) cannot be easily assessed, and the literature shows a very wide range of results. The transposition of physical impacts into monetary terms is a difficult and sometimes contentious step, given that climate change impacts involve both market and non-market goods and services, covering health, environmental and social effects, and potential large-scale climatic events potentially irreversible in nature. The most common ways of defining the costs of inaction to climate change are either as 'total costs' or 'marginal costs'.

Total costs are usually measured as the discounted aggregate of all future welfare changes over some planning horizon. At the global level, there is an emerging literature, and studies have presented the total costs of climate change impacts to the world economy as a percentage change. For some regions, climate change could result in economic benefit for some of the sectors in the short to medium term. However, the evidence reported from the IPCC 4th Assessment Report is that the aggregated global impacts of climate change will result in net costs into the future and these costs will grow over time (IPCC, 2007b). On a global scale, previous economic estimates of the costs of climate change impacts — as a result of rising sea levels, falls in agricultural productivity and energy demand changes for instance — are up to around 2 % of global GDP per year (EEA, 2007b). But other studies and reviews have indicated that the costs may be more significant (Ackerman and Stanton, 2006). The Stern Review in particular (i.e. the British government's prominent report on the economics of climate change, 2006) takes a global perspective and estimates that if greenhouse gas emissions are not reduced, the total cost under a business-as-usual scenario will reduce welfare equivalent to a reduction in consumption per head of between 5 and 20 %.

The marginal costs of climate change are the additional damage costs of climate change from a current emission to the atmosphere of one unit of greenhouse gases. The IPCC (2007b) compiled the estimated marginal costs across some of the relevant studies in the literature and it can be seen how wide the range of results is. The estimates range from – 10 USD to + 350 USD per tonne of carbon. Peer-reviewed estimates have a mean value of USD 43 per tonne of carbon with a standard deviation of USD 83 per tonne (IPCC, 2007b). It is also important to note that the marginal cost of climate change is likely to increase over time, in line with the expected rising costs of damage (Watkiss, 2006).

While this information is very valuable in informing climate change policy, it is clear that there are many methodological issues involved in estimating the cost of inaction. Climate change is comprised of many types of climatic parameter, which in turn affect many sectors (market and non-market) in different ways. It is clear that different estimates of the costs of climate change are based on different types of climate effects, and include different impacts across different sectors. Literature reviews (Watkiss, 2006; EEA, 2007b) indicate that most studies focus on market damage from predictable events and leave out non-market and socially-contingent effects. All current estimates of the costs of inaction are therefore incomplete, though we do not know by how much. What is needed is recognition that the costs have a wide range and policies should be designed so that they take this uncertainty into account. Also, it should be clearly communicated that there is no one single 'true' cost out there which science could deliver to policy makers.

8 Data gaps, uncertainties and future needs

This chapter gives an overview of uncertainties in general and those related to the climate change indicators in this report in particular. The main purpose is to show the gaps in observed trends and projections and the need for further improvements in monitoring (*in situ* and satellites) and modelling of future climate change.

8.1 Introduction

Need to address uncertainty

Decision making should take into account the rate of climate change, its impacts and the availability and effectiveness of measures to mitigate global climate change and adapt to the impacts. Actions are needed to adapt to current and projected climate change even with substantial mitigation measures in place. Ignoring uncertainty increases the risk of inappropriate action to tackle the challenge of climate change and its impacts on the environment, the economy and human well-being. Decision makers also need to take into account the precautionary principle according to which absence of full scientific certainty should not be used as a reason to postpone measures where there is a risk of serious or irreversible harm to public health or the environment. They can also take advantage of 'no-regret measures' and profit from 'win-win situations'. For example, in the transport sector, measures leading to a more efficient use of energy reduce greenhouse gas emissions and can have positive effects on the economy and health. Other examples are multiple benefits from protection of wetlands for biodiversity and flood protection, establishing mixed forests for biodiversity and increasing resilience of forests to changing environmental conditions, and greening urbanisation to improve local climate and human health.

Main types of uncertainty

Three basic types of uncertainty can be distinguished.

1. **Incomplete knowledge**
   Lack of understanding of the physical, chemical and biological processes, and attribution of climate change to anthropogenic and natural factors are all sources of uncertainty, as is attribution of impacts to climatic or non-climatic drivers. There may be still unknown processes in the Earth's systems. However the physical processes in the atmosphere and its interaction with land and sea surface are reasonably well understood. This is shown by the fact that climate models are able to reproduce the past and present climate rather well. However, there remain uncertainties in the understanding of the climate system, of which the last IPCC report (IPCC, 2007) gives a good overview, including impacts of cloud cover on the energy balance of the atmosphere, which implies uncertainty in climate sensitivity, a key variable in climate change modelling.

   Another process-related uncertainty for climate impact analysis is related to the 'double attribution': the attribution of climate change to anthropogenic activities and the attribution of observed changes in the environment to climate change impacts. The former attribution is approached indirectly by running models with and without anthropogenic forcing and comparing the results with observations. The latter type occurs especially in systems that are intensively managed or affected by human activities. Generally, this type of attribution is approached by analysing the consistency of observed indicator changes with observed climate change, taking into account understanding of the climate-dependency of the indicator, e.g. derived from controlled experiments or model analysis. Increase in crop yield for example may be caused by a combination of higher temperatures, CO_2 fertilisation, growth of new crop varieties and/or improved management. Responses in systems with high levels of complexity like biological, social or economic systems are very difficult to assess. Climate impacts can either be increased by other, non-climatic factors, or compensated by adaptation of the system, or internally compensated until a critical level of resilience is exceeded. Sensitivity analysis with computer models can support a better understanding of these systems by analysing the different combinations of drivers.

2. **Insufficient observed trends**
There may be high confidence in the understanding of particular processes of climate change and impacts. But if there are insufficient observation data and trends, assessments can often only give qualitative information which is of limited value for mitigation and adaptation strategies. There have been far more observation data available in recent years that clearly demonstrate that the climate system reacts very sensitively to changes in forcing, and small changes are already leading to significant impacts on nature and human well-being (see also Chapter 2).

   However in cases where data are still too limited for appropriate modelling and assessments, confidence in the findings is usually low. Data may be completely missing or have insufficient spatial or temporal resolution or coverage. Time-series can be too short for detecting trends and understanding causal links with either anthropogenic climate change or natural variability. For instance, the question of whether the frequency and intensity of hurricanes and floods is changing due to anthropogenic climate change or as part of natural variability is still unresolved. This is partly because the time-series of the observed trends are still too short and partly because the variability of these events is much higher than the trend in climate change. Scarcity in terms of temporal and spatial coverage of data describing the so-called lower boundary conditions of the climate system, like sea surface temperature, ice and snow cover, and permafrost, still limit the reliability of climate modelling (GCOS, 2003). Observed data and trends for many of the impact indicators presented in this report often lack the appropriate spatial and temporal scale.

3. **Uncertainty in future socio-economic developments**
The most important sources of uncertainty are human behaviour, evolution of political systems, demographic, technological and socio-economic developments. Policies to control greenhouse gas emissions affect the rate and intensity of future climate warming. For projections of climate change and impacts, the unpredictable component of the anthropogenic forcing is handled by using ensembles of potential futures based on different storylines of socio-economic development leading to a set of emission scenarios, such as the ones presented in the last IPCC reports (IPCC, 2001; 2007). These scenarios are used to analyse the influence of human activities on the climate system in an 'if — then' mode: if emissions increase or decrease to a certain degree then the anthropogenic impacts on the climate system will change in a certain way. The IPCC scenarios describe a range of such possible futures (Nakićenović *et al.*, 2000) (see also Chapter 4).

Several decades of climate research and the series of IPCC reports allow a first comparison of early projections with observations over the past 20 years. The results show that there is increasing evidence that emissions of greenhouse gases and increases in temperatures tend to be underestimated in projections. Even 'business as usual' or 'worst case' scenarios projected lower emissions and rises in temperatures in the past 20 years than the actual measurements in the same period show (IPCC, 2007). Underestimation of economic growth, energy demand and the carbon intensity of energy supply might be one of the reasons.

The projected range of temperature increase to the end of the 21st century has only changed slightly, from 1.4–5.8 °C in the third IPCC assessment report (IPCC, 2001) to 1.1–6.4 °C with a best estimate of 1.8–4.0 °C in the fourth assessment report (IPCC, 2007). This is the current best available framework for decision makers when they consider options for climate policy measures.

The scenarios for the climate change impacts and vulnerability indicators presented in this report are based mainly on these global IPCC scenarios and contain spatially detailed European information for only few indicators. They are also incomplete and differ between indicators. Regular interaction is needed between the climate modelling community and the user community that is analysing impacts, vulnerability and adaptation in order to develop high-resolution, tailor-made climate change scenarios for the regional and local level. It would be useful if European research projects were to adopt the same contrasting set of climate scenarios for global development, such as those used by IPCC, and make use of regional climate projections as soon as they become available.

Data and scenario requirements for adaptation planning

The need for regional assessments for better understanding of climate change and impacts requires analysis at higher spatial resolutions (e.g. more detailed than the currently available 50 x 50 km scale), including seasonal changes over the year (IPCC, 2007). To adequately support decisions on adaptation measures, more precise information at a regional and local level is required. Unfortunately, uncertainty in projections of future climate increases from the global to the regional and the local level because other factors like topography and other environmental conditions are important at such more detailed scales. Planning for winter tourism for example requires very detailed information on local climate, especially on changes in temperatures and snow-fall during winter, to analyse the cost-effectiveness of managing ski resorts and the environmental impacts of running these facilities. Taking climate change impacts into account for flood protection measures requires very detailed information on changes in precipitation frequency and intensity for appropriate planning of dams and dikes.

However, in the absence of definite information, stakeholders have to make decisions under uncertainty and (possibly) increasing information over time, aiming for no-regret measures. Preparation for the future does not require fully accurate prediction, but rather a foundation of knowledge upon which to base action, a capacity to learn from experience, close attention to what is going on in the present, and healthy and resilient institutions that can effectively respond or adapt to change in a timely manner.

8.2 Gaps in observations and uncertainties in projections

The number of indicators and the quality of the underlying information in terms of pan-European coverage for describing climate change impacts have been significantly increased since the last EEA climate change indicator report 2004. New indicators have been developed, especially for systems like ecosystems, biodiversity, forestry and agriculture (Table 8.1). Others have been dropped or incorporated in other indicators either because they have not been considered to be important for the communication of climate change impacts (e.g. greenhouse gas concentration) or because they have been replaced by a more Europe-wide view (e.g. plant species distribution in mountains).

Most of the indicators are based on studies published in reviewed papers. This means that it has not been possible to create a standard set of emission scenarios and climate model runs for the impact assessments. Table 8.2 gives an overview of the emission scenarios and climate models used for impact analysis for each indicator. In most cases, emission scenario A1B, A2, B1 or B2 are used as input for the climate models (see Box 4.1 in Chapter 4). For climate data, different versions of the Hadley Centre model (Had) or the ECHAM model from the Max Planck Institute for Meteorology (MPI-M)) have mostly been used. In some cases, regional climate (e.g. REMO) and weather models such as Hirham have been applied for a more detailed regional projection of future climate. The use of different emission scenarios and climate models leads to different results for future changes in temperature and precipitation. These changes vary over the seasons and also across European regions.

Because different scenarios have been presented in this report it is useful to understand how these results can be compared across the different indicators. An overview of all models and scenarios used in this report is therefore presented in Figure 8.1.

The uncertainties in climate projections (2071–2100 average value) for winter (December–February, DJF) and summer (June–August, JJA), for northern and southern Europe, are shown in Figure 8.1. The graphs show a clear relationship between temperature and precipitation increases in the north European winter (Figure 8.1a). Almost all models project higher temperatures and lower precipitation for the summer in southern Europe (Figure 8.1d). There are also clear indications of higher temperatures in north European summers (Figure 8.1b) and south European winters for all models (Figure. 8.1c) while models project different changes in precipitation (either small increases or decreases). Because of the uncertainty in projected precipitation in these cases the uncertainty in the impact indicators presented in this report, that are linked to precipitation and water supply/demand, such as floods, droughts, irrigation demand and crop growth, is high.

The current state in terms of uncertainties and data needs are summarised below for each indicator category presented in this report.

Atmosphere and climate

Atmospheric routine measurements have taken place for many decades. Data availability is in general therefore relatively good compared with other indicators, although it also differs among the climate indicators and among regions. At the global

Table 8.1 Major changes in indicators 2004–2008

Sector	New indicator in 2008	Replaced or removed indicator from 2004 report
Atmosphere and climate	Storms and storm surges in Europe	
	Air pollution by ozone	
		Greenhouse gas concentrations
Cryosphere	Greenland ice sheet	
	Mountain permafrost	
Water quantity, river floods and droughts	River floods (number of events)	
	River flow drought	
Freshwater quality and biodiversity	Water temperature	
	Lake and river ice cover	
	Freshwater biodiversity and water quality	
Terrestrial ecosystems and biodiversity	Distribution of animal species	Bird survival
	Animal phenology	
	Species-ecosystem relationships	
Soil	Soil organic carbon	Terrestrial carbon uptake *
	Soil erosion by water	
	Water retention	
Agriculture and forestry	Growing season for agricultural crops	
	Timing of the cycle of agricultural crops (agrophenology)	
	Crop-yield variability	Crop yield losses in 2003
	Water requirement	
	Forest growth	
	Forest fire danger	
Human health	Water- and food-borne diseases	
Economic sectors	Normalised losses from river flood disasters	
	Coastal areas	
	Public water supply and drinking water management	
	Agriculture and forestry (crop yield)	
	Biodiversity and ecosystem goods and services	
	Energy	
	Tourism and recreation	
	Health	
	Costs of climate change for society	

Note: * from section 'Terrestrial ecosystems and biodiversity'.

level, major gaps in coverage are identified mainly for Africa, the oceans and the polar regions (GCOS, 2003). For Europe there is still lack of data for regional and local assessments at the appropriate spatial resolution and quality. More detailed and quantitative, tailor-made information is especially needed for regional climate impact assessments and the development of cost-effective adaptation strategies. Climate reanalysis at global and regional level (see Box 5.2) is a tool to create data sets from land and oceans (surface to the upper layers of atmosphere) for periods up to 50 years and can thus improve study of climate and climate variability.

For adaptation particularly, information on extreme events is most important, but changes in storms and storm surges in relation to climate change are still uncertain since time-series of observed data are too short to understand the contributions of natural

Table 8.2 Emission scenarios and climate models used for impact studies

Indicator		IPCC SRES Scenario	Climate model	Remark
5.2	**Atmosphere and climate**			
5.2.2	Global and European temperature	A1B	*	21 climate models
5.2.3	European precipitation	A1B	*	21 climate models
5.2.4	Temperature extremes in Europe	A2	Hirham4 + HadCM3	
5.2.5	Precipitation extremes in Europe	A1B	Echam4	
5.2.6	Storms and storm surges in Europe	A2, B2	ECHAM4 + (HadAM3H)	
5.2.7	Air pollution by ozone	A2, B2	RegCM (climate) + CHIMERE (air quality)	JRC analysis
5.3	**Cryosphere**			
5.3.2	Glaciers	B2	HadCM3 & Echam4	Alps: sensitivity study
5.3.3	Snow cover	A1B, B1, A2	REMO; RCM-H-A2 (multi-model)	
5.3.4	Greenland ice sheet	---	---	
5.3.5	Arctic sea ice	*	*	13 IPCC AR4 climate models
5.3.6	Mountain permafrost	A1B, A2, B1	REMO	
5.4	**Marine biodiversity and ecosystems**			
5.4.2	Sea-level rise	*	*	Different scenarios and models
5.4.3	Sea surface temperature	A1B	*	Different models
5.4.4	Marine phenology	---	---	
5.4.5	Northward movement of marine species	---	---	
5.5	**Water quantity, river floods and droughts**			
5.5.2	River flow	A2	HIRHAM + HadAM3H	JRC analysis
5.5.3	River floods	A2	HIRHAM + HadAM3H	JRC analysis
5.5.4	River flow drought	A2	HIRHAM + HadAM3H	JRC analysis
5.6	**Freshwater quality and biodiversity**			
5.6.2	Water temperature	*	*	Different scenarios and models, 50–70 % of air temperature increase
5.6.3	Lake and river ice cover	A2	RCM	JRC analysis
5.6.4	Freshwater biodiversity and water quality	A2	---	
5.7	**Terrestrial ecosystems and biodiversity**			
5.7.2	Distribution of plant species	A2	HadCM2	
5.7.3	Plant phenology	---	---	
5.7.4	Distribution of animal species	A2	HadCM3	
5.7.5	Animal phenology	---	---	
5.7.6	Species-ecosystem relationship	A2	HadCM3	
5.8	**Soil**			
5.8.2	Soil organic carbon	A2	HadCM3	JRC analysis
5.8.3	Soil erosion by water	---	---	
5.8.4	Water retention	A2	ECHAM5/T106L31	JRC analysis
5.9	**Agriculture and forestry**			
5.9.2	Growing season for agricultural crops	---	---	
5.9.3	Timing of the cycle of agricultural crops (agrophenology)	---	---	
5.9.4	Crop-yield variability	---	---	
5.9.5	Water requirement	---	---	
5.9.6	Forest growth	A1B	NCAR-CCM3	
5.9.7	Forest fire danger	A2	Hirham4+DMI	
5.10	**Human health**			
5.10.2	Heat and health	A2	Normalised per °C	JRC PESETA project
5.10.3	Vector-borne diseases	Various	Normalised per °C and rainfall (mm)	IPCC model ensemble
5.10.4	Water- and food-borne diseases	Various	Normalised per °C	IPCC model ensemble
7	**Economic consequences of climate change**			
7.2	Direct losses from weather disasters	---	---	
7.3	Normalised losses from river flood disasters	A2, B2	HadAM3H, HIRHAM	JRC PESETA project
7.4	Coastal areas	A2	ECHAM4	JRC PESETA project

Table 8.2 Emission scenarios and climate models used for impact studies (cont.)

Indicator		IPCC SRES Scenario	Climate model	Remark
7.5	Public water supply and drinking water management	A2	ECHAM4, HadCM3	WaterGAP model
7.6	Agriculture and forestry	A2	HadCM3/ HIRHAM ECHAM4/RCA3	JRC PESETA project
7.7	Biodiversity and ecosystem goods and services	---	---	
7.8	Energy	A1B, B2	ECHAM4, HadCM3	WaterGAP model
7.9	Tourism and recreation	A2	HadCM3/ HIRHAM	JRC PESETA project
7.10	Health	SRES A2, B2	---	JRC PESETA project
7.11	Costs of climate change for society	Various	---	IPCC 2007

Note: --- projection based on observed sensitivity to climate change and expected qualitative trends in climate.

* combined assessment based on multiple scenarios and/or climate models mostly based on IPCC SRES.

variability and anthropogenic forcing. Sufficient data for better analysis of changes in the frequency and intensity of other extreme events like heat waves and heavy rain falls are still lacking, in parts of Europe and in terms of the length of the observed time-series.

Cryosphere

Ice and snow cover have been monitored directly for at least a century, the last decades also from space. Measuring techniques and coverage have gradually improved. Particularly important are changes in mass balances of ice-sheets and glaciers which are the key information for assessing water availability and changes in sea level. Changes in the extent and duration of snow-cover and sea-ice are also important due to the feedback mechanisms in the global climate system created by their change (albedo effect).

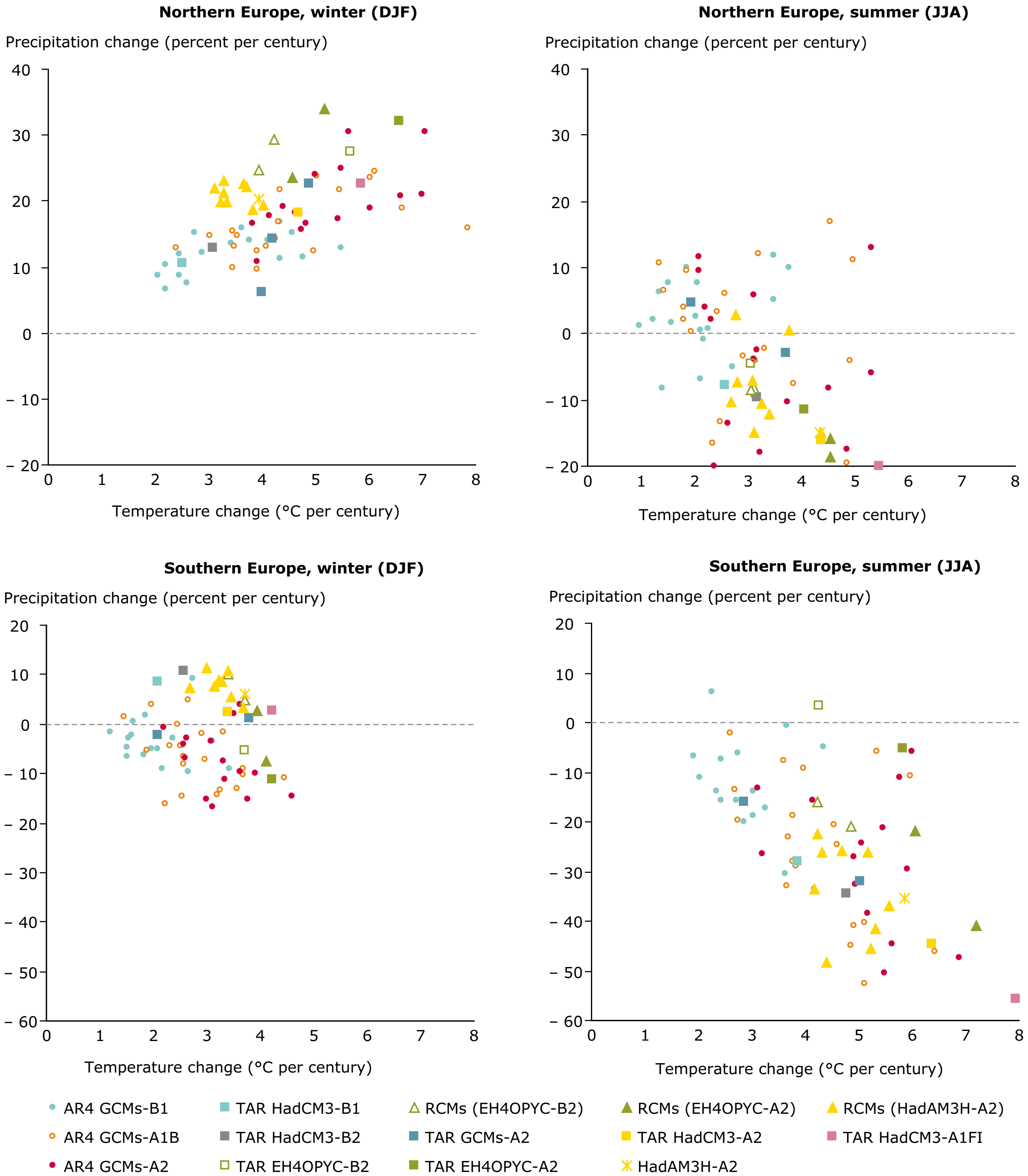
The evidence for these changes is robust for the selected mountain glaciers that are monitored intensively. But the majority of glaciers are not, and especially for the Greenland ice sheet, uncertainty in changes in mass-balances is still high. There is more and more evidence that melting rates for the Greenland ice sheet and Arctic sea ice are accelerating rapidly, with an unknown risk of reaching tipping points. Monitoring and research activities in Greenland have only recently been stepped up, and in time understanding may improve. Melting of permafrost has been observed, but data and knowledge for quantitative assessments are still rather poor due to too short time-series.

Marine biodiversity and ecosystems

Observations of both sea-level change and sea surface temperature are made using a network of ground-based stations and by satellites. The land-based observations of sea level are less accurate and are affected by vertical movements of the earths crust (sometimes called isostatic rebound), and cover only few points in space. Observations of sea surface temperature are made in a network of ocean based stations, and similarly have low spatial resolution, but both parameters have been measured for more than a century. The satellite observations of both sea surface elevation and sea surface temperature are more accurate and are temporally and spatially comprehensive, but have only been made for a relatively short period. By combining the two types of measurements, accurate time series of historical changes in mean sea level and sea surface temperature have been compiled. Projections of both sea-level change and sea surface temperature are, however, highly uncertain because some of the most important physical processes involved are poorly understood. In the case of sea-level change the processes include the internal ice-dynamics of the Greenland and Antarctic ice sheets, changes in the thermal structure of the oceans, and changes in the vertical movement of land. Sea surface temperature is affected by changes in ocean heat content and large-scale ocean circulation, and because the physical processes are poorly understood they are subject to intense scientific investigation and debate.

In the marine biological environment, observations have been made that indicate that marine organisms are changing their seasonality and southerly species are moving northward which in some cases can have serious ramifications for the entire marine foodweb. The studies that have been done at the planktonic level (the bottom of the marine food web) are primarily made by the Sir Alistair Hardy Foundation for Ocean Science using the Continuous Plankton Recorder. These observations are the only ones that have been made for a long enough time-period (observations were started in 1958) and that cover a

Figure 8.1 Comparison of scenarios of air temperature and precipitation applied in impact studies described in this report



Note: Data are from the PRUDENCE project (http://prudence.dmi.dk/index.html.). Results are split between northern (a,b) and southern Europe (c,d), winter (December–February, DJF) and summer (June–August, JJA). Projections are for the last 30 years of the 21st century relative to simulated present-day climate under different SRES scenarios of greenhouse gas and aerosol emissions. Projections from global climate models (GCMs) were reported in the IPCC Third (TAR) and Fourth (AR4) Assessment Reports. Outputs from two TAR GCMs (HadAM3H and EH4OPYC) were dynamically downscaled in the FP5 PRUDENCE project using regional climate models (RCMs — triangular symbols). Other TAR GCM projections (square symbols) were selected as scenarios in various FP5 and FP6 impact studies (e.g. ATEAM, ACCELERATES, ALARM). Recent AR4 multi-model ensemble GCM projections (small circles) are shown for comparison. Definitions of northern Europe differ slightly: for the AR4 GCMs, 48.0°N–75.0°N, 10.0°W–40.0°E (data from Isaac Held, personal communication); for the TAR GCMs, 47.5°N–67.5°N, 10.0°W–40.0°E (data from Ruosteenoja *et al.*, 2003); for the RCMs, 47.5°N–75.0°N, 15°W–35°E.

Source: Carter and Fronzek, 2008.

sufficiently large area (the North East Atlantic and North Sea) to document that large-scale changes are occurring. The bottom of the marine foodweb will also be first to be impacted by changes in ocean acidification; however the rate at which oceans will become acidified is uncertain. Satellite observation of ocean colour is a promising new monitoring technology, but can not yet show large scale changes in chlorophyll concentrations because time series availability is currently too short (10 years). There is also a shortage of ground observations available to interpret the causes of changes observed from space. Observations have been made of some species of fish moving northward, but analysing community changes is an area of emerging research. Because both the changes in the physical oceanographic environment and marine biological response to the physical changes are poorly understood, it is not possible to make projections for changes in marine biodiversity and ecosystems. A more systematic evaluation of changes in marine ecosystems is needed in terms of coverage of European seas and comparability of methods used.

Water quantity

The assessment of changes in water quantity and especially floods is linked to quantification of trends in mean and extreme precipitation which are still uncertain, especially for summer rainfall. Small differences in projected precipitation can lead to very large differences in water quantity, especially in areas with low annual precipitation (see Figure 8.1). In some areas of Europe, river discharge is also linked to changes in the mass balances of snow and ice. Water extraction as well as water management across catchments and changes in land use and management also make it very difficult to attribute changes in average water discharge, floods and droughts to climate-change forcing.

Monitoring networks for river discharge and groundwater levels are relatively dense and deliver robust numbers on average water flows. But due to non-climatic factors, uncertainties in climate-change-induced impacts are rather high. For projections, uncertainties in climate models further increase uncertainties in projected changes in water quantities. In particular, projections of changes in floods and droughts require much more detailed information on regional changes in precipitation and land management. Reliable information on quantities is the key information for appropriate water management and flood protection.
A pan-European view on river discharges and changes is still missing but will be implemented in the Water Information System for Europe (WISE) in the near future.

Water quality

There are already many observations of marked changes in water temperature, ice coverage, and stratification in European rivers and lakes that can be attributed mainly to higher air temperatures. Some long-term observations clearly describe the changes and these are supported by a growing set of shorter-term observations (30–50 years) that provide additional evidence of changes in the temperature regimes of rivers and lakes.

European freshwaters and their biodiversity, which plays an important role for water quality, are already affected by many human pressures related to land use, pollution with nutrients and hazardous substances, and acid deposition. Because of difficulties of disentangling the effects of climatic factors from other pressures, there is limited empirical evidence to demonstrate unequivocally the impact of climate change on water quality and freshwater ecology. On the other hand, there are many indications that freshwaters that are already under stress from human activities are highly susceptible to climate change impacts.

Changes in oxygen content and stratification of lakes which can be attributed to climate change are derived from national and local research and monitoring activities. It is obvious that especially higher temperatures and subsequent lower oxygen content will increase pressure on freshwater ecosystems, especially if nutrient and pollutant loads are already high, but quantification of these processes is still highly uncertain. European water quality is regularly monitored and reported as part of the Water Framework Directive and data are available via WISE.

Terrestrial ecosystems and biodiversity

Phenology and diversity of plants and animals show significant changes, but observed trends are still rather fragmentary in terms of European coverage and number of observed species. A fundamental problem is the different sensitivity of individual species to changes in temperature, precipitation, humidity and other climate variables. Using the observed distribution of species in relation to current climate conditions allows projections of the natural habitat of these species under future climates. However, these take no account of the individual resilience and adaptation capacity of the species, positive and negative impacts of management and risk of disconnection of predator — prey relations in the food web. The impact of climate change on the number of individuals per species (abundance), which is also very important for genetic variety and consequently for survival, so far was considered only to a very limited extent. Monitoring of biodiversity is based partly on regular screening of plants and species in protected areas. Most of the pan-European information is based on temporary research projects, voluntary networks and the activities of NGOs.

There is more information on observed changes in phenology, based mainly on voluntary observation networks than for changes in distribution. However there are only very general projections on phenological changes, based mainly on interpretations of changes in temperatures. More efforts are needed to improve monitoring, especially in areas where data sampling is still rather poor or data exist but are not accessible. A more systematic and harmonised observation of species and their abundance across Europe is needed to improve the still very fragmented knowledge of climate change impacts on ecosystems and biodiversity.

Soil

Climate is a key factor of soil development that controls the main soil-forming processes and directly or indirectly affects major soil threats in the EU. Wind soil erosion is triggered mainly by wind speed combined with droughts. Changes in heavy rainfalls and the loss of vegetation cover increase the risk of water erosion. However, the amounts of soil material removed by the erosion are quantified only for small areas. There is only information available on erosion risks and not on the real soil loss. Uncertainties concerning total soil loss and the impact of climate change in relation to human management are very high.

Soils are the biggest reservoir of carbon on earth. Under constant environmental conditions the rate of carbon accumulation in soil is balanced by the loss of carbon due to decomposition of dead vegetation remains and mineralisation of humus. This balance results in storage of carbon in soils over long periods. Higher temperature and less precipitation increase the rates of decomposition/mineralisation and accelerate the release of CO_2 from soils into the atmosphere. Decay of peat also leads to significant emissions of CH_4 and N_2O into the atmosphere. The amount of these GHG emissions from soils can be much higher than reductions through mitigation measures and can therefore seriously accelerate global warming. The magnitude of the carbon turnover in soils on the EU scale is insufficiently understood, making assessment and quantification of the effect of climate change on soils and evaluation of feedback of soil impact on climate uncertain.

Biodiversity of soil organisms is very complex and still poorly monitored. The organisms are very important for processes such as the decomposition of organic matter and for ecosystem stability. But there are only very few data about species that are winners or losers under changing climate and the impacts these changes may have on ecosystem functioning.

A better understanding of soil processes under climate change would need more information on trends in extreme weather events, more detailed data on carbon storage and in-depth understanding of soil processes under changing climate.

Agriculture and forestry

The agriculture and forestry sectors are affected by climate change and non-climatic impacts. Both sectors are clearly dominated by management, and it is therefore difficult to attribute specific trends from field observations uniquely to a changing climate.

Nevertheless, direct observations and model-based reconstructions allow the identification of specific climate-related impacts on plant growth. Also very extensive experiments e.g. FACE (free-air CO_2 enrichment experiments) are being performed to investigate the impacts of climate change on crop and tree species, including interactions with increasing atmospheric CO_2 concentrations and the impacts of management. Results are then extrapolated using models to simulate the physiological response of plants to changing conditions. There is still significant lack of knowledge and data on the individual responses of species to climate change and the subsequent changes in competition in forests and grasslands, also because the responses of species depend on age and time of exposure. More precise analyses and projections for agriculture and forestry would further require more detailed information on management for each site and forest stand. Projections of fire risks are rather robust but projections of the impacts of other extreme events like storms are very uncertain. There is a big gap in information on the possible changes in pressures from pests and diseases on crops and forests under a changing climate.

Pan-European assessments will certainly be more precise and accurate when specific local conditions and physiological constrains of crops, trees and pests are fully taken into account. But lack of knowledge on physiological responses of individual plant species to climate change and still inaccurate projections of future climate at the regional level make projections rather uncertain, especially in areas where precipitation is the limiting factor for agriculture and forestry. Projections for areas where temperatures are the limiting factor are expected to deliver more robust results.

Human health

Climate change impacts on human health include direct impacts due mainly to heat waves, storms and floods, and indirect impacts by vector-, water-, and food-borne diseases. Positive impacts include a lower risk of deaths from low temperatures. Quantification of the direct impacts of temperature has been attempted in several studies; quantification of the other extreme events and indirect impacts lacks empirical studies. A review of the health impact assessments of climate change has been made in the context of the fourth assessment report of the IPCC (WG II, chapter 8: human health; Confalonieri *et al.*, 2007). Several research needs have also been identified in the cCASHh and EDEN projects. Regarding projections, few assessments of the potential future health impacts of climate change have been made. They stress various limitations and rarely quantify the health impacts. Methods and tools to assess 'unpredictable' events, e.g. unknown and new pathogen agents and transmission modes, are needed. There is also a need for integrated approaches through international networks and research combining vector biology and ecology, microbiology, hosts, vectors and pathogens genetics, epidemiology, medical and social sciences, including economics. There are many data gaps at the appropriate spatial and temporal resolution, needed for proper climate change related decision making. An example is the lack of information on vector competence under a changing climate of many arthropod species (insects, ticks), competence of many vertebrate (rodents, bats, other wild mammals, birds) species and an understanding of the genetic, biological and ecological basis of vector/host distribution and their transmission competence for bacteria, viruses and parasites.

An important source of uncertainty is the extent to which adaptation actions, such as preventive measures and appropriate changes in health systems, will be implemented and effective over the next few decades (Confalonieri *et al.*, 2007; Campbell-Lendrum *et al.* 2007; McMichael *et al.*, 2004). Furthermore analysis is needed of effective combinations of climate change mitigation and adaptation actions to reduce cardio-respiratory diseases.

Economy

Economic effects of climate change include direct impacts of extreme events like storms, floods, heat waves, and indirect impacts via changes in ecosystem services for agriculture, forestry, biodiversity and ecosystem goods and services, tourism, energy and water, and human health. Changes in temperature are also affecting energy demand, leading to less heating in winter and more cooling in summer. The economic effects of climate change vary across Europe and depend to a large extent on the resilience of societies and their capability to adapt to the changes.

For more comprehensive economic assessments of increasing damage costs, more integrated data and studies across all sectors are needed on the specific contribution of anthropogenic climate change, and of social change and economic developments (e.g. increases in wealth and infrastructure). Only limited data on the costs of adaptation are available and much more information on good practices at the local, regional and national levels is needed. In addition, assessment methodologies need to be significantly improved to capture the variety and complexity of economic effects linked to climate change, with a particular focus on the valuation of ecosystems.

8.3 Future needs

To address the data gaps identified above (Section 8.2) a sustained integrated monitoring and observation system for Europe should be considered. Integration should take place across the main climate system elements, including atmospheric, oceanographic, terrestrial, cryospheric and biological observations. It should be sustained to be able to produce sufficiently long and accurate data of all key system elements from both *in situ* and satellite sources.

There are many efforts to improve climate-change related data availability in Europe which are also linked to global activities. For improving understanding of the climate system, the Global Climate Observing System (GCOS) network identified a data set as described in Table 8.3. requiring long-term time-series on atmospheric, marine and terrestrial processes with appropriate temporal and spatial resolution (GCOS, 2003). Most of these are also part of EEA's indicators on climate change impacts, such as near-surface atmospheric conditions, sea surface temperature, ice and snow cover, and permafrost.

The EU 'Global Monitoring for Environment and Security' (GMES) Programme (EC, 2004) aims to strengthen monitoring capacity in Europe and the world by making data available as 'services' from 2008 onwards. The combination of satellite and ground-based information to services and the envisaged long-term funding of the services will significantly improve the availability of data on changes in the environment. Many of the services developed will also improve the availability of essential climate variables. For example information in 'Service marine' will include sea surface temperatures and salinity, 'Service land monitoring' will provide information on land-cover changes, and 'Service atmosphere' will monitor greenhouse gas concentrations, aerosols and radiation. The services will be extended stepwise over the coming years and will be fully established by 2013. GMES is also contributing to the global activities currently coordinated and streamlined in the Global Observation System of the Systems (GEOSS) programme (GEOSS, 2005). Another important programme aimed at monitoring is the Data User Element (DUE) of the European Space Agency (ESA) which include global and regional data on land cover (GlobCover), ocean colour (GlobColour), carbon (GlobCarbon), cryosphere (GlobIce, GlobSnow, Permafrost), and other climate-relevant data.

European research projects are improving our understanding of processes and impacts and enhancing data availability. However there is normally lack in continuity of funding. Consequently, measurements performed in these projects only cover short time-periods and/or small areas which often limits the value of the information for climate change assessments. Some projects are funded for implementing GMES monitoring services such as MERSEA and MyOcean for marine, Geoland-1 and Geoland-2 for land and GEMS and MACC for atmosphere services. These projects will be transferred into a long-term operational programme from 2013 onwards.

Climate-related projects (see Box 8.1 for further details), such as PRUDENCE, and ENSEMBLES, are improving the availability of regional projections of climate change. Other ongoing or already completed projects deal with specific sectors, like ACCELERATES for agriculture and ALARM for biodiversity or EUROLIMPACS and CLIME for freshwater ecosystems. Some projects focus on regions, like CIRCE for the Mediterranean area, or investigate climate change impacts and their social and economic impacts, like ATEAM on vulnerability of ecosystem services in Europe. cCASHh has focused on understanding the adaptation needs for human health and ADAM is focused on adaptation and mitigation strategies for supporting European climate policy, and PESETA deals with projections of economic impacts of climate change in different sectors and regions like coastal systems, energy demand, human health, agriculture, tourism, and floods. The EuroHEAT project analysed the effectiveness of early warning and public health action and the MicroDYS project analysed disasters, relevant not only for Europe but globally. A more comprehensive overview on climate change related research activities can be found in EC, 2005; EC, 2006a; 2006b; 2006c; EC, 2007a, 2007b.

Table 8.3 Essential climate variables as required by UNFCCC for detecting and modelling climate change

Domain	Essential climate variables	
Atmospheric (over land, sea and ice)	**Surface:**	Air temperature, precipitation, air pressure, surface radiation budget, wind speed and direction, water vapour.
	Upper-air:	Earth radiation budget (including solar irradiance), upper-air temperature (including MSU — microwave sounding unit — radiances), wind speed and direction, water vapour, cloud properties.
	Composition:	Carbon dioxide, methane, ozone, other long-lived greenhouse gases, aerosol properties.
Oceanic	**Surface:**	Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, current, ocean colour (for biological activity), carbon dioxide partial pressure.
	Sub-surface:	Temperature, salinity, current, nutrients, carbon, ocean tracers, phytoplankton.
Terrestrial	River discharge, water use, ground water, lake levels, snow cover, glaciers and ice caps, permafrost and seasonally-frozen ground, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), biomass, fire disturbance.	

Source: GCOS, 2003.

There are also many activities at the national and regional level, including both public and non-governmental research and monitoring programmes (e.g. transboundary projects of the Interreg Programme).

The monitoring activities and results of this research will further help to understand, and maybe reduce, the uncertainties related to lack of data and knowledge about climate change and its impacts, and will therefore improve the basis for decision making. In summary, from the perspective of climate change impacts and adaptation, future efforts should aim mainly at:

- better data and better models for projections for the coming decades (in addition to models for the period up to 2100) in terms of spatial density, quality and length of time-series (including historic data) for detecting environmental changes due to climate change;
- improved information on extreme events, especially needed for adaptation;
- improved, timely and free public access to data and tools through metadata description, standardisation, harmonisation, improved architecture and infrastructure for data management including distributed data centres and portals for standardised access;
- research to advance understanding of the linkages between the behaviour of vulnerable systems, climatic changes, and non-climatic drivers and positive and negative feedbacks.

Planned research programmes at both the national and the European level will result in a rapidly increasing amount of data and information on climate change impacts, vulnerability and adaptation. A European clearing house on climate change impacts, vulnerability and adaptation can make this information widely available to potential users across Europe. The information can include data on observed and projected climatic changes, information on vulnerable systems, indicators, tools for impacts assessments, and good practice adaptation measures. Such a Clearing House should be developed and made consistent with the existing European environmental data centres that are currently managed by EEA (on climate change, water, land use, biodiversity and air) and JRC (forestry and soil) other existing information platforms such as the European Community Biodiversity Clearinghouse Mechanism (hosted by EEA) and the WHO Climate, Environment and Health action and Information system (CEHAIS). Such a system can also effectively provide important European information to international organisations such as UNFCCC.

Box 8.1 European climate change impacts and adaptation research

Various research projects of the European Commission focus on climate change impacts in Europe or on providing the basis for assessing them. Fewer projects as yet address adaptation issues. The projects aim at better understanding of the functioning of the Earth system, the origin and impacts of climate change and predicting its future evolution, to guide and support the EU's international commitments and EU policies, and to provide a basis for effective mitigation and adaptation measures. Most FP6 projects have not yet been finalised, but some intermediate results could be used for this report. The following are important pan-European projects funded within the EU Research Framework (FP5 and FP6) and European Regional Development Fund (Interreg) Programmes and the GMES initiative.

ADAGIO (Adaptation of Agriculture in European Regions at Environmental Risk under Climate Change; FP6). ADAGIO will evaluate and disseminate potential adaptation measures to climatic change in agriculture, considering three main vulnerable regions of Europe (south Europe and the Mediterranean area, middle Europe and eastern Europe) in cooperation with 11 partners. Compared with the many-fold potential impacts of climate change on agro-ecosystems, potential adaptation measures are even more complex because of the high number of options available through the human factor. New policies must therefore be adopted under climate change conditions considering all potential and realistic adaptation measures.

ADAM (Adaptation and Mitigation Strategies: supporting European climate policy; FP6).The project will lead to a better understanding of the synergies, trade-offs and conflicts that exist between adaptation and mitigation policies at multiple scales. ADAM will support EU policy development in the next stage of the development of the Kyoto Protocol, in particular negotiations around a post-2012 global climate policy regime, and will inform the emergence of new adaptation strategies for Europe.

Box 8.1 European climate change impacts and adaptation research (cont.)

ACCELERATES (Assessing Climate Change Effects on Land use and Ecosystems; from Regional Analysis to The European Scale; FP5). This project has constructed regional and Europe-wide geo-referenced databases, developed models that represent biophysical and socio-economic processes of agro-ecosystems on the European scale and advanced methodologies at fine spatial and temporal resolutions. In the project, adaptive responses to climate change of agro-ecosystems were analysed, using integrated models.

AMICA (Adaptation and Mitigation — an Integrated Climate Policy Approach; Interreg IIIC). AMICA is a completely new approach to environmental policy designed to combine long-term climate protection with short- and medium-term adaptation measures on the local level as a means to improve coherence of decisions and allocation of financial means.

ASTRA (Developing Policies & Adaptation Strategies to Climate Change in the Baltic Sea Region; Interreg IIIB). The main objective is to assess regional impacts of continuing global climate change and develop strategies and policies for climate change adaptation. The project will address threats arising from climate change in the BSR, such as extreme temperatures, droughts, forest fires, storm surges, winter storms and floods. In order to elaborate adaptation and mitigation strategies it is essential to involve regional and local spatial planners and stakeholders.

ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling; FP5). ATEAM's primary objective was to assess the vulnerability of human sectors relying on ecosystem services with respect to global change. We consider vulnerability to be a function of potential impacts and adaptive capacity to global change. Multiple, internally-consistent scenarios of potential impacts and vulnerabilities of the agriculture and forestry sectors, carbon storage, water, nature conservation and mountain tourism in the 21st century were mapped for Europe at a regional scale for four time slices (1990, 2020, 2050, 2080).

BRANCH (Biodiversity Requires Adaption in Northwest Europe under a CHanging climate; Interreg IIIB). Biodiversity must adapt to climate change. For many habitats and species, this will be difficult because the landscape across Europe is fragmented and past decisions limit the opportunities for adaptation. Spatial planners must act now to create a landscape and coastline that can withstand the effects of climate change. BRANCH provides the guidance and evidence to take action. It has brought together planners policy makers and scientists from England, France and the Netherlands, to show how spatial planning could help biodiversity to adapt to climate change.

CIRCE (Climate Change and Impacts Research: the Mediterranean Environment; FP6). The project will predict and quantify the physical impacts of climate change and evaluate the consequences of climate change for the society and economy of the populations in the Mediterranean area. Adaptation and mitigation strategies will be identified in collaboration with regional stakeholders.

CIRCLE (Climate Impact Research for a Larger Europe; FP6). Climate impact analysis and adaptation response must be informed by a coherent body of research and it is CIRCLE's prime objective to contribute to such efforts by networking and aligning national research programmes in the 19 CIRCLE partner countries. Implementation of a European Research Area (ERA) for climate change is CIRCLE's final goal.

CASHh (Climate change and adaptation strategies for human health; FP5). The project assessed the impacts of climate change water, food and vector boren diseases, as well as the consequences for health of floods and heat-waves. It came up with a set of recommendations for adaptation action in Europe.

ClimChAlp (Climate Change, Impacts and Adaptation Strategies in the Alpine Space; Interreg III B). The ClimChAlp project aims at supporting the political decisions regarding protection and natural disasters prevention due to climate change in the Alps. Climate change poses a serious challenge to social and economic development. The Alps are particularly sensitive to climate change, and recent warming has been roughly three times the global average. Climate models project changes in the coming decades, including a reduction in snow cover at low altitudes, receding glaciers and melting permafrost at higher altitudes.

CLIME (Climate and Lake Impacts in Europe; FP5). The central aim of CLIME was to develop a suite of methods and models that can be used to manage lakes and catchments under future as well as current climatic conditions. The most up-to-date regional climate scenarios, and existing catchment and lake models were used in CLIME to address issues that are central to the implementation of the Water Framework Directive. CLIME took advantage of automatic water quality monitoring systems already deployed on many of our target lakes. CLIME had a socio-economic component which paid particular attention to two water quality issues that are likely to become increasingly important.

EDEN (Emerging Diseases in a changing European eNvironment; FP6). This integrated project aims to identify and catalogue those European ecosystems and environmental conditions which can influence the spatial and temporal distribution and dynamics of human pathogenic agents. The project develops and co-coordinates a set of generic methods, tools and skills such as predictive models, early warning and monitoring tools which can be used by decision makers for risk assessment, decision support for intervention and public health policies.

Box 8.1 European climate change impacts and adaptation research (cont.)

ENSEMBLES (Ensemble-based predictions of climate changes and their impacts; FP6). This project aims to develop an ensemble prediction system for climate change based on the principal state-of-the-art, high resolution, global and regional Earth System models developed in Europe, validated against quality-controlled, high-resolution gridded datasets for Europe. Eventually, the outputs of the ensemble prediction system are intended to be used for a range of impacts analyses, including agriculture, health, food security, energy, water resources, insurance and weather risk management.

ESPACE (European Spatial Planning — Adapting to Climate Events). Recognising the vital role of spatial planning in enabling society to adapt to climate change, the ESPACE project aims to change the philosophy and practice of spatial planning. ESPACE has focused on managing climate change impacts on spatial planning for water management, including: flooding — coastal, estuarine and riverine; water resources and water quality.

EUROLIMPACS (Evaluating the Impacts of global change on European Freshwater Ecosystems; FP6). Euro-limpacs is a project designed to assess the effects of future global change on Europe's freshwater ecosystems. The research programme is relevant to the EU Water Framework Directive and other European and international directives and protocols and supports the EU's charter on Sustainable Development. The four main areas of investigation in Euro-limpacs are: stressors of aquatic ecosystem change, the impact of climate change on different temporal scales, tools for ecosystem management and cross-cutting themes.

GEMS (Global and regional Earth-system (Atmosphere) Monitoring using Satellite and *in situ* data; GMES initiative). GEMS is developing comprehensive monitoring and forecasting systems for trace atmospheric constituents important for climate and air quality. The systems will provide the basis for value-added data and information services to be developed as part of Europe's Global Monitoring for Environment and Security (GMES) initiative. The GEMS project will create a new European operational system for operational global monitoring of atmospheric chemistry and dynamics and an operational system to produce improved medium-range and short-range air-chemistry forecasts, through much improved exploitation of satellite data.

MACIS (Minimisation of and Adaptation to Climate change Impacts on BiodiverSity; FP6). MACIS summarises what is already know about the impacts of climate change on biodiversity and develops methods to assess the potential impacts in the future. In joint co- operation with policy makers and stakeholders MACIS shows what can be done to stop biodiversity loss. Specifically, MACIS develops methods to identify habitats at greatest risks and to identify all habitats that buffer against negative impacts. Together with policy makers and stakeholders MACIS and the closely linked projects COCONUT and ALARM identify policy options to stop biodiversity loss due to climate and land-use change.

MERSEA (Marine Environment and Security for the European Area; GMES initiative). MERSEA aims to develop by 2008 a European system for operational monitoring and forecasting the ocean physics, bio-geochemistry and ecosystems on global and regional scales. This ocean monitoring system is envisioned as an operational network that systematically acquires data (earth observation from satellites, *in situ* from ocean observing networks, and surface forcing fields from numerical weather prediction agencies) and disseminates information to serve the various user needs. The prediction time scales of interest extend from days to months. This integrated system will be the Ocean component of GMES ('Global Monitoring for Environment and Security').

MICRODIS (Integrated Health Social and Economic Impacts of Extreme Events: Evidence, Methods and Tools; FP6). This project has the overall goal to strengthen preparedness, mitigation and prevention strategies in order to reduce the health, social and economic impacts of extreme events on communities. The main objectives and goals are to strengthen the scientific and empirical foundation on the relationship between extreme events and their health, social and economic impacts, to develop and integrate concepts, methods, tools and databases towards a common global approach, and to improve human resources and coping capacity in Asia and Europe though training and knowledge sharing.

NeWater (New Approaches to Adaptive Water Management under Uncertainty; FP6). NeWater identifies key elements of current water management regimes and investigates their interdependence. The project recognises the value of highly integrated solutions and advocates integrated water resource management (IWRM) concepts. However, NeWater is based on the hypothesis that IWRM cannot be realised unless current water management regimes undergo a transition towards more adaptive water management. Research is therefore focused on transformation processes of these elements in the transition to adaptive integrated water resources management.

PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis; FP6). PESETA aims to make a multi-sectoral assessment of the impacts of climate change in Europe for the 2011–2040 and 2071–2100 time horizons, focusing on the impacts of climate change on coastal systems, energy demand, human health, agriculture, tourism, and floods. The emphasis is on the economic costs of climate change in Europe based on physical impact assessment and state-of-art high-resolution climate scenarios.

Box 8.1 European climate change impacts and adaptation research (cont.)

PRUDENCE ('Prediction of regional scenarios and uncertainties for defining European climate change risks and effects'; FP5). Prudence used several regional models to assess climate change at spatial scales between 30–50 km. The project developed scenarios for the variability of climate change with levels of confidence for the period 2071–2100, providing a quantitative basis for assessing the risks arising from changes in regional weather and climate in different parts of Europe. Future changes in extreme events such as drought, flooding and wind storms were estimated and a robust estimation of the likelihood and magnitude of such changes provided.

SCENES (Water Scenarios for Europe and for Neighbouring States; FP6). SCENES is a 4-year project developing and analysing a set of comprehensive scenarios of Europe's freshwater futures up to 2025, covering all of 'Greater' Europe reaching to the Caucasus and Ural Mountains, and including the Mediterranean rim countries of north Africa and the near East. These scenarios will provide a reference point for long-term strategic planning of European water resource development, alert policymakers and stakeholders about emerging problems, and allow river basin managers to test regional and local water plans against uncertainties and surprises which are inherently imbedded in a longer term strategic planning process.

WATCH (Water and Global Change; FP6). This project will bring together the hydrological, water resources and climate communities to analyse, quantify and predict the components of the current and future global water cycles and related water resources states; evaluate their uncertainties and clarify the overall vulnerability of global water resources related to the main societal and economic sectors.

Glossary ([32])

Abrupt climate change — The nonlinearity of the climate system may lead to abrupt climate change, sometimes called rapid climate change, abrupt events or even surprises. The term abrupt often refers to time scales faster than the typical time scale of the responsible forcing. However, not all abrupt climate changes need be externally forced. Some possible abrupt events that have been proposed include a dramatic reorganisation of the thermohaline circulation, rapid deglaciation and massive melting of permafrost or increases in soil respiration leading to fast changes in the carbon cycle. Others may be truly unexpected, resulting from a strong, rapidly changing forcing of a nonlinear system.

Aerosols — A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 μm that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds.

Adaptation — Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation.

Adaptive capacity (in relation to climate change impacts) — The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Albedo — The fraction of solar radiation reflected by a surface or object, often expressed as a percentage.

Anthropogenic — Resulting from or produced by human beings.

Atmosphere — The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen and oxygen, together with trace gases including carbon dioxide and ozone.

Baseline/reference — The baseline (or reference) is the state against which change is measured. It might be a 'current baseline', in which case it represents observable, present-day conditions. It might also be a 'future baseline', which is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.

Biosphere (terrestrial and marine) — The part of the Earth system comprising all ecosystems and living organisms, in the atmosphere, on land (terrestrial biosphere) or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.

Carbon cycle — The term used to describe the flow of carbon (in various forms, e.g. carbon dioxide) through the atmosphere, ocean, terrestrial biosphere and lithosphere.

Climate — Climate in a narrow sense is usually defined as the 'average weather', or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. The classical period of time is 30 years, as defined by the World Meteorological Organization (WMO).

Climate change — Climate change refers to any change in climate over time, whether due to natural

([32]) This glossary was compiled by selecting the most relevant terms from various glossaries of the IPCC's 4th Assessment reports (IPCC, 2007) (See: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-annexes.pdf; http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-app.pdf; http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-annex1.pdf).

variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines 'climate change' as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'.

Climate (change) scenario — A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships and assumptions of radiative forcing, typically constructed for explicit use as input to climate change impact models. A 'climate change scenario' is the difference between a climate scenario and the current climate.

Climate sensitivity — In IPCC reports, equilibrium climate sensitivity refers to the equilibrium change in the annual mean global surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. Due to computational constraints, the equilibrium climate sensitivity in a climate model is usually estimated by running an atmospheric general circulation model coupled to a mixed-layer ocean model, because equilibrium climate sensitivity is largely determined by atmospheric processes. Efficient models can be run to equilibrium with a dynamic ocean. The effective climate sensitivity is a related measure that circumvents the requirement of equilibrium. It is evaluated from model output for evolving non-equilibrium conditions. It is a measure of the strengths of the climate feedbacks at a particular time and may vary with forcing history and climate state. The climate sensitivity parameter (units: °C $(W\ m^{-2})^{-1}$) refers to the equilibrium change in the annual mean global surface temperature following a unit change in radiative forcing. The transient climate response is the change in the global surface temperature, averaged over a 20-year period, centred at the time of atmospheric carbon dioxide doubling, that is, at year 70 in a 1 % yr^{-1} compound carbon dioxide increase experiment with a global coupled climate model. It is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing.

Climate system — The climate system is defined by the dynamics and interactions of five major components: atmosphere, hydrosphere, cryosphere, land surface, and biosphere. Climate system dynamics are driven by both internal and external forcing, such as volcanic eruptions, solar variations, or human-induced modifications to the planetary radiative balance, for instance via anthropogenic emissions of greenhouse gases and/or land-use changes.

Climate variability — Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Control run — A model run carried out to provide a 'baseline' for comparison with climate-change experiments. The control run uses constant values for the radiative forcing due to greenhouse gases and anthropogenic aerosols appropriate to pre-industrial conditions.

Cost-benefit analysis — Monetary measurement of all negative and positive impacts associated with a given action. Costs and benefits are compared in terms of their difference and/or ratio as an indicator of how a given investment or other policy effort pays off seen from the society's point of view.

Cryosphere — The component of the climate system consisting of all snow, ice and frozen ground (including permafrost) on and beneath the surface of the Earth and ocean.

Desertification — Land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Further, the United Nations Convention to Combat Desertification (UNCCD) defines land degradation as a reduction or loss in arid, semi-arid, and dry sub-humid areas of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including those arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical, and biological or economic properties of soil; and (iii) long-term loss of natural vegetation.

Emission scenario — A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g. greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections. In IPCC (1992) a set of emission scenarios was presented which were used as a basis for the climate projections in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emission Scenarios (Nakićenović and Swart, 2000) new emission scenarios, the so-called SRES scenarios, were published, some of which were used, among others, as a basis for the climate projections presented in TAR-IPCC (2001) and 4AR-IPCC (2007).

Energy balance — The difference between the total incoming and total outgoing energy. If this balance is positive, warming occurs; if it is negative, cooling occurs. Averaged over the globe and over long time periods, this balance must be zero. Because the climate system derives virtually all its energy from the Sun, zero balance implies that, globally, the amount of incoming solar radiation on average must be equal to the sum of the outgoing reflected solar radiation and the outgoing thermal infrared radiation emitted by the climate system. A perturbation of this global radiation balance, be it anthropogenic or natural, is called radiative forcing.

Erosion — The process of removal and transport of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, winds and underground water.

Extreme weather event — An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. Single extreme events cannot be simply and directly attributed to anthropogenic climate change, as there is always a finite chance the event in question might have occurred naturally. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g. drought or heavy rainfall over a season).

Feedback — An interaction mechanism between processes is called a feedback. When the result of an initial process triggers changes in a second process and that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

Forecast — Projected outcome from established physical, technological, economic, social, behavioral, etc. patterns.

Global warming — Global warming refers to the gradual increase, observed or projected, in global surface temperature, as one of the consequences of radiative forcing caused by anthropogenic emissions.

Greenhouse effect — Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus, greenhouse gases trap heat within the surface-troposphere system. This is called the greenhouse effect. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, – 19 °C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of, on average, + 14 °C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called enhanced greenhouse effect.

Greenhouse gas (GHG) — Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Gross domestic product — Gross domestic product (GDP) is the monetary value of all goods and services produced within a nation.

Hydrosphere — The component of the climate system comprising liquid surface and subterranean water, such as oceans, seas, rivers, fresh water lakes, underground water, etc.

Land-use — The total of arrangements, activities and inputs undertaken in a certain land-cover type (a set of human actions). The social and economic purposes for which land is managed (e.g. grazing, timber extraction, and conservation). Land-use change occurs when, e.g. forest is converted to agricultural land or to urban areas.

Likelihood — The likelihood of an occurrence, an outcome or a result, where this can be estimated probabilistically.

Macroeconomic costs — These costs are usually measured as changes in gross domestic product or changes in the growth of gross domestic product, or as loss of welfare or consumption.

Measures — Measures are technologies, processes, and practices that reduce GHG emissions or effects below anticipated future levels. Examples of measures are renewable energy technologies, waste minimization processes and public transport commuting practices, etc.

Mitigation — An anthropogenic intervention to reduce the anthropogenic forcing of the climate system; it includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks.

North Atlantic Oscillation (NAO) — The North Atlantic Oscillation (NAO) consists of opposing variations of barometric pressure near Iceland and near the Azores. It is the dominant mode of winter climate variability in the North Atlantic region.

Palaeoclimate — Climate during periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available.

Phenology — The study of natural phenomena that recur periodically (e.g. development stages, migration) and their relation to climate and seasonal changes.

Projection — The potential evolution of a quality or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasise that projections involve assumptions — concerning, for example, future socio-economic and technological developments, that may or may not be realised — and are therefore subject to substantial uncertainty.

Radiative forcing — Radiative forcing is the change in the net vertical irradiance (expressed in Watts per square metre; Wm^{-2}) at the tropopause due to an internal or external change in the forcing of the climate system, such as a change in the concentration of CO_2 or the output of the sun.

Reinsurance — The transfer of a portion of primary insurance risks to a secondary tier of insurers (reinsurers); essentially 'insurance for insurers'.

Resilience — The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change.

River discharge/streamflow — Water flow within a river channel, for example expressed in m^3/s.

Runoff — That part of precipitation that does not evaporate and is not transpired.

Salinisation — The accumulation of salts in soils.

Scenario — A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline.

Sink — Any process, activity or mechanism that removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere.

Socio-economic scenarios — Scenarios concerning future conditions in terms of population, gross domestic product and other socio-economic factors relevant to understanding the implications of climate change.

Sustainable development — Development that meets the cultural, social, political and economic needs of the present generation without compromising the ability of future generations to meet their own needs.

Thermal infrared radiation — Radiation emitted by the Earth's surface, the atmosphere and the clouds. It is also known as terrestrial or longwave radiation, and is to be distinguished from the near-infrared radiation that is part of the solar spectrum. Infrared radiation, in general, has a distinctive range of wavelengths (spectrum) longer than the wavelength of the red colour in the visible part of the spectrum. The spectrum of thermal infrared radiation is practically distinct from that of shortwave or solar radiation because of the difference in temperature between the Sun and the Earth-atmosphere system.

Thermohaline circulation — Large-scale circulation in the ocean that transforms low-density upper ocean waters to higher density intermediate and deep waters and returns those waters back to the upper ocean. The circulation is asymmetric, with conversion to dense waters in restricted regions at high latitudes and the return to the surface involving slow upwelling and diffusive processes over much larger geographic regions. The THC is driven by high densities at or near the surface, caused by cold temperatures and/or high salinities, but despite its suggestive though common name, is also driven by mechanical forces such as wind and tides.

Threshold — The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.

Uncertainty — An expression of the degree to which a value (e.g. the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgement of a team of experts.

Vulnerability — Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

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Chapter 8 Data gaps, uncertainties and future needs

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