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Europe

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Executive summary

Many of the results reported here are based on a range of emissions scenarios extending up to the end of the 21st century and assume no specific climate policies to mitigate greenhouse gas emissions.

For the first time, wide ranging impacts of changes in current climate have been documented in Europe (very high confidence).

The warming trend and spatially variable changes in rainfall have affected composition and functioning of both the cryosphere (retreat of glaciers and extent of permafrost) as well as natural and managed ecosystems (lengthening of growing season, shift of species) [12.2.1]. Another example is the European heatwave in 2003 which had major impacts on biophysical systems and society [12.6.1]. The observed changes are consistent with projections of impacts due to climate change [12.4].

Climate-related hazards will mostly increase, although changes will vary geographically (very high confidence).

Winter floods are likely to increase in maritime regions and flash floods are likely to increase throughout Europe [12.4.1]. Coastal flooding related to increasing storminess and sea-level rise is likely to threaten up to 1.6 million additional people annually [12.4.2]. Warmer, drier conditions will lead to more frequent and prolonged droughts, as well as to a longer fire season and increased fire risk, particularly in the Mediterranean region [12.3.1.2, 12.4.4.1]. During dry years, catastrophic fires are expected on drained peatlands in central Europe [12.4.5]. The frequency of rock falls will increase due to destabilisation of mountain walls by rising temperatures and melting of permafrost [12.4.3].Without adaptive measures, risks to health due to more frequent heatwaves, particularly in central and southern Europe, and flooding, and greater exposure to vector- and food-borne diseases are anticipated to increase [12.3.1.2, 12.6.1]. Some impacts may be positive, as in reduced risk of extreme cold events because of increasing winter temperatures. However, on balance, health risks are very likely to increase [12.4.11].

Climate change is likely to magnify regional differences of Europe's natural resources and assets (very high confidence).

Climate scenarios indicate significant warming, greater in winter in the North and in summer in southern and central Europe [12.3.1]. Mean annual precipitation is projected to increase in the North and decrease in the South [12.3.1]. Crop suitability is likely to change throughout Europe, and crop productivity (all other factors remaining unchanged) is likely to increase in northern Europe, and decrease along the Mediterranean and in south-eastern Europe [12.4.7.1]. Forests are projected to expand in the North and retreat in the South [12.4.4.1]. Forest productivity and total biomass is likely to increase in the North and decrease in central Europe, while tree mortality is likely to accelerate in the South [12.4.4.1]. Differences in water availability between regions are anticipated to become sharper (annual average runoff increases in the North and North-west, and to decrease in the South and South-east) [12.4.1].

Water stress will increase, as well as the number of people living in river basins under high water stress (high confidence).

Water stress will increase over central and southern Europe. The percentage area under high water stress is likely to increase from 19% today to 35% by the 2070s, and the additional number of people affected by the 2070s is expected to be between 16 millions and 44 millions [12.4.1]. The most affected regions are southern Europe and some parts of central and eastern Europe, where summer flows may be reduced by up to 80% [12.4.1]. The hydropower potential of Europe is expected to decline on average by 6% but by 20 to 50% around the Mediterranean by the 2070s [12.4.8.1].

It is anticipated that Europe's natural (eco)systems and biodiversity will be substantially affected by climate change (very high confidence). The great majority of organisms and ecosystems are likely to have difficulty in adapting to climate change (high confidence).

Sea-level rise is likely to cause an inland migration of beaches and the loss of up to 20% of coastal wetlands [12.4.2], reducing habitat availability for several species that breed or forage in low-lying coastal areas [12.4.6]. Small glaciers will disappear and larger glaciers substantially shrink during the 21st century [12.4.3]. Many permafrost areas in the Arctic are projected to disappear [12.4.5]. In the Mediterranean, many ephemeral aquatic ecosystems are projected to disappear, and permanent ones to shrink [12.4.5]. Recruitment and production of marine fisheries in the North Atlantic are likely to increase [12.4.7.2]. The northward expansion of forests is projected to reduce current tundra areas under some scenarios [12.4.4]. Mountain plant communities face up to a 60% loss of species under high emissions scenarios [12.4.3]. A large percentage of the European flora is likely to become vulnerable, endangered, or committed to extinction by the end of this century [12.4.6]. Options for adaptation are likely to be limited for many organisms and ecosystems. For example, limited dispersal is very likely to reduce the range of most reptiles and amphibians [12.4.6]. Low-lying, geologically subsiding coasts are likely to be unable to adapt to sea-level rise [12.5.2]. There are no obvious climate adaptation options for either tundra or alpine vegetation [12.5.3]. The adaptive capacity of ecosystems can be enhanced by reducing human stresses [12.5.3, 12.5.5]. New sites for conservation may be needed because climate change is very likely to alter conditions of suitability for many species in current sites [12.5.6].

Climate change is estimated to pose challenges to many European economic sectors and is expected to alter the distribution of economic activity (high confidence).

Agriculture will have to cope with increasing water demand for irrigation in southern Europe, and with additional restrictions due to increases in crop-related nitrate leaching [12.5.7]. Winter heating demands are expected to decrease and summer cooling demands to increase: around the Mediterranean, two to three fewer weeks in a year will require heating but an additional two to five weeks will need cooling by 2050 [12.4.8.1]. Peak electricity demand is likely to shift in some locations from winter to summer [12.4.8.1]. Tourism along the Mediterranean is likely to decrease in summer and increase in spring and autumn. Winter tourism in mountain regions is anticipated to face reduced snow cover [12.4.9].

Adaptation to climate change is likely to benefit from experiences gained in reaction to extreme climate events, by specifically implementing proactive climate change risk management adaptation plans (high confidence).
Since the Third Assessment Report, governments have increased greatly the number of actions for coping with extreme climate events. Current thinking about adaptation to extreme climate events has moved away from reactive disaster relief towards more proactive risk management. A prominent example is the implementation in several countries of early warning systems for heatwaves [12.6.1]. Other actions have addressed long-term climate changes. For example, national action plans have been developed for adapting to climate change [12.5] and more specific plans have been incorporated into European and national policies for agriculture, energy, forestry, transport, and other sectors [12.2.3, 12.5.2]. Research has also provided new insights into adaptation policies (e.g., studies showed that crops that become less economically viable under climate change can be replaced profitably by bioenergy crops) [12.5.7].

Although the effectiveness and feasibility of adaptation measures are expected to vary greatly, only a few governments and institutions have systematically and critically examined a portfolio of measures (very high confidence).
As an example, some reservoirs used now as a measure for adapting to precipitation fluctuations may become unreliable in regions where long-term precipitation is projected to decrease [12.4.1]. In terms of forestry, the range of management options to cope with climate change varies largely among forest types, some having many more options than others [12.5.4].

12.1 Introduction

This chapter reviews existing literature on the anticipated impacts, adaptation and vulnerability of Europe to climate change during the 21st century. The area covered under Europe in this report includes all countries from Iceland in the west to Russia (west of the Urals) and the Caspian Sea in the east, and from the northern shores of the Mediterranean and Black Seas and the Caucasus in the south to the Arctic Ocean in the north. Polar issues, however, are covered in greater detail in Chapter 15.

12.1.1 Summary of knowledge from the Third Assessment Report

Climate trends in the 20th century

During the 20th century, most of Europe experienced increases in average annual surface temperature (average increase over the continent 0.8°C), with stronger warming over most regions in winter than in summer. The 1990s were the warmest in the instrumental record. Precipitation trends in the 20th century showed an increase in northern Europe (10 to 40%) and a decrease in southern Europe (up to 20% in some parts). The latest data reported in this assessment have confirmed these trends.

Climate change scenarios

The most recent climate modelling results available to the Third Assessment Report (TAR) showed an increase in annual temperature in Europe of 0.1 to 0.4°C/decade over the 21st century based on a range of scenarios and models. The models show a widespread increase in precipitation in the north, small decreases in the south, and small or ambiguous changes in central Europe. It is likely that the seasonality of precipitation will change and the frequency of intense precipitation events will increase, especially in winter. The TAR noted a very likely increase in the intensity and frequency of summer heatwaves throughout Europe, and one such major heatwave has occurred since the TAR.

Sensitivities to climate

With regards to its current sensitivities to climate, Europe was found to be most sensitive to the following conditions:

- extreme seasons, in particular exceptionally hot and dry summers and mild winters,
- short-duration events such as windstorms and heavy rains, and
- slow, long-term changes in climate which, among other impacts, will put particular pressure on coastal areas e.g., through sea-level rise.

More information is now available on the geographic variability of Europe's sensitivity to changes in climate.

Variability of impacts in regions and on social groups

Impacts of climate change will vary substantially from region to region, and from sector to sector within regions. More adverse impacts are expected in regions with lower economic development which is often related to lower adaptive capacity. Climate change will have greater or lesser impacts on different social groups (e.g., age classes, income groups, occupations).

Economic effects

The TAR identified many climate change impacts on Europe's economy:

- sea-level rise will affect important coastline industries,
- increasing CO_2 concentrations may increase agricultural yields, although this may be counteracted by decreasing water availability in southern and south-eastern Europe,
- recreation preferences are likely to change (more outdoor activity in the north, less in the south),
- the insurance industry should expect increased climate-related claims, and
- warmer temperatures and higher CO_2 levels may increase the potential timber harvest in northern Europe, while warmer temperatures may increase forest fire risk in southern Europe.

12.2 Current sensitivity/vulnerability

12.2.1 Climate factors and trends

The warming trend throughout Europe is well established (+0.90°C for 1901 to 2005; updated from Jones and Moberg, 2003). However, the recent period shows a trend considerably higher than the mean trend (+0.41°C/decade for the period 1979 to 2005; updated from Jones and Moberg, 2003). For the 1977 to 2000 period, trends are higher in central and north-eastern Europe and in mountainous regions, while lower trends are found in the Mediterranean region (Böhm et al., 2001; Klein Tank, 2004). Temperatures are increasing more in winter than summer (Jones and Moberg, 2003). An increase of daily temperature variability is observed during the period 1977 to 2000 due to an increase in warm extremes, rather than a decrease of cold extremes (Klein Tank et al., 2002; Klein Tank and Können, 2003).

Precipitation trends are more spatially variable. Mean winter precipitation is increasing in most of Atlantic and northern Europe (Klein Tank et al., 2002). In the Mediterranean area, yearly precipitation trends are negative in the east, while they are non-significant in the west (Norrant and Douguédroit, 2006). An increase in mean precipitation per wet day is observed in most parts of the continent, even in some areas which are becoming drier (Frich et al., 2002; Klein Tank et al., 2002; Alexander et al., 2006). Some of the European systems and sectors have shown particular sensitivity to recent trends in temperature and (to a lesser extent) precipitation (Table 12.1).

12.2.2 Non-climate factors and trends

Europe has the highest population density (60 persons/km^2) of any continent. Of the total European population, 73% lives in urban areas (UN, 2004), with 67% in southern Europe and 83% in northern Europe. The 25 countries belonging to the European Union (EU25) have stable economies, high productivity and integrated markets. Economic conditions among the non-EU countries are more varied. European income (as annual gross domestic product (GDP) per capita based on market exchange rate) ranges from US$1,760 in Moldova to US$55,500 in Luxembourg (World Bank, 2005). The EU25 cover 60% of the total European population, but only 17% of the total European land area and 36% of its agricultural area. In 2003, the European Union (EU) with its then 15 countries (EU15), contributed 20% of global GDP and 40% of global exports of goods and services (IMF, 2004). Central and Eastern Europe (CEE) plus European Russia constituted 16% of global GDP.

Since 1990, countries in CEE have undergone dramatic economic and political change towards a market economy and democracy and, for some countries, also integration in the EU. Annual GDP growth rates have exceeded 4% for all CEE countries and Russia, as compared to 2% in the EU (IMF, 2004).

Energy use in Europe constituted *circa* 30% of global energy consumption in 2003 (EEA, 2006a). More than 60% of this consumption occurred in the Organisation for Economic Co-operation and Development (OECD) countries (EEA, 2006a), whereas oil resources in Russia alone are more than four times higher than those of OECD Europe. Combustion of fossil fuels accounts for almost 80% of total energy consumption and 55% of electricity production in EU25 (EEA, 2006a). The large reliance on external fossil fuel resources has led to an increasing focus on renewable energy sources, including bioenergy (EEA, 2006a, b). In 2003, renewable energy contributed 6% and 13% to total energy and gross electricity consumption in EU25, respectively (EEA, 2006a).

The EU25 in 2002 had average greenhouse gas emissions of 11 tonnes CO_2 per capita (EEA, 2004a) and this is projected to increase to 12 tonnes CO_2 per capita in 2030 under baseline conditions (EEA, 2006a). Most European countries have ratified the Kyoto Protocol, and the EU15 countries have a common reduction target between 2008 and 2012 of 8% (Babiker and Eckaus, 2002). From 1990 to 2003 EU25 greenhouse gas emissions, excluding Land Use, Land Use Change and Forestry (LULUCF), decreased by 5.5%, but emissions in the transport sector grew 23% in the EU15 (EEA, 2005).

The hydrological characteristics of Europe are very diverse, as well as its approaches to water use and management. Of the total withdrawals of 30 European countries (EU plus adjacent countries) 32% are for agriculture, 31% for cooling water in power stations, 24% for the domestic sector and 13% for manufacturing (Flörke and Alcamo, 2005). Freshwater abstraction is stable or declining in northern Europe and growing slowly in southern Europe (Flörke and Alcamo, 2005). There are many pressures on water quality and availability including those arising from agriculture, industry, urban areas, households and tourism (Lallana et al., 2001). Recent floods and droughts have placed additional stresses on water supplies and infrastructure (Estrela et al., 2001).

Europe is one of the world's largest and most productive suppliers of food and fibre (in 2004: 21% of global meat production and 20% of global cereal production). About 80% of this production occurred in the EU25. The productivity of European agriculture is generally high, in particular in western Europe: average cereal yields in the EU are more than 60% higher than the global average. During the last decade the EU Common Agricultural Policy (CAP) has been reformed to reduce overproduction, reduce environmental impacts and improve rural development. This is not expected to greatly affect agricultural production in the short term (OECD, 2004). However, agricultural reforms are expected to enhance the current process of structural adjustment leading to larger and fewer farms (Marsh, 2005).

The forested areas of Europe are increasing and annual fellings are considerably below sustainable levels (EEA, 2002). Forest policies have been modified during the past decade to promote multiple forest services at the expense of timber production (Kankaanpää and Carter, 2004). European forests are a sink of atmospheric CO_2 of about 380 Tg C/yr (mid 1990s) (Janssens et al., 2003). However, CO_2 emissions from the agricultural and peat sectors reduce the net carbon uptake in Europe's terrestrial biosphere to between 135 and 205 Tg C/yr, equivalent to 7 to 12% of European anthropogenic emissions in 1995 (Janssens et al., 2003).

Despite policies to protect fish, over-fishing has put many fish stocks in European waters outside sustainable limits (62-

Table 12.1. *Attribution of recent changes in natural and managed ecosystems to recent temperature and precipitation trends. See Chapter 1, Section 1.3 for additional data.*

Region	Observed change	Reference
Coastal and marine systems		
North-east Atlantic, North Sea	Northward movement of plankton and fish	Brander and Blom, 2003; Edwards and Richardson, 2004; Perry et al., 2005
Terrestrial ecosystems		
Europe	Upward shift of the tree line	Kullman, 2002; Camarero and Gutiérrez, 2004; Shiyatov et al., 2005; Walther et al., 2005a
Europe	Phenological changes (earlier onset of spring events and lengthening of the growing season); increasing productivity and carbon sink during 1950 to 1999 of forests (in 30 countries)	Menzel et al., 2006a Nabuurs et al., 2003, Shvidenko and Nilsson, 2003; Boisvenue and Running, 2006
Alps	Invasion of evergreen broad-leaved species in forests; upward shift of *Viscum album*	Walther, 2004; Dobbertin et al., 2005
Scandinavia	Northward range expansion of *Ilex aquifolium*	Walter et al., 2005a
Fennoscandian mountains and sub-Artic	Disappearance of some types of wetlands (palsa mires[1]) in Lapland; increased species richness and frequency at altitudinal margin of plant life	Klanderud and Birks, 2003; Luoto et al., 2004
High mountains	Change in high mountain vegetation types and new occurrence of alpine vegetation on high summits.	Grabherr et al., 2001; Kullman, 2001; Pauli et al., 2001; Klanderud and Birks, 2003; Peñuelas and Boada, 2003; Petriccione, 2003; Sanz Elorza and Dana, 2003; Walther et al., 2005a
Agriculture		
Northern Europe	Increased crop stress during hotter, drier summers; increased risk to crops from hail	Viner et al., 2006
Britain, southern Scandinavia	Increased area of silage maize (more favourable conditions due to warmer summer temperatures)	Olesen and Bindi, 2004
France	Increases in growing season of grapevine; changes in wine quality	Jones and Davis, 2000; Duchene and Schneider, 2005
Germany	Advance in the beginning of growing season for fruit trees	Menzel, 2003; Chmielewski et al., 2004
Cryosphere		
Russia	Decrease in thickness and areal extent of permafrost and damages to infrastructure	Frauenfeld et al., 2004; Mazhitova et al., 2004
Alps	Decrease in seasonal snow cover (at lower elevation)	Laternser and Schneebeli, 2003; Martin and Etchevers, 2005
Europe	Decrease in glacier volume and area (except some glaciers in Norway)	Hoelzle et al., 2003
Health		
North, East	Movement of tick vectors northwards, and possibly to high altitudes	Lindgren and Gustafson, 2001; Randolph, 2002; Beran et al., 2004; Danielova et al., 2004; Izmerov, 2004; Daniel et al., 2005; Materna et al., 2005
Mediterranean, West, South	Northward movement of *Visceral Leishmaniasis* in dogs and humans [low confidence]	Molyneux, 2003; Kuhn et al., 2004; WHO, 2005; Lindgren and Naucke, 2006
Mediterranean, Atlantic, Central	Heatwave mortality	Fischer et al., 2004; Kosatsky, 2005; Nogueira et al., 2005, Pirard et al., 2005
Atlantic, Central, East, North	Earlier onset and extension of season for allergenic pollen	Huynen and Menne, 2003; van Vliet et al., 2003; Beggs, 2004 [Chapter 1.3.7.5]

92% of commercial fish stocks in north-eastern Atlantic, 100% in the western Irish Sea, 75% in the Baltic Sea, and 65-70% in the Mediterranean) (EEA, 2002; Gray and Hatchard, 2003). Aquaculture is increasing its share of the European fish market leading to possible adverse environmental impacts in coastal waters (Read and Fernandes, 2003).

Increasing urbanisation and tourism, as well as intensification of agriculture, have put large pressures on land resources (EEA, 2004a), yet there is increasing political attention given to the sustainable use of land and natural resources. Despite general reductions in the extent of air pollution in Europe over the last decades, significant problems still remain with acidification,

[1] Palsa mire: a type of peatland typified by high mounds with permanently frozen cores and separated by wet depressions; they form where the ground surface is only frozen for part of the year.

terrestrial nitrogen deposition, ozone, particulate matter and heavy metals (WGE, 2004). Environmental protection in the EU has led to several directives such as the Emissions Ceilings Directive and the Water Framework Directive. The EU Species and Habitats Directive and the Wild Birds Directive have been integrated in the Natura 2000 network, which protects nature in over 18% of the EU territory. Awareness of environmental issues is also growing in CEE (TNS Opinion and Social, 2005).

12.2.3 Current adaptation and adaptive capacity

It is apparent that climate variability and change already affects features and functions of Europe's production systems (e.g., agriculture, forestry and fisheries), key economic sectors (e.g., tourism, energy) and its natural environment. Some of these effects are beneficial, but most are estimated to be negative (EEA, 2004b). European institutions have recognised the need to prepare for an intensification of these impacts even if greenhouse gas emissions are substantially reduced (e.g., EU Environmental Council meeting, December 2004).

The sensitivity of Europe to climate change has a distinct north-south gradient, with many studies indicating that southern Europe will be more severely affected than northern Europe (EEA, 2004b). The already hot and semi-arid climate of southern Europe is expected to become warmer and drier, and this will threaten its waterways, agricultural production and timber harvests (e.g., EEA, 2004b). Nevertheless, northern countries are also sensitive to climate change.

The Netherlands is an example of a country highly susceptible to both sea-level rise and river flooding because 55% of its territory is below sea level where 60% of its population lives and 65% of its Gross National Product (GNP) is produced. As in other regions, natural ecosystems in Europe are more vulnerable to climate change than managed systems such as agriculture and fisheries (Hitz and Smith, 2004). Natural ecosystems usually take decades or longer to become established and therefore adapt more slowly to climatic changes than managed systems. The expected rate of climate change in Europe is likely to exceed the current adaptive capacity of various non-cultivated plant species (Hitz and Smith, 2004). Sensitivity to climate variability and change also varies across different ecosystems. The most sensitive natural ecosystems in Europe are located in the Arctic, in mountain regions, in coastal zones (especially the Baltic wetlands) and in various parts of the Mediterranean (WBGU, 2003). Ecosystems in these regions are already affected by an increasing trend in temperature and decreasing precipitation in some areas and may be unable to cope with expected climate change.

The possible consequences of climate change in Europe have stimulated efforts by the EU, national governments, businesses, and Non-Governmental Organisations (NGOs) to develop adaptation strategies. The EU is supporting adaptation research at the pan-European level while Denmark, Finland, Hungary, Portugal, Slovakia, Spain and the UK are setting up national programmes for adapting to climate change. Plans for adaptation to climate change have been included in flood protection plans of the Czech Republic and coastal protection plans of the Netherlands and Norway.

12.3 Assumptions about future trends

12.3.1 Climate projections

12.3.1.1 Mean climate

Results presented here and in the following sections are for the period 2070 to 2099 and are mostly based on the IPCC Special Report on Emissions Scenarios (SRES: Nakićenović and Swart, 2000; see also Section 12.3.2) using the climate normal period (1961 to 1990) as a baseline.

Europe undergoes a warming in all seasons in both the SRES A2 and B2 emissions scenarios (A2: 2.5 to 5.5°C, B2: 1 to 4°C; the range of change is due to different climate modelling results). The warming is greatest over eastern Europe in winter (December to February: DJF) and over western and southern Europe in summer (June to August: JJA) (Giorgi et al., 2004). Results using two regional climate models under the PRUDENCE project (Christensen and Christensen, 2007) showed a larger warming in winter than in summer in northern Europe and the reverse in southern and central Europe. A very large increase in summer temperatures occurs in the south-western parts of Europe, exceeding 6°C in parts of France and the Iberian Peninsula (Kjellström, 2004; Räisänen et al., 2004; Christensen and Christensen, 2006; Good et al., 2006).

Generally for all scenarios, mean annual precipitation increases in northern Europe and decreases further south, whilst the change in seasonal precipitation varies substantially from season to season and across regions in response to changes in large-scale circulation and water vapour loading. Räisänen et al. (2004) identified an increase in winter precipitation in northern and central Europe. Likewise, Giorgi et al. (2004) found that increased Atlantic cyclonic activity in DJF leads to enhanced precipitation (up to 15-30%) over much of western, northern and central Europe. Precipitation during this period decreases over Mediterranean Europe in response to increased anticyclonic circulation. Räisänen et al. (2004) found that summer precipitation decreases substantially (in some areas up to 70% in scenario A2) in southern and central Europe, and to a smaller degree in northern Europe up to central Scandinavia. Giorgi et al. (2004) identified enhanced anticyclonic circulation in JJA over the north-eastern Atlantic, which induces a ridge over western Europe and a trough over eastern Europe. This blocking structure deflects storms northward, causing a substantial and widespread decrease in precipitation (up to 30-45%) over the Mediterranean Basin as well as over western and central Europe. Both the winter and summer changes were found to be statistically significant (very high confidence) over large areas of the regional modelling domain. Relatively small precipitation changes were found for spring and autumn (Kjellström, 2004; Räisänen et al., 2004).

Change in mean wind speed is highly sensitive to the differences in large-scale circulation that can result between different global models (Räisänen et al., 2004). From regional simulations based on ECHAM4 and the A2 scenario, mean annual wind speed increases over northern Europe by about 8% and decreases over Mediterranean Europe (Räisänen et al., 2004; Pryor et al., 2005). The increase for northern Europe is largest in winter and early spring, when the increase in the average north-south pressure gradient is largest. Indeed, the simulation of DJF mean pressure indicates an increase in average westerly flow over northern Europe when the ECHAM4 global model is used, but a slight decrease when the HadAM3H model (Gordon et al., 2000) is used. For France and central Europe, all four of the simulations documented by Räisänen et al. (2004) indicate a slight increase in mean wind speeds in winter and some decrease in spring and autumn. None of the reported simulations show significant change during summer for northern Europe.

12.3.1.2 Extreme events

The yearly maximum temperature is expected to increase much more in southern and central Europe than in northern Europe (Räisänen et al., 2004; Kjellström et al., 2007). Kjellström (2004) shows that, in summer, the warming of large parts of central, southern and eastern Europe may be more closely connected to higher temperatures on warm days than to a general warming. A large increase is also expected for yearly minimum temperature across most of Europe, which at many locations exceeds the average winter warming by a factor of two to three. Much of the warming in winter is connected to higher temperatures on cold days, which indicates a decrease in winter temperature variability. An increase in the lowest winter temperatures, although large, would primarily mean that current cold extremes would decrease. In contrast, a large increase in the highest summer temperatures would expose Europeans to unprecedented high temperatures.

Christensen and Christensen (2003), Giorgi et al. (2004) and Kjellström (2004) all found a substantial increase in the intensity of daily precipitation events. This holds even for areas with a decrease in mean precipitation, such as central Europe and the Mediterranean. Impact over the Mediterranean region during summer is not clear due to the strong convective rainfall component and its great spatial variability (Llasat, 2001). Palmer and Räisänen (2002) estimate that the probability of extreme winter precipitation exceeding two standard deviations above normal would increase by a factor of five over parts of the UK and northern Europe, while Ekström et al. (2005) have found a 10% increase in short duration (1 to 2 days) precipitation events across the UK. Lapin and Hlavcova (2003) found an increase in short duration (1 to 5 days) summer rainfall events in Slovakia of up to 40% for a 3.5°C summer warming.

The combined effects of warmer temperatures and reduced mean summer precipitation would enhance the occurrence of heatwaves and droughts. Schär et al. (2004) conclude that the future European summer climate would experience a pronounced increase in year-to-year variability and thus a higher incidence of heatwaves and droughts. Beniston et al. (2007) estimated that countries in central Europe would experience the same number of hot days as currently occur in southern Europe and that Mediterranean droughts would start earlier in the year and last longer. The regions most affected could be the southern Iberian Peninsula, the Alps, the eastern Adriatic seaboard, and southern Greece. The Mediterranean and even much of eastern Europe may experience an increase in dry periods by the late 21st century (Polemio and Casarano, 2004). According to Good et al. (2006), the longest yearly dry spell could increase by as much as 50%, especially over France and central Europe. However, there is some recent evidence (Lenderink et al., 2007) that these projections for droughts and heatwaves may be slightly over-estimated due to the parameterisation of soil moisture (too small soil storage capacity resulting in soil drying out too easily) in regional climate models.

Regarding extreme winds, Rockel and Woth (2007) and Leckebusch and Ulbrich (2004) found an increase in extreme wind speeds for western and central Europe, although the changes were not statistically significant for all months of the year. Beniston et al. (2007) found that extreme wind speeds increased for the area between 45°N and 55°N, except over and south of the Alps. Woth et al. (2005) and Beniston et al. (2007) conclude that this could generate more North Sea storms leading to increases in storm surges along the North Sea coast, especially in the Netherlands, Germany and Denmark.

12.3.2 Non-climate trends

The European population is expected to decline by about 8% over the period from 2000 to 2030 (UN, 2004). The relative overall stability of the population of Europe is due to population growth in western Europe alone, mainly from immigration (Sardon, 2004). Presently, CEE and Russia have a surplus of deaths over births, with the balance of migration being positive only in Russia. Fertility rates vary considerably across the continent, from 1.10 children per woman in Ukraine to 1.97 in Ireland. There is a general decline in old-age mortality in most European countries (Janssen et al., 2004), although there has been a reduction in life expectancy in Russia during the 1990s. The low birth rate and increase in duration of life lead to an overall older population. The proportion of the population over 65 years of age in the EU15 is expected to increase from 16% in 2000 to 23% in 2030, which will likely affect vulnerability in recreational (see Section 12.4.9) and health aspects (see Section 12.4.11).

The SRES scenarios (see Chapter 2 Section 2.4.6) for socio-economic development have been adapted to European conditions (Parry, 2000; Holman et al., 2005; Abildtrup et al., 2006). Electricity consumption in the EU25 is projected to continue growing twice as fast as the increase in total energy consumption (EEA, 2006a), primarily due to higher comfort levels and larger dwellings increasing demand for space heating and cooling, which will have consequences for electricity demand during summer (see Section 12.4.8.1).

Assumptions about future European land use and the environmental impact of human activities depend greatly on the development and adoption of new technologies. For the SRES scenarios it has been estimated that increases in crop productivity relative to 2000 could range between 25 and 163% depending on the time slice (2020 to 2080) and scenario (Ewert et al., 2005). These increases were found to be smallest for the B2 and highest for the A1FI scenario. Temporally and spatially explicit future scenarios of European land use have been developed for the four core SRES scenarios (Schröter et al., 2005; Rounsevell et al., 2006). These scenarios show large declines in agricultural land area, resulting primarily from the assumptions about technological development and its effect on crop yield (Rounsevell et al., 2005), although climate change may also play a role (see Section 12.5.7). The expansion of urban area is similar between the scenarios, and forested areas also increase in all scenarios (Schröter et al., 2005). The scenarios showed decreases in European cropland for 2080 of 28 to 47% and decreases in grassland of 6 to 58% (Rounsevell et al., 2005). This decline in agricultural area will mean that land resources will be available for other uses such as biofuel production and nature reserves. Over the shorter term (up to 2030) changes in agricultural land area may be small (van Meijl et al., 2006).

12.4 Key future impacts and vulnerabilities

The wide range of climate change impacts and vulnerabilities expected in Europe is summarised in Figure 12.3 and Table 12.4.

12.4.1 Water resources

It is likely that climate change will have a range of impacts on water resources. Projections based on various emissions scenarios and General Circulation Models (GCMs) show that annual runoff increases in Atlantic and northern Europe (Werritty, 2001; Andréasson et al., 2004), and decreases in central, Mediterranean and eastern Europe (Chang et al., 2002; Etchevers et al., 2002; Menzel and Bürger, 2002; Iglesias et al., 2005). Most of the hydrological impact studies reported here are based on global rather than regional climate models. Annual average runoff is projected to increase in northern Europe (north of 47°N) by approximately 5 to 15% up to the 2020s and 9 to 22% up to the 2070s, for the SRES A2 and B2 scenarios and climate scenarios from two different climate models (Alcamo et al., 2007) (Figure 12.1). Meanwhile, in southern Europe (south of 47°N), runoff decreases by 0 to 23% up to the 2020s and by 6 to 36% up to the 2070s (for the same set of assumptions). The projected changes in annual river basin discharge by the 2020s are likely to be affected as much by climate variability as by climate change. Groundwater recharge is likely to be reduced in central and eastern Europe (Eitzinger et al., 2003), with a larger reduction in valleys (Krüger et al., 2002) and lowlands (e.g., in the Hungarian steppes) (Somlyódy, 2002).

Studies show an increase in winter flows and decrease in summer flows in the Rhine (Middelkoop and Kwadijk, 2001), Slovakian rivers (Szolgay et al., 2004), the Volga and central and eastern Europe (Oltchev et al., 2002). It is likely that glacier retreat will initially enhance summer flow in the rivers of the

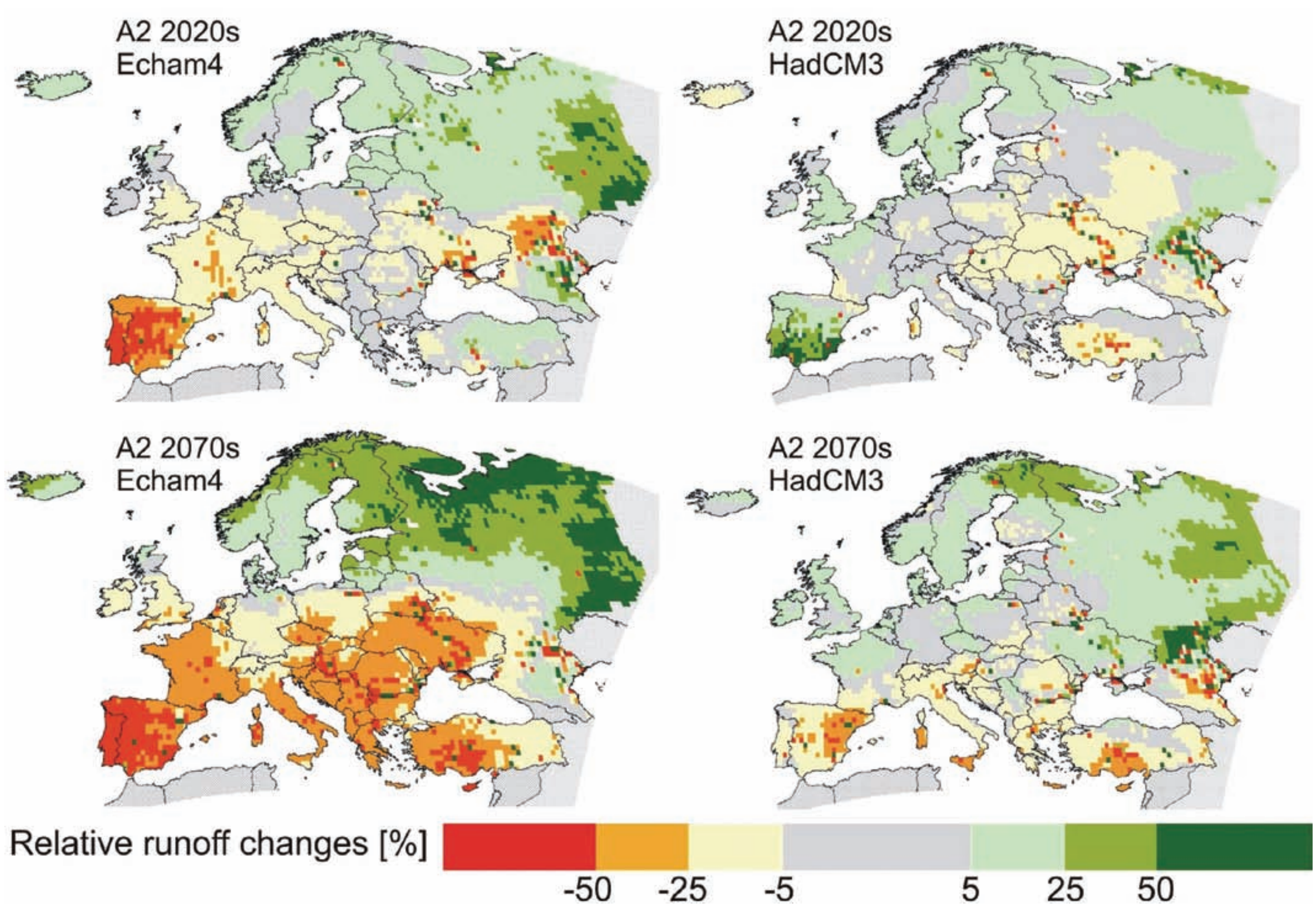

Figure 12.1. *Change in annual river runoff between the 1961-1990 baseline period and two future time slices (2020s and 2070s) for the A2 scenarios (Alcamo et al., 2007).*

Alps; however, as glaciers shrink, summer flow is likely to be significantly reduced (Hock et al., 2005), by up to 50% (Zierl and Bugmann, 2005). Summer low flow may decrease by up to 50% in central Europe (Eckhardt and Ulbrich, 2003), and by up to 80% in some rivers in southern Europe (Santos et al., 2002).

Changes in the water cycle are likely to increase the risk of floods and droughts. Projections under the IPCC IS92a scenario (similar to SRES A1B; IPCC, 1992) and two GCMs (Lehner et al., 2006) indicate that the risk of floods increases in northern, central and eastern Europe, while the risk of drought increases mainly in southern Europe (Table 12.2). Increase in intense short-duration precipitation in most of Europe is likely to lead to increased risk of flash floods (EEA, 2004b). In the Mediterranean, however, historical trends supporting this are not extensive (Ludwig et al., 2003; Benito et al., 2005; Barrera et al., 2006).

Increasing flood risk from climate change could be magnified by increases in impermeable surface due to urbanisation (de Roo et al., 2003) and modified by changes in vegetation cover (Robinson et al., 2003) in small catchments. The effects of land use on floods in large catchments are still being debated. The more frequent occurrence of high floods increases the risk to areas currently protected by dykes. The increasing volume of floods and peak discharge would make it more difficult for reservoirs to store high runoff and prevent floods.

Table 12.2. *Impact of climate change on water availability, drought and flood occurrence in Europe for various time slices and under various scenarios based on the ECHAM4 and HadCM3 models.*

Time slice	Water availability and droughts	Floods
2020s	Increase in annual runoff in northern Europe by up to 15% and decrease in the south by up to 23%.[a] Decrease in summer flow.[b]	Increasing risk of winter flood in northern Europe, of flash flooding across all of Europe. Risk of snowmelt flood shifts from spring to winter.[c]
2050s	Decrease in annual runoff by 20-30% in south-eastern Europe.[d]	
2070s	Increase in annual runoff in the north by up to 30% and decrease by up to 36% in the south.[a] Decrease in summer low flow by up to 80%.[d, b] Decreasing drought risk in northern Europe, increasing drought risk in western and southern Europe. Today's 100-year droughts return every 50 years (or less) in southern and south-eastern Europe (Portugal, all Mediterranean countries, Hungary, Romania, Bulgaria, Moldova, Ukraine, southern Russia).[c]	Today's 100-year floods occur more frequently in northern and north-eastern Europe (Sweden, Finland, northern Russia), in Ireland, in central and eastern Europe (Poland, Alpine rivers), in Atlantic parts of southern Europe (Spain, Portugal), and less frequently in large parts of southern Europe.[c]

[a] Alcamo et al., 2007; [b] Santos et al., 2002; [c] Lehner et al., 2006; [d] Arnell, 2004

Increasing drought risk for western Europe (e.g., Great Britain; Fowler and Kilsby, 2004) is primarily caused by climate change; for southern and eastern Europe increasing risk from climate change would be amplified by an increase in water withdrawals (Lehner et al., 2006). The regions most prone to an increase in drought risk are the Mediterranean (Portugal, Spain) and some parts of central and eastern Europe, where the highest increase in irrigation water demand is projected (Döll, 2002; Donevska and Dodeva, 2004). Irrigation requirements are likely to become substantial in countries (e.g., Ireland) where demand now hardly exists (Holden et al., 2003). It is likely that, due to both climate change and increasing water withdrawals, the river-basin area affected by severe water stress (withdrawal : availability >0.40) will increase and lead to increasing competition for available water resources (Alcamo et al., 2003; Schröter et al., 2005). Under the IS92a scenario, the percentage of river basin area in the severe water stress category increases from 19% today to 34-36% by the 2070s (Lehner et al., 2001). The number of additional people living in water-stressed watersheds in the EU15 plus Switzerland and Norway is likely to increase to between 16 million and 44 million, based on climate projected by the HadCM3 GCM under the A2 and B1 emissions scenarios, respectively (Schröter et al., 2005).

12.4.2 Coastal and marine systems

Climate variability associated with the North Atlantic Oscillation (NAO) determines many physical coastal processes in Europe (Hurrell et al., 2003, 2004), including variations in the seasonality of coastal climates, winter wind speeds and patterns of storminess and coastal flooding in north-west Europe (Lozano et al., 2004; Stone and Orford, 2004; Yan et al., 2004). For Europe's Atlantic coasts and shelf seas, the NAO also has a strong influence on the dynamic sea-surface height and geographic distribution of sea-level rise (Woolf et al., 2003), as well as some relation to coastal flooding and water levels in the Caspian Sea (Lal et al., 2001). Most SRES-based climate scenarios show a continuation of the recent positive phase of the NAO for the first decades of the 21st century with significant impacts on coastal areas (Cubasch et al., 2001; Hurrell et al., 2003).

Wind-driven waves and storms are seen as the primary drivers of short-term coastal processes on many European coasts (Smith et al., 2000). Climate simulations using the IS92a and A2 and B2 SRES scenarios (Meier et al., 2004; Räisänen et al., 2004) reinforce existing trends in storminess. These indicate some further increase in wind speeds and storm intensity in the north-eastern Atlantic during at least the early part of the 21st century (2010 to 2030), with a shift of storm centre maxima closer to European coasts (Knippertz et al., 2000; Leckebusch and Ulbrich, 2004; Lozano et al., 2004). These experiments also show a decline in storminess and wind intensity eastwards into the Mediterranean (Busuioc, 2001; Tomozeiu et al., 2007), but with localised increased storminess in parts of the Adriatic, Aegean and Black Seas (Guedes Soares et al., 2002).

Ensemble modelling of storm surges and tidal levels in shelf seas, particularly for the Baltic and southern North Sea, indicate fewer but more extreme surge events under some SRES emissions scenarios (Hulme et al., 2002; Meier et al., 2004;

Lowe and Gregory, 2005). In addition, wave simulations show higher significant wave heights of >0.4m in the north-eastern Atlantic by the 2080s (Woolf et al., 2002; Tsimplis et al., 2004a; Wolf and Woolf, 2006). Higher wave and storm-surge elevations will be particularly significant because they will cause erosion and flooding in estuaries, deltas and embayments (Flather and Williams, 2000; Lionello et al., 2002; Tsimplis et al., 2004b; Woth et al., 2005; Meier et al., 2007).

Model projections of the IPCC SRES scenarios give a global mean sea-level rise of 0.09 to 0.88 m by 2100, with sea level rising at rates *circa* 2 to 4 times faster than those of the present day (EEA, 2004b; Meehl et al., 2007). In Europe, regional influences may result in sea-level rise being up to 50% higher than these global estimates (Woodworth et al., 2005). The impact of the NAO on winter sea levels provides an additional uncertainty of 0.1 to 0.2 m to these estimates (Hulme et al., 2002; Tsimplis et al., 2004a). Furthermore, the sustained melting of Greenland ice and other ice stores under climate warming, coupled with the impacts of a possible abrupt shut-down of the Atlantic meridional overturning circulation (MOC) after 2100, provide additional uncertainty to sea-level rise for Europe (Gregory et al., 2004; Levermann et al., 2005; Wigley, 2005; Meehl et al., 2007).

Sea-level rise can have a wide variety of impacts on Europe's coastal areas; causing flooding, land loss, the salinisation of groundwater and the destruction of built property and infrastructures (Devoy, 2007; Nicholls and de la Vega-Leinert, 2007). Over large areas of formerly glaciated coastlines the continued decline in isostatic land uplift is bringing many areas within the range of sea-level rise (Smith et al., 2000). For the Baltic and Arctic coasts, sea-level rise projections under some SRES scenarios indicate an increased risk of flooding and coastal erosion after 2050 (Johansson et al., 2004; Meier et al., 2004, 2006; Kont et al., 2007). In areas of coastal subsidence or high tectonic activity, as in the low tidal range Mediterranean and Black Sea regions, climate-related sea-level rise could significantly increase potential damage from storm surges and tsunamis (Gregory et al., 2001). Sea-level rise will also cause an inland migration of Europe's beaches and low-lying, soft sedimentary coasts (Sánchez-Arcilla et al., 2000; Stone and Orford, 2004; Hall et al., 2007). Coastal retreat rates are currently 0.5 to 1.0 m/yr for parts of the Atlantic coast most affected by storms and under sea-level rise these rates are expected to increase (Cooper and Pilkey, 2004; Lozano et al., 2004).

The vulnerability of marine and nearshore waters and of many coasts is very dependent on local factors (Smith et al., 2000; EEA, 2004b; Swift et al., 2007). Low-lying coastlines with high population densities and small tidal ranges will be most vulnerable to sea-level rise (Kundzewicz et al., 2001). Coastal flooding related to sea-level rise could affect large populations (Arnell et al., 2004). Under the SRES A1FI scenario up to an additional 1.6 million people each year in the Mediterranean, northern and western Europe, might experience coastal flooding by 2080 (Nicholls, 2004). Approximately 20% of existing coastal wetlands may disappear by 2080 under SRES scenarios for sea-level rise (Nicholls, 2004; Devoy, 2007). Impacts of climate warming upon coastal and marine ecosystems are also likely to intensify the problems of eutrophication and stress on these biological systems (EEA, 2004b; Robinson et al., 2005; SEPA, 2005; SEEG, 2006).

12.4.3 Mountains and sub-Arctic regions

The duration of snow cover is expected to decrease by several weeks for each °C of temperature increase in the Alps region at middle elevations (Hantel et al., 2000; Wielke et al., 2004; Martin and Etchevers, 2005). An upward shift of the glacier equilibrium line is expected from 60 to 140 m/°C (Maisch, 2000; Vincent, 2002; Oerlemans, 2003). Glaciers will experience a substantial retreat during the 21st century (Haeberli and Burn, 2002). Small glaciers will disappear, while larger glaciers will suffer a volume reduction between 30% and 70% by 2050 (Schneeberger et al., 2003; Paul et al., 2004). During the retreat of glaciers, spring and summer discharge will decrease (Hagg and Braun, 2004). The lower elevation of permafrost is likely to rise by several hundred metres. Rising temperatures and melting permafrost will destabilise mountain walls and increase the frequency of rock falls, threatening mountain valleys (Gruber et al., 2004). In northern Europe, lowland permafrost will eventually disappear (Haeberli and Burns, 2002). Changes in snowpack and glacial extent may also alter the likelihood of snow and ice avalanches, depending on the complex interaction of surface geometry, precipitation and temperature (Martin et al., 2001; Haeberli and Burns, 2002).

It is virtually certain that European mountain flora will undergo major changes due to climate change (Theurillat and Guisan, 2001; Walther, 2004). Change in snow-cover duration and growing season length should have much more pronounced effects than direct effects of temperature changes on metabolism (Grace et al., 2002; Körner, 2003). Overall trends are towards increased growing season, earlier phenology and shifts of species distributions towards higher elevations (Kullman 2002; Körner, 2003; Egli et al., 2004; Sandvik et al., 2004; Walther, 2004). Similar shifts in elevation are also documented for animal species (Hughes, 2000). The treeline is predicted to shift upward by several hundred metres (Badeck et al., 2001). There is evidence that this process has already begun in Scandinavia (Kullman, 2002), the Ural Mountains (Shiyatov et al., 2005), West Carpathians (Mindas et al., 2000) and the Mediterranean (Peñuelas and Boada, 2003; Camarero and Gutiérrez, 2004). These changes, together with the effect of abandonment of traditional alpine pastures, will restrict the alpine zone to higher elevations (Guisan and Theurillat, 2001; Grace et al., 2002; Dirnböck et al., 2003; Dullinger et al., 2004), severely threatening nival flora[2] (Gottfried et al., 2002). The composition and structure of alpine and nival communities are very likely to change (Guisan and Theurillat, 2000; Walther, 2004). Local plant species losses of up to 62% are projected for Mediterranean and Lusitanian mountains by the 2080s under the A1 scenario (Thuiller et al., 2005). Mountain regions may additionally experience a loss of endemism due to invasive species (Viner et al., 2006). Similar extreme impacts are

[2] Nival flora: growing in or under snow.

expected for habitat and animal diversity as well, making mountain ecosystems among the most threatened in Europe (Schröter et al., 2005).

12.4.4 Forests, shrublands and grasslands

12.4.4.1 Forests

Forest ecosystems in Europe are very likely to be strongly influenced by climate change and other global changes (Shaver et al., 2000; Blennow and Sallnäs, 2002; Askeev et al., 2005; Kellomäki and Leinonen, 2005; Maracchi et al., 2005). Forest area is expected to expand in the north (Kljuev, 2001; MNRRF, 2003; Shiyatov et al., 2005), decreasing the current tundra area by 2100 (White et al., 2000), but contract in the south (Metzger et al., 2004). Native conifers are likely to be replaced by deciduous trees in western and central Europe (Maracchi et al., 2005; Koca et al., 2006). The distribution of a number of typical tree species is likely to decrease in the Mediterranean (Schröter et al., 2005). Tree vulnerability will increase as populations/plantations are managed to grow outside their natural range (Ray et al., 2002; Redfern and Hendry, 2002; Fernando and Cortina, 2004).

In northern Europe, climate change will alter phenology (Badeck et al., 2004) and substantially increase net primary productivity (NPP) and biomass of forests (Jarvis and Linder, 2000; Rustad et al., 2001; Strömgren and Linder, 2002; Zheng et al., 2002; Freeman et al., 2005; Kelomäki et al., 2005; Boisvenue and Running, 2006). In the boreal forest, soil CO_2 fluxes to the atmosphere increase with increased temperature and atmospheric CO_2 concentration (Niinisto et al., 2004), although many uncertainties remain (Fang and Moncrieff, 2001; Ågren and Bosatta, 2002; Hyvönen et al., 2005). Climate change may induce a reallocation of carbon to foliage (Magnani et al., 2004; Lapenis et al., 2005) and lead to carbon losses (White et al., 2000; Kostiainen et al., 2006; Schaphoff et al., 2006). Climate change may alter the chemical composition and density of wood while impacts on wood anatomy remain uncertain (Roderick and Berry, 2001; Wilhelmsson et al., 2002; Kostiainen et al., 2006).

In the northern and maritime temperate zones of Europe, and at higher elevations in the Alps, NPP is likely to increase throughout the century. However, by the end of the century (2071 to 2100) in continental central and southern Europe, NPP of conifers is likely to decrease due to water limitations (Lasch et al., 2002; Lexer et al., 2002; Martínez-Vilalta and Piñol, 2002; Freeman et al., 2005; Körner et al., 2005) and higher temperatures (Pretzch and Dursky, 2002). Negative impacts of drought on deciduous forests are also likely (Broadmeadow et al., 2005). Water stress in the south may be partially compensated by increased water-use efficiency (Magnani et al., 2004), elevated CO_2 (Wittig et al., 2005) and increased leaf area index (Kull et al., 2005), although this is currently under debate (Medlyn et al., 2001; Ciais et al., 2004).

Abiotic hazards for forest are likely to increase, although expected impacts are regionally specific and will be substantially dependent on the forest management system used (Kellomäki and Leinonen, 2005). A substantial increase in wind damage is not predicted (Barthod, 2003; Nilsson et al., 2004; Schumacher and Bugmann, 2006). In northern Europe, snow cover will decrease, and soil frost-free periods and winter rainfall increase, leading to increased soil waterlogging and winter floods (Nisbet, 2002; KSLA, 2004). Warming will prevent chilling requirements from being met[3], reduce cold-hardiness during autumn and spring, and increase needle loss (Redfern and Hendry, 2002). Frost damage is expected to be reduced in winter, unchanged in spring and more severe in autumn due to later hardening (Linkosalo et al., 2000; Barklund, 2002; Redfern and Hendry, 2002), although this may vary among regions and species (Jönsson et al., 2004). The risk of frost damage to trees may even increase after possible dehardening and growth onset during mild spells in winter and early spring (Hänninen, 2006). Fire danger, length of the fire season, and fire frequency and severity are very likely to increase in the Mediterranean (Santos et al., 2002; Pausas, 2004; Moreno, 2005; Pereira et al., 2005; Moriondo et al., 2006), and lead to increased dominance of shrubs over trees (Mouillot et al., 2002). Albeit less, fire danger is likely to also increase in central, eastern and northern Europe (Goldammer et al., 2005; Kellomäki et al., 2005; Moriondo et al., 2006). This, however, does not translate directly into increased fire occurrence or changes in vegetation (Thonicke and Cramer, 2006). In the forest-tundra ecotone, increased frequency of fire and other anthropogenic impacts is likely to lead to a long-term (over several hundred years) replacement of forest by low productivity grassy glades or wetlands over large areas (Sapozhnikov, 2003). The range of important forest insect pests may expand northward (Battisti, 2004), but the net impact of climate and atmospheric change is complex (Bale et al., 2002; Zvereva and Kozlov, 2006).

12.4.4.2 Shrublands

The area of European shrublands has increased over recent decades, particularly in the south (Moreira et al., 2001; Mouillot et al., 2003; Alados et al., 2004). Climate change is likely to affect its key ecosystem functions such as carbon storage, nutrient cycling, and species composition (Wessel et al., 2004). The response to warming and drought will depend on the current conditions, with cold, moist sites being more responsive to temperature changes, and warm, dry sites being more responsive to changes in rainfall (Peñuelas et al., 2004). In northern Europe, warming will increase microbial activity (Sowerby et al., 2005), growth and productivity (Peñuelas et al., 2004), hence enabling higher grazing intensities (Wessel et al., 2004). Encroachment by grasses (Werkman and Callaghan, 2002) and elevated nitrogen leaching (Emmet et al., 2004; Gorissen et al., 2004; Schmidt et al., 2004) are also likely. In southern Europe, warming and, particularly, increased drought, are likely to lead to reduced plant growth and primary productivity (Ogaya et al., 2003; Llorens et al., 2004), reduced nutrient turnover and nutrient availability (Sardans and Peñuelas, 2004, 2005), altered plant recruitment (Lloret et al., 2004; Quintana et al., 2004), changed phenology (Llorens and Peñuelas, 2005), and changed species interactions (Maestre and Cortina, 2004; Lloret et al.,

[3] Many plants, and most deciduous fruit trees, need a period of cold temperatures (the chilling requirement) during the winter in order for the flower buds to open in the spring.

2005). Shrubland fires are likely to increase due to their higher propensity to burn (Vázquez and Moreno, 2001; Mouillot et al., 2005; Nunes et al., 2005; Salvador et al., 2005). Furthermore, increased torrentiality (Giorgi et al., 2004) is likely to lead to increased erosion risk (de Luis et al., 2003) due to reduced plant regeneration after frequent fires (Delitti et al., 2005).

12.4.4.3 Grasslands

Permanent pastures occupied 37% of the agricultural area in Europe in 2000 (FAOSTAT, 2005). Grasslands are expected to decrease in area by the end of this century, the magnitude varying depending on the emissions scenario (Rounsevell et al., 2006). Climate change is likely to alter the community structure of grasslands in ways specific to their location and type (Buckland et al., 2001; Lüscher et al., 2004; Morecroft et al., 2004). Management and species richness may increase resilience to change (Duckworth et al., 2000). Fertile, early succession grasslands were found to be more responsive to climate change than more mature and/or less fertile grasslands (Grime et al., 2000). In general, intensively-managed and nutrient-rich grasslands will respond positively to both increased CO_2 concentration and temperature, given that water and nutrient supply is sufficient (Lüscher et al., 2004). Nitrogen-poor and species-rich grasslands may respond to climate change with small changes in productivity in the short-term (Winkler and Herbst, 2004). Overall, productivity of temperate European grassland is expected to increase (Byrne and Jones, 2002; Kammann et al., 2005). Nevertheless, warming alone is likely to have negative effects on productivity and species mixtures (Gielen et al., 2005; de Boeck et al., 2006). In the Mediterranean, changes in precipitation patterns are likely to negatively affect productivity and species composition of grasslands (Valladares et al., 2005).

12.4.5 Wetlands and aquatic ecosystems

Climate change may significantly impact northern peatlands (Vasiliev et al., 2001). The common hypothesis is that elevated temperature will increase productivity of wetlands (Dorrepaal et al., 2004) and intensify peat decomposition, which will accelerate carbon and nitrogen emissions to the atmosphere (Vasiliev et al., 2001; Weltzin et al., 2003). However, there are opposing results, reporting decreasing radiative forcing for drained peatlands in Finland (Minkkinen et al., 2002). Loss of permafrost in the Arctic (ACIA, 2004) will likely cause a reduction of some types of wetlands in the current permafrost zone (Ivanov and Maximov, 2003). During dry years, catastrophic fires are expected on drained peatlands in European Russia (Zeidelman and Shvarov, 2002; Bannikov et al., 2003). Processes of paludification[4] are likely to accelerate in northern regions with increasing precipitation (Lavoie et al., 2005).

Throughout Europe, in lakes and rivers that freeze in the winter, warmer temperatures may result in earlier ice melt and longer growing seasons. A consequence of these changes could be a higher risk of algal blooms and increased growth of toxic cyanobacteria in lakes (Moss et al., 2003; Straile et al., 2003; Briers et al., 2004; Eisenreich, 2005). Higher precipitation and reduced frost may enhance nutrient loss from cultivated fields (Eisenreich, 2005). These factors may result in higher nutrient loadings (Bouraoui et al., 2004; Kaste et al., 2004; Eisenreich, 2005) and concentrations of dissolved organic matter in inland waters (Evans and Monteith, 2001; ACIA, 2004; Worrall et al., 2006). Higher nutrient loadings may intensify the eutrophication of lakes and wetlands (Jeppesen et al., 2003). Streams in catchments with impermeable soils may have increased runoff in winter and deposition of organic matter in summer, which could reduce invertebrate diversity (Pedersen et al., 2004).

Inland waters in southern Europe are likely to have lower volume and increased salinisation (Williams, 2001; Zalidis et al., 2002). Many ephemeral ecosystems may disappear, and permanent ones shrink (Alvarez Cobelas et al., 2005). Although an overall drier climate may decrease the external loading of nutrients to inland waters, the concentration of nutrients may increase because of the lower volume of inland waters (Zalidis et al., 2002). Also an increased frequency of high rainfall events could increase nutrient discharge to some wetlands (Sánchez Carrillo and Alvarez Cobelas, 2001).

Warming will affect the physical properties of inland waters (Eisenreich, 2005; Livingstone et al., 2005). The thermocline of summer-stratified lakes will descend, while the bottom-water temperature and duration of stratification will increase, leading to higher risk of oxygen depletion below the thermocline (Catalán et al., 2002; Straile et al., 2003; Blenckner, 2005). Higher temperatures will also reduce dissolved oxygen saturation levels and increase the risk of oxygen depletion (Sand-Jensen and Pedersen, 2005).

12.4.6 Biodiversity

Climate change is affecting the physiology, phenology and distribution of European plant and animal species (e.g., Thomas et al., 2001; Warren et al., 2001; van Herk et al., 2002; Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003, 2005; Brommer, 2004; Austin and Rehfisch, 2005; Hickling et al., 2005, 2006; Robinson et al., 2005; Learmonth et al., 2006; Menzel et al., 2006a, b). A Europe-wide assessment of the future distribution of 1,350 plant species (nearly 10% of the European flora) under various SRES scenarios indicated that more than half of the modelled species could become vulnerable, endangered, critically endangered or committed to extinction by 2080 if unable to disperse (Thuiller et al., 2005). Under the most severe climate scenario (A1), and assuming that species could adapt through dispersal, 22% of the species considered would become critically endangered, and 2% committed to extinction. Qualitatively-similar results were obtained by Bakkenes et al. (2002). According to these analyses, the range of plants is very likely to expand northward and contract in southern European mountains and in the Mediterranean Basin. Regional studies (e.g., Theurillat and Guisan, 2001; Walther et al., 2005b) are consistent with Europe-wide projections.

[4] Peat bog formation.

An assessment of European fauna indicated that the majority of amphibian (45% to 69%) and reptile (61% to 89%) species could expand their range under various SRES scenarios if dispersal was unlimited (Araújo et al., 2006). However, if unable to disperse, then the range of most species (>97%) would become smaller, especially in the Iberian Peninsula and France. Species in the UK, south-eastern Europe and southern Scandinavia are projected to benefit from a more suitable climate, although dispersal limitations may prevent them from occupying new suitable areas (Figure 12.2). Consistent with these results, another Europe-wide study of 47 species of plants, insects, birds and mammals found that species would generally shift from the south-west to the north-east (Berry et al., 2006; Harrison et al., 2006). Endemic plants and vertebrates in the Mediterranean Basin are also particularly vulnerable to climate change (Malcolm et al., 2006). Habitat fragmentation is also likely to increase because of both climate and land-use changes (del Barrio et al., 2006).

Currently, species richness in inland freshwater systems is highest in central Europe declining towards the south and north because of periodic droughts and salinisation (Declerck et al., 2005). Increased projected runoff and lower risk of drought in the north will benefit the fauna of these systems (Lake, 2000; Daufresne et al., 2003), but increased drought in the south will have the opposite effect (Alvarez Cobelas et al., 2005). Higher temperatures are likely to lead to increased species richness in freshwater ecosystems in northern Europe and decreases in parts of south-western Europe (Gutiérrez Teira, 2003). Invasive species may increase in the north (McKee et al., 2002). Woody plants may encroach upon bogs and fens (Weltzin et al., 2003). Cold-adapted species will be forced further north and upstream; some may eventually disappear from Europe (Daufresne et al., 2003; Eisenreich, 2005).

Sea-level rise is likely to have major impacts on biodiversity. Examples include flooding of haul-out sites used for breeding nurseries and resting by seals (Harwood, 2001). Increased sea temperatures may also trigger large scale disease-related mortality events of dolphins in the Mediterranean and of seals in Europe (Geraci and Lounsbury, 2002). Seals that rely on ice for breeding are also likely to suffer considerable habitat loss (Harwood, 2001). Sea-level rise will reduce habitat availability for bird species that nest or forage in low-lying coastal areas. This is particularly important for the populations of shorebirds that breed in the Arctic and then winter on European coasts (Rehfisch and Crick, 2003). Lowered water tables and increased anthropogenic use and abstraction of water from inland wetlands are likely to cause serious problems for the populations of migratory birds and bats that use these areas while on migration within Europe and between Europe and Africa (Robinson et al., 2005).

12.4.7 Agriculture and fisheries

12.4.7.1 Crops and livestock

The effects of climate change and increased atmospheric CO_2 are expected to lead to overall small increases in European crop productivity. However, technological development (e.g., new

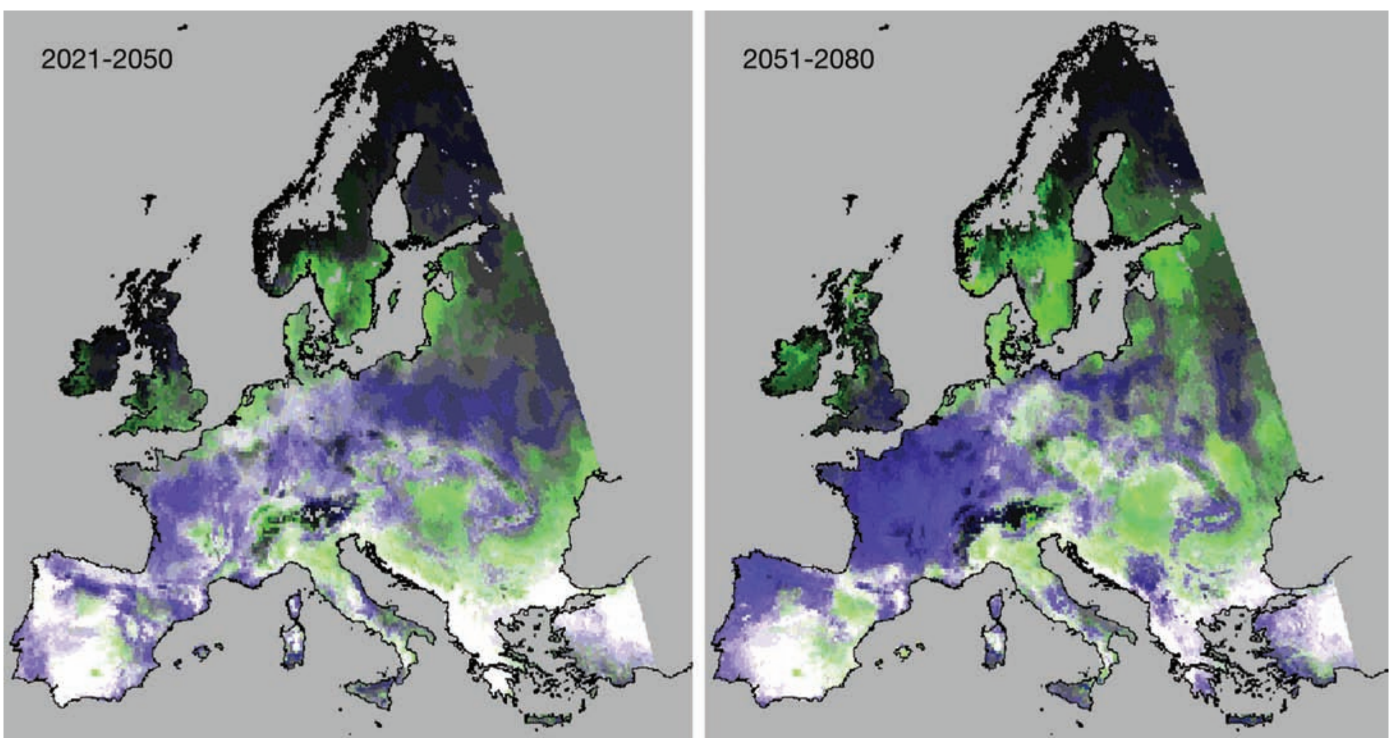

Figure 12.2. *Change in combined amphibian and reptile species richness under climate change (A1FI emissions; HadCM3 GCM), assuming unlimited dispersal. Depicted is the change between current and future species richness projected for two 30-year periods (2021 to 2050 and 2051 to 2080), using artificial neural networks. Increasing intensities of purple indicate a decrease in species richness, whereas increasing intensities of green represent an increase in species richness. Black, white and grey cells indicate areas with stable species richness: black grid cells show low species richness in both periods; white cells show high species richness; grey cells show intermediate species richness (Araújo et al., 2006).*

crop varieties and better cropping practices) might far outweigh the effects of climate change (Ewert et al., 2005). Combined yield increases of wheat by 2050 could range from 37% under the B2 scenario to 101% under the A1 scenario (Ewert et al., 2005). Increasing crop yield and decreasing or stabilising food and fibre demand could lead to a decrease in total agricultural land area in Europe (Rounsevell et al., 2005). Climate-related increases in crop yields are expected mainly in northern Europe, e.g., wheat: +2 to +9% by 2020, +8 to +25% by 2050, +10 to +30% by 2080 (Alexandrov et al., 2002; Ewert et al., 2005; Audsley et al., 2006; Olesen et al., 2007), and sugar beet +14 to +20% until the 2050s in England and Wales (Richter and Semenov, 2005), while the largest reductions of all crops are expected in the Mediterranean, the south-west Balkans and in the south of European Russia (Olesen and Bindi, 2002; Alcamo et al., 2005; Maracchi et al., 2005). In southern Europe, general decreases in yield (e.g., legumes -30 to + 5%; sunflower -12 to +3% and tuber crops -14 to +7% by 2050) and increases in water demand (e.g., for maize +2 to +4% and potato +6 to +10% by 2050) are expected for spring sown crops (Giannokopoulos et al., 2005; Audsley et al., 2006). The impacts on autumn sown crops are more geographically variable; yield is expected to strongly decrease in most southern areas, and increase in northern or cooler areas (e.g., wheat: +3 to +4% by 2020, -8 to +22% by 2050, -15 to +32% by 2080) (Santos et al., 2002; Giannakopoulos et al., 2005; Audsley et al., 2006; Olesen et al., 2007).

Some crops that currently grow mostly in southern Europe (e.g., maize, sunflower and soybeans) will become viable further north or at higher-altitude areas in the south (Audsley et al., 2006). Projections for a range of SRES scenarios show a 30 to 50% increase in the area suitable for grain maize production in Europe by the end of the 21st century, including Ireland, Scotland, southern Sweden and Finland (Hildén et al., 2005; Olesen et al., 2007). By 2050 energy crops (e.g, oilseeds such as rape oilseed and sunflower), starch crops (e.g., potatoes), cereals (e.g., barley) and solid biofuel crops (such as sorghum and Miscanthus) show a northward expansion in potential cropping area, but a reduction in southern Europe (Tuck et al., 2006). The predicted increase in extreme weather events, e.g., spells of high temperature and droughts (Meehl and Tebaldi, 2004; Schär et al., 2004; Beniston et al., 2007), is expected to increase yield variability (Jones et al., 2003) and to reduce average yield (Trnka et al., 2004). In particular, in the European Mediterranean region, increases in the frequency of extreme climate events during specific crop development stages (e.g., heat stress during flowering period, rainy days during sowing time), together with higher rainfall intensity and longer dry spells, are likely to reduce the yield of summer crops (e.g., sunflower). Climate change will modify other processes on agricultural land. Projections made for winter wheat showed that climate change beyond 2070 may lead to a decrease in nitrate leaching from agricultural land over large parts of eastern Europe and some smaller areas in Spain, and an increase in the UK and in other parts of Europe (Olesen et al., 2007).

An increase in the frequency of severe heat stress in Britain is expected to enhance the risk of mortality of pigs and broiler chickens grown in intensive livestock systems (Turnpenny et al., 2001). Increased frequency of droughts along the Atlantic coast (e.g., Ireland) may reduce the productivity of forage crops such that they are no longer sufficient for livestock at current stocking rates without irrigation (Holden and Brereton, 2002, 2003; Holden et al., 2003). Increasing temperatures may also increase the risk of livestock diseases by (i) supporting the dispersal of insects, e.g., *Culicoides imicola*, that are main vectors of several arboviruses, e.g., bluetongue (BT) and African horse sickness (AHS); (ii) enhancing the survival of viruses from one year to the next; (iii) improving conditions for new insect vectors that are now limited by colder temperatures (Wittmann and Baylis, 2000; Mellor and Wittmann, 2002; Colebrook and Wall, 2004; Gould et al., 2006).

12.4.7.2 Marine fisheries and aquaculture

An assessment of the vulnerability of the north-east Atlantic marine ecoregion concluded that climate change is very likely to produce significant impacts on selected marine fish and shellfish (Baker, 2005). Temperature increase has a major effect on fisheries production in the North Atlantic, causing changes in species distribution, increased recruitment and production in northern waters and a marked decrease at the southern edge of current ranges (Clark et al., 2003; Dutil and Brander, 2003; Hiscock et al., 2004; Perry et al., 2005). High fishing pressure is likely to exacerbate the threat to fisheries, e.g., for Northern cod (Brander, 2005). Sea-surface temperature changes as low as 0.9°C over the 45 years to 2002 have affected the North Sea phytoplankton communities, and have led to mismatches between trophic levels (see Glossary) throughout the community and the seasonal cycle (Edwards and Richardson, 2004). Together with fishing pressure, these changes are expected to influence most regional fisheries operating at trophic levels close to changes in zooplankton production (Anadón et al., 2005; Heath, 2005). Long-term climate variability is an important determinant of fisheries production at the regional scale (see Klyashtorin, 2001; Sharp, 2003), with multiple negative and positive effects on ecosystems and livelihoods (Hamilton et al., 2000; Eide and Heen, 2002; Roessig et al., 2004). Our ability to assess biodiversity impacts, ecosystem effects and socio-economic costs of climate change in coastal and marine ecosystems is still limited but is likely to be substantial for some highly dependent communities and enterprises (Gitay et al., 2002; Pinnegar et al., 2002; Robinson and Frid, 2003; Anadón et al, 2005; Boelens, et al., 2005). The overall interactions and cumulative impacts on the marine biota of sea-level rise (coastal squeeze with losses of nursery and spawning habitats), increased storminess, changes in the NAO, changing salinity, acidification of coastal waters, and other stressors such as pollutants, are likely but little known.

Marine and freshwater fish and shellfish aquaculture represented 33% of the total EU fishery production value and 17% of its volume in 2002 (EC, 2004). Warmer sea temperatures have increased growing seasons, growth rates, feed conversion and primary productivity (Beaugrand et al., 2002; Edwards et al., 2006), all of which will benefit shellfish production. Opportunities for new species will arise from expanded geographic distribution and range (Beaugrand and Reid, 2003), but increased temperatures will increase stress and susceptibility to pathogens (Anadón et al., 2005). Ecosystem changes with new invasive or non-native species such as gelatinous zooplankton and medusa, toxic algal blooms, increased fouling and decreased dissolved oxygen events, will increase operation costs. Increased storm-induced damage to equipment and facilities will increase capital costs. Aquaculture has its own local environmental impacts derived from particulate organic wastes and the spread of pathogens to wild populations, which are likely to compound climate-induced ecosystem stress (SECRU, 2002; Boelens et al., 2005).

12.4.8 Energy and transport

12.4.8.1 Energy

Under future climate change, demand for heating decreases and demand for cooling increases relative to 1961 to 1990 levels (Santos et al., 2002; Livermore, 2005; López Zafra et al., 2005; Hanson et al., 2006). In the UK and Russia, a 2°C warming by 2050 is estimated to decrease space heating needs in winter, thus decreasing fossil fuel demand by 5 to 10% and electricity demand by 1 to 3% (Kirkinen et al., 2005). Wintertime heating demand in Hungary and Romania is expected to decrease by 6 to 8% (Vajda et al., 2004) and by 10% in Finland (Venalainen et al., 2004) by the period 2021 to 2050. By 2100, this decrease rises from 20 to 30% in Finland (Kirkinen et al., 2005) to around 40% in the case of Swiss residential buildings (Frank, 2005; Christenson et al., 2006). Around the Mediterranean, two to three fewer weeks a year will require heating but an additional two to three (along the coast) to five weeks (inland areas) will need cooling by 2050 (Giannakopoulos et al., 2005). Cartalis et al. (2001) estimated up to 10% decrease in energy heating requirements and up to 28% increase in cooling requirements in 2030 for the south-east Mediterranean region. Fronzek and Carter (2007) reported a strong increase in cooling requirements for central and southern Europe (reaching 114% for Madrid) associated with an increase in inter-annual variability by 2071 to 2100. Summer space cooling needs for air conditioning will particularly affect electricity demand (Valor et al., 2001; Giannakopoulos and Psiloglou, 2006) with increases of up to 50% in Italy and Spain by the 2080s (Livermore, 2005). Peaks in electricity demand during summer heatwaves are very likely to equal or exceed peaks in demand during cold winter periods in Spain (López Zafra et al., 2005).

The current key renewable energy sources in Europe are hydropower (19.8% of electricity generated) and wind. By the 2070s, hydropower potential for the whole of Europe is expected to decline by 6%, translated into a 20 to 50% decrease around the Mediterranean, a 15 to 30% increase in northern and eastern Europe and a stable hydropower pattern for western and central Europe (Lehner et al., 2005). There will be a small increase in the annual wind energy resource over Atlantic and northern Europe, with more substantial increases during the winter season by 2071 to 2100 (Pryor et al., 2005). Biofuel production is largely determined by the supply of moisture and the length of the growing season (Olesen and Bindi, 2002). By the 22nd century, land area devoted to biofuels may increase by a factor of two to three in all parts of Europe (Metzger et al., 2004). More solar energy will be available in the Mediterranean region (Santos et al., 2002). Climate change could have a negative impact on thermal power production since the availability of cooling water may be reduced at some locations because of climate-related decreases (Arnell et al., 2005) or seasonal shifts in river runoff (Zierl and Bugmann, 2005). The distribution of energy is also vulnerable to climate change. There is a small increase in line resistance with increasing mean temperatures (Santos et al., 2002) coupled with negative effects on line sag and gas pipeline compressor efficiency due to higher maximum temperatures (López Zafra et al., 2005). All these combined effects add to the overall uncertainty of climate change impacts on power grids.

12.4.8.2 Transport

Higher temperatures can damage rail and road surfaces (AEAT, 2003; Wooller 2003; Mayor of London, 2005) and affect passenger comfort. There is likely to be an increased use of air conditioning in private vehicles and where public transport is perceived to be uncomfortable, modal switch may result (London Climate Change Partnership, 2002). The likely increase in extreme weather events may cause flooding, particularly of underground rail systems and roads with inadequate drainage (London Climate Change Partnership, 2002; Defra, 2004a; Mayor of London, 2005). High winds may affect the safety of air, sea and land transport whereas intense rainfall can also impact adversely on road safety although in some areas this may be offset to a degree by fewer snowy days (Keay and Simmonds, 2006). Reduced incidences of frost and snow will also reduce maintenance and treatment costs. Droughts and the associated reduced runoff may affect river navigation on major thoroughfares such as the Rhine (Middelkoop and Kwadijk, 2001) and shrinkage and subsidence may damage infrastructure (Highways Agency, 2005a). Reduced sea ice and thawing ground in the Arctic will increase marine access and navigable periods for the Northern Sea Route; however, thawing of ground permafrost will disrupt access through shorter ice road seasons and cause damage to existing infrastructure (ACIA, 2004).

12.4.9 Tourism and recreation

Tourism is closely linked to climate, in terms of the climate of the source and destination countries of tourists and climate seasonality, i.e., the seasonal contrast that drives demand for summer vacations in Europe (Viner, 2006). Conditions for tourism as described by the Tourism Comfort Index (Amelung and Viner, 2006) are expected to improve in northern and western Europe (Hanson et al., 2006). Hamilton et al. (2005) indicated that an arbitrary climate change scenario of 1°C would lead to a gradual shift of tourist destinations further north and up mountains affecting the preferences of sun and beach lovers from western and northern Europe. Mountainous parts of France, Italy and Spain could become more popular because of their relative coolness (Ceron and Dubois, 2000). Higher summer temperatures may lead to a gradual decrease in summer tourism in the Mediterranean but an increase in spring and perhaps autumn (Amelung and Viner, 2006). Maddison (2001) has shown that Greece and Spain will experience a lengthening and a flattening of their tourism season by 2030. Occupancy rates associated with a longer tourism season in the Mediterranean will spread demand evenly and thus alleviate the pressure on summer water supply and energy demand (Amelung and Viner, 2006).

The ski industry in central Europe is likely to be disrupted by significant reductions in natural snow cover especially at the beginning and end of the ski season (Elsasser and Burki, 2002). Hantel et al. (2000) found at the most sensitive elevation in the Austrian Alps (600 m in winter and 1400 m in spring) and with no snowmaking adaptation considered, a 1°C rise leads to four fewer weeks of skiing days in winter and six fewer weeks in spring. Beniston et al. (2003) calculated that a 2°C warming with no precipitation change would reduce the seasonal snow cover at a Swiss Alpine site by 50 days/yr, and with a 50% increase in precipitation by 30 days.

12.4.10 Property insurance

Insurance systems differ widely between countries (e.g., in many countries flood damage is not insured) and this affects the vulnerability of property to climate change. The value of property at risk also varies between countries. The damage from a wind speed of 200 km/h varies from 0.2% of the value of insured property in Austria, to around 1.2% in Denmark (Munich Re, 2002). While insurers are able in principle to adapt quickly to new risks such as climate change, the uncertainty of future climate impacts has made it difficult for them to respond to this new threat.

The uncertainty of future climate as well as socio-economic factors leads to a wide range of estimates for the costs of future flood damage. For instance, annual river flood damage in the UK is expected to increase by the 2080s between less than twice the current level of damages under the B2 scenario to greater than twenty times more under the A1 scenario (ABI, 2004). Moreover, future insurance costs will rise significantly if current rare events become more common. This is because the costs of infrequent catastrophic events are much higher than more frequent events, e.g., in the UK, the cost of a 1000-year extreme climate event is roughly 2.5 times larger than the cost of a 100-year event (Swiss Re, 2000), and in Germany, insurance claims increase as the cube of maximum wind speed (Klawa and Ulbrich, 2003).

12.4.11 Human health

Countries in Europe currently experience mortality due to heat and cold (Beniston, 2002; Ballester et al., 2003; Crawford et al., 2003; Keatinge and Donaldson, 2004). Heat-related deaths are apparent at relatively moderate temperatures (Huynen et al., 2001; Hajat et al., 2002; Keatinge, 2003; Hassi 2005; Páldy et al., 2005), but severe impacts occur during heatwaves (Kosatsky, 2005; Pirard et al. 2005; Kovats and Jendritzky, 2006; WHO, 2006; see also Section 12.6.1). Over the next century, heatwaves are very likely to become more common and severe (Meehl and Tebaldi, 2004). Heat-related deaths are likely to increase, even after assuming acclimatisation (Casimiro and Calheiros, 2002; Department of Health, 2002). Cold mortality is a problem in mid-latitudes (Keatinge et al., 2000; Nafstad et al., 2001; Mercer, 2003; Hassi, 2005) but is likely to decline with milder winters (Department of Health, 2002; Dessai, 2003). Major determinants of winter mortality include respiratory infections and poor quality housing (Aylin et al., 2001; Wilkinson et al., 2001, 2004; Mitchell et al., 2002; Izmerov et al., 2004; Díaz et al., 2005). Climate change is likely to increase the risk of mortality and injury from wind storms, flash floods and coastal flooding (Kirch et al., 2005). The elderly, disabled, children, women, ethnic minorities and those on low incomes are more vulnerable and need special consideration (Enarson and Fordham, 2001; Tapsell and Tunstall, 2001; Hajat et al., 2003; WHO, 2004, 2005; Penning-Rowsell et al., 2005; Ebi, 2006).

Changes in tick distribution consistent with climate warming have been reported in several European locations, although evidence is not conclusive (Kovats et al., 2001; Lindgren and Gustafson, 2001; Department of Health, 2002; Bröker and Gniel, 2003; Hunter, 2003; Butenco and Larichev, 2004; Korenberg, 2004; Kuhn et al., 2004). The effect of climate variability on tick-borne encephalitis (TBE) or Lyme disease incidence is still unclear (Randolph, 2002; Beran et al., 2004; Izmerov et al., 2004; Daniel et al., 2006; Lindgren and Jaenson, 2006; Rogers and Randolph, 2006). Future changes in tick-host habitats and human-tick contacts may be more important for disease transmission than changes in climate (Randolph, 2004). Visceral leishmaniasis is present in the Mediterranean region and climate change may expand the range of the disease northwards (Department of Health, 2002; Molyneux, 2003; Korenberg, 2004; Kuhn et al., 2004; Lindgren and Naucke, 2006). The re-emergence of endemic malaria in Europe due to climate change is very unlikely (Reiter, 2000, 2001; Semenov et al., 2002; Yasukevich, 2003; Kuhn et al., 2004; Reiter et al., 2004; Sutherst, 2004; van Lieshout et al., 2004). The maintenance of the current malaria situation is projected up to 2025 in Russia (Yasyukevich, 2004). An increased risk of localised outbreaks is possible due to climate change, but only if suitable vectors are present in sufficient numbers (Casimiro and Calheiros, 2002; Department of Health 2002). Increases in malaria outside Europe may affect the risk of imported cases. Diseases associated with rodents are known to be sensitive to climate variability, but no assessments on the impacts of climate change have been published for Europe.

Climate change is also likely to affect water quality and quantity in Europe, and hence the risk of contamination of public and private water supplies (Miettinen et al., 2001; Hunter, 2003; Elpiner, 2004; Kovats and Tirado, 2006). Higher temperatures have implications for food safety, as transmission of salmonellosis is temperature sensitive (Kovats et al, 2004; Opopol and Nicolenco, 2004; van Pelt et al. 2004). Both extreme rainfall and droughts can increase the total microbial loads in freshwater and have implications for disease outbreaks and water quality monitoring (Howe et al., 2002; Kistemann et al., 2002; Opopol et al. 2003; Knight et al., 2004; Schijven and de Roda Husman, 2005).

Important climate change effects on air quality are likely in Europe (Casimiro and Calheiros, 2002; Sanderson et al., 2003; Langner et al., 2005; Stevenson et al., 2006). Climate change may increase summer episodes of photochemical smog due to increased temperatures, and decreased episodes of poor air quality associated with winter stagnation (Hennessy, 2002; Revich and Shaposhnikov, 2004; Stedman, 2004; Kislitsin et al., 2005), but model results are inconsistent. Stratospheric ozone depletion and warmer summers influence human exposure to ultra-violet radiation and therefore increase the risk of skin cancer (Inter-Agency Commission, 2002; van der Leun and de Gruijl, 2002; de Gruijl et al., 2003; Diffey, 2004). Pollen phenology is changing in response to observed climate change, especially in central Europe, and at a wide range of elevations (Emberlin et al., 2002; Bortenschlager and Bortenschlager, 2005). Earlier onset and extension of the allergenic pollen seasons are likely to affect some allergenic diseases (van Vliet et al., 2002; Verlato et al., 2002; Huynen and Menne, 2003; Beggs, 2004; Weiland et al., 2004).

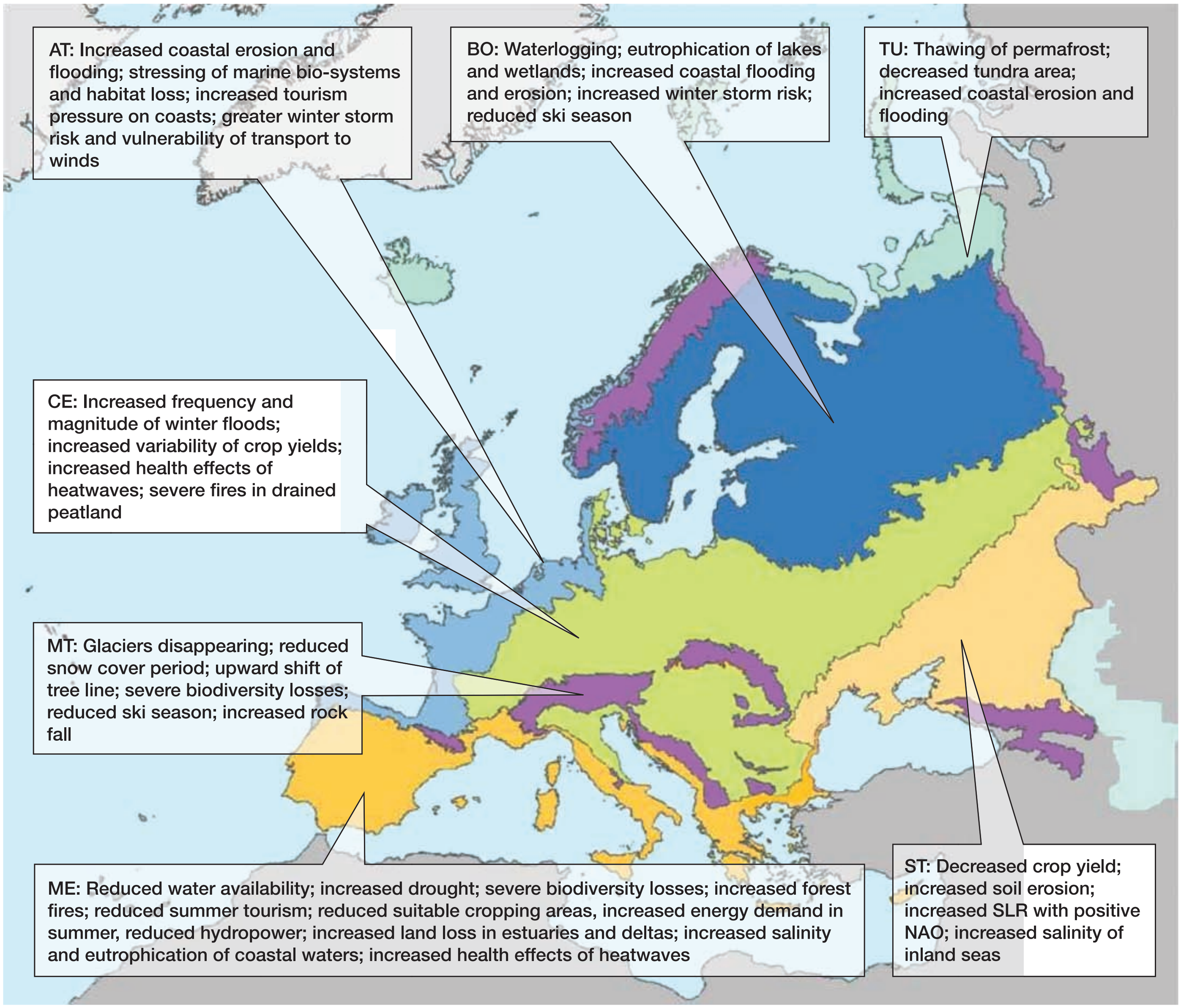

Figure 12.3. *Key vulnerabilities of European systems and sectors to climate change during the 21st century for the main biogeographic regions of Europe (EEA, 2004a): TU: Tundra, pale turquoise. BO: Boreal, dark blue. AT: Atlantic, light blue. CE: Central, green; includes the Pannonian Region. MT: Mountains, purple. ME: Mediterranean, orange; includes the Black Sea region. ST: Steppe, cream. SLR: sea-level rise. NAO: North Atlantic Oscillation. Copyright EEA, Copenhagen. http://www.eea.europa.eu*

12.5 Adaptation: practices, options and constraints

12.5.1 Water resources

Climate change will pose two major water management challenges in Europe: increasing water stress mainly in south-eastern Europe, and increasing risk of floods throughout most of the continent. Adaptation options to cope with these challenges are well-documented (IPCC, 2001). The main structural measures to protect against floods are likely to remain reservoirs and dykes in highland and lowland areas respectively (Hooijer et al., 2004). However, other planned adaptation options are becoming more popular such as expanded floodplain areas (Helms et al., 2002), emergency flood reservoirs (Somlyódy, 2002), preserved areas for flood water (Silander et al., 2006), and flood warning systems, especially for flash floods. Reducing risks may have substantial costs.

To adapt to increasing water stress the most common and planned strategies remain supply-side measures such as impounding rivers to form in-stream reservoirs (Santos et al., 2002; Iglesias et al., 2005). However, new reservoir construction is being increasingly constrained in Europe by environmental regulations (Barreira, 2004) and high investment costs (Schröter et al., 2005). Other supply-side approaches such as wastewater reuse and desalination are being more widely considered but their popularity is reduced by health concerns related to using wastewater (Geres, 2004) and the high energy costs of desalination (Iglesias et al., 2005). Some planned demand-side strategies are also feasible (AEMA, 2002), such as household, industrial and agricultural water conservation, the reduction of leaky municipal and irrigation water systems (Donevska and Dodeva, 2004; Geres, 2004), and water pricing (Iglesias et al., 2005). Irrigation water demand may be reduced by introducing crops more suitable to the changing climate. As is the case for the supply-side approaches, most demand-side approaches are not specific to Europe. An example of a unique European approach to adapting to water stress is that regional and watershed-level strategies to adapt to climate change are being incorporated into plans for integrated water management (Kabat et al., 2002; Cosgrove et al., 2004; Kashyap, 2004) while national strategies are being designed to fit into existing governance structures (Donevska and Dodeva, 2004).

12.5.2 Coastal and marine systems

Strategies for adapting to sea-level rise are well documented (Smith et al., 2000; IPCC, 2001; Vermaat et al., 2005). Although a large part of Europe's coastline is relatively robust to sea-level rise (Stone and Orford, 2004), exceptions are the subsiding, geologically 'soft', low-lying coasts with high populations, as in the southern North Sea and coastal plains/deltas of the Mediterranean, Caspian and Black Seas. Adaptation strategies on low-lying coasts have to address the problem of sediment loss from marshes, beaches and dunes (de Groot and Orford, 2000; Devoy et al., 2000). The degree of coastal erosion that may result from sea-level rise is very uncertain (Cooper and Pilkey, 2004), though feedback processes in coastal systems do provide a means of adaptation to such changes (Devoy, 2007). Modelling changes in coastal sediment flux under climate warming scenarios shows some 'soft' coasts responding with beach retreat rates of >40 m/100 years, contrasting with gains in others by accretion of about 10 m/100 years (Walkden and Hall, 2005; Dickson et al., 2007).

The development of adaptation strategies for coastal systems has been encouraged by an increase in public and scientific awareness of the threat of climate change to coastlines (Nicholls and Klein, 2004). Many countries in north-west Europe have adopted the approach of developing detailed shoreline management plans that link adaptation measures with shoreline defence, accommodation and retreat strategies (Cooper et al., 2002; Defra, 2004b; Hansom et al., 2004). Parts of the Mediterranean and eastern European regions have been slower to follow this pattern and management approaches are more fragmented (Tol et al., 2007).

A key element of adaptation strategies for coastlines is the development of new laws and institutions for managing coastal land (de Groot and Orford, 2000; Devoy, 2007). For example, no EU Directive exists for coastal management, although EU member governments were required to develop and publish coastal policy statements by 2006. The lack of a Directive reflects the complexity of socio-economic issues involved in coastal land use and the difficulty of defining acceptable management strategies for the different residents, users and interest groups involved with the coastal region (Vermaat et al., 2005).

12.5.3 Mountains and sub-Arctic regions

Mountainous and sub-Arctic regions have only a limited number of adaptation options. In northern Europe it will become necessary to factor in the dissipation and eventual disappearance of permafrost in infrastructure planning (Nelson, 2003) and building techniques (Mazhitova et al., 2004). There are few obvious adaptation options for either tundra or alpine vegetation. It may be possible to preserve many alpine species in managed gardens at high elevation since many mountain plants are likely to survive higher temperatures if they are not faced with competition from other plants (Guisan and Theurillat, 2005). However, this option remains very uncertain because the biotic factors determining the distribution of mountain plant species are not well known. Another minimal adaptation option is the reduction of other stresses on high elevation ecosystems, e.g., by lessening the impact of tourism (EEA, 2004b). Specific management strategies have yet to be defined for mountain forests (Price, 2005).

12.5.4 Forests, shrublands and grasslands

Since forests are managed intensively in Europe, there is a wide range of available management options that can be employed to adapt forests to climate change. General strategies for adaptation include changing the species composition of forest stands and planting forests with genetically improved seedlings adapted to a new climate (if the risk of genetically modified species is considered acceptable) (KSLA, 2004). Extending the rotation period of commercially important tree species may increase sequestration and/or the storage of carbon, and can be viewed as an adaptation measure (Kaipainen et al., 2004). Adaptive forest management could substantially decrease the risk of forest destruction by wind and other extreme weather events (Linder, 2000; Olofsson and Blennow 2005; Thurig et al., 2005). Strategies for coniferous forests include the planting of deciduous trees better adapted to the new climate as appropriate, and the introduction of multi-species planting into currently mono-species coniferous plantations (Fernando and Cortina, 2004; Gordienko and Gordienko, 2005).

Adaptation strategies need to be specific to different parts of Europe. The range of alternatives is constrained, among other factors, by the type of forest. Forests that are already moisture limited (Mediterranean forests) or temperature limited (boreal forests) will have greater difficulty in adapting to climate change than other forests, e.g., in central Europe (Gracia et al., 2005). Fire protection will be important in Mediterranean and boreal forests and includes the replacement of highly flammable species, regulation of age-class distributions, and widespread management of accumulated fuel, eventually through prescribed burning (Baeza et al., 2002; Fernandes and Botelho, 2004). Public education, development of advanced systems of forest inventories, and forest health monitoring are important prerequisites of adaptation and mitigation.

Productive grasslands are closely linked to livestock production. Dairy and cattle farming may become less viable because of climate risks to fodder production and therefore grasslands could be converted to cropland or other uses (Holman et al., 2005). Grassland could be adapted to climate change by changing the intensity of cutting and grazing, or by irrigating current dryland pastures (Riedo et al., 2000). Another option is to take advantage of continuing abandonment of cropland in Europe (Rounsevell et al., 2005) to establish new grassland areas.

12.5.5 Wetlands and aquatic ecosystems

Better management practices are needed to compensate for possible climate-related increases in nutrient loading to aquatic ecosystems from cultivated fields in northern Europe (Ragab and Prudhomme, 2002; Viner et al., 2006). These practices include ‘optimised’ fertiliser use and (re-)establishment of wetland areas and river buffer zones as sinks for nutrients (Olesen et al., 2004). New wetlands could also dampen the effects of increased frequency of flooding. A higher level of treatment of domestic and industrial sewage and reduction in farmland areas can further reduce nutrient loadings to surface waters and also compensate for climate-related increases in these loadings. Practical possibilities for adaptation in northern wetlands are limited and may only be realised as part of integrated landscape management including the minimisation of unregulated anthropogenic pressure, avoiding the physical destruction of surface and applying appropriate technologies for infrastructure development on permafrost (Ivanov and Maximov, 2003). Protection of drained peatlands against fire in European Russia is an important regional problem which requires the restoration of drainage systems and the regulation of water regimes in such territories (Zeidelman and Shvarov, 2002).

In southern Europe, to compensate for increased climate-related risks (lowering of the water table, salinisation, eutrophication, species loss) (Williams, 2001; Zalidas et al., 2002), a lessening of the overall human burden on water resources is needed. This would involve stimulating water saving in agriculture, relocating intensive farming to less environmentally sensitive areas and reducing diffuse pollution, increasing the recycling of water, increasing the efficiency of water allocation among different users, favouring the recharge of aquifers and restoring riparian vegetation, among others (Alvarez Cobelas et al., 2005).

12.5.6 Biodiversity

Climate change threatens the assumption of static species ranges which underpins current conservation policy. The ability of countries to meet the requirements of EU Directives and other international conventions is likely to be compromised by climate change, and a more dynamic strategy for conservation is required for sustaining biodiversity (Araújo et al., 2004; Brooker and Young, 2005; Robinson et al., 2005; Harrison et al., 2006). Conservation strategies relevant to climate change can take at least two forms: *in situ* involving the selection, design and management of conservation areas (protected areas, nature reserves, NATURA 2000 sites, wider countryside), and *ex situ* involving conservation of germplasm in botanical gardens, museums and zoos. A mixed strategy is the translocation of species into new regions or habitats (e.g., Edgar et al., 2005). In Europe, appropriate *in situ* and *ex situ* conservation measures for mitigating climate change impacts have not yet been put in place. Conservation experts have concluded that an expansion of reserve areas will be necessary to conserve species in Europe. For example, Hannah et al. (2007) calculated that European protected areas need to be increased by 18% to meet the EU goal of providing conditions by which 1,200 European plant species can continue thriving in at least 100 km^2 of habitat. To meet this goal under climate change they estimated that the current reserve area must be increased by 41%. They also point out that it would be more cost effective to expand protected areas proactively rather than waiting for climate change impacts to occur and then acting reactively. Dispersal corridors for species are another important adaptation tool (Williams et al., 2005), although large heterogeneous reserves that maximise microclimate variability might sometimes be a suitable alternative. Despite the importance of modifying reserve areas, some migratory species are vulnerable to loss of habitat outside Europe (e.g., Viner et al., 2006). For these migratory species, trans-continental conservation policies need to be put in place.

12.5.7 Agriculture and fisheries

Short-term adaptation of agriculture in southern Europe may include changes in crop species (e.g., replacing winter with spring wheat) (Mínguez et al., 2007), cultivars (higher drought resistance and longer grain-filling) (Richter and Semenov,

2005) or sowing dates (Olesen et al., 2007). Introducing new crops and varieties are also an alternative for northern Europe (Hildén et al., 2005), even if this option may be limited by soil fertility, e.g., in northern Russia. A feasible long-term adaptation measure is to change the allocation of agricultural land according to its changing suitability under climate change. Large-scale abandonment of cropland in Europe estimated under the SRES scenarios (Rounsevell et al., 2006) may provide an opportunity to increase the cultivation of bioenergy crops (Schröter et al., 2005). Moreover, Schröter et al. (2005) and Berry et al. (2006) found that different types of agricultural adaptation (intensification, extensification and abandonment) may be appropriate under different IPCC SRES scenarios and at different locations. It is indisputable that the reform of EU agricultural policies will be an important vehicle for encouraging European agriculture to adapt to climate change (Olesen and Bindi, 2002) and for reducing the vulnerability of the agricultural sector (Metzger et al., 2006).

At the small scale there is evidence that fish and shellfish farming industries are adapting their technology and operations to changing climatic conditions, for example, by expanding offshore and selecting optimal culture sites for shellfish cages (Pérez et al., 2003). However, adaptation is more difficult for smaller coastal-based fishery businesses which do not have the option to sail long distances to new fisheries as compared to larger businesses with long distance fleets. At the larger scale, adaptation options have not yet been considered in important policy institutions such as the European Common Fisheries Policy (CFP) although its production quotas and technical measures provide an ideal platform for such adaptation actions. Another major adaptation option is to factor the long-term potential impacts of climate change into the planning for new Marine Protected Areas (Soto, 2001). Adaptation strategies should eventually be integrated into comprehensive plans for managing coastal areas of Europe. However, these plans are lacking, especially around the Mediterranean, and need to be developed urgently (Coccossis, 2003).

12.5.8 Energy and transport

A wide variety of adaptation measures are available in the energy sector ranging from the redesign of the energy supply system to the modification of human behaviour (Santos et al., 2002). The sensitivity of European energy systems to climate change could be reduced by enhancing the interconnection capacity of electricity grids and by using more decentralised electric generation systems and local micro grids (Arnell et al., 2005). Another type of adaptation would be to reduce the exposure of energy users and producers to impacts of unfavourable climate through the mitigation of greenhouse gas emissions, for example by reducing overall energy use. This can be accomplished through various energy conservation measures such as energy-saving building codes and low-electricity standards for new appliances, increasing energy prices and through training and public education. Over the medium to long term, shifting from fossil fuels to renewable energy use will be an effective adaptive measure (Hanson et al., 2006).

Clearly, one aspect of adaptation may be through measures to mitigate emissions from transport through cleaner technologies and adapting behaviour (National Assessment Synthesis Team, 2001; AEAT, 2003; Highways Agency, 2005a). There is clearly a need for capacity building in the response to incidents, risk assessments, developments in maintenance, renewal practice and design standards for new infrastructure (Highways Agency, 2005b; Mayor of London, 2005). Assessment of the costs and benefits of adapting existing infrastructure or raising standards in the design of new vehicles and infrastructure to improve system resilience and reliability to the range of potential impacts should consider the wider economic and social impacts of disruption to the transport system.

12.5.9 Tourism and recreation

A variety of adaptation measures are available to the tourism industry (WTO, 2003, Hanson et al., 2006). Regarding winter tourism, compensating for reduced snowfall by artificial snowmaking is already common practice for coping with year-to-year snow pack variability. However, this adaptation strategy is likely to be economic only in the short term, or in the case of very high elevation resorts in mountain regions, and may be ecologically undesirable. New leisure industries, such as grass-skiing or hiking could compensate for any income decrease experienced by the ski industry due to snow deterioration (Fukushima et al., 2002). Regarding coastal tourism, the protection of resorts from sea-level rise may be feasible by constructing barriers or by moving tourism infrastructure further back from the coast (Pinnegar et al., 2006). In the Mediterranean region, the likely reduction of tourism during the hotter summer months may be compensated for by promoting changes in the temporal pattern of seaside tourism, for example by encouraging visitors during the cooler months (Amelung and Viner, 2006). The increasing, new climate-related risks to health, availability of water, energy demand and infrastructure are likely to be dealt with through efficient co-operation with local governments. Another adaptive measure for European tourism, in general, is promoting new forms of tourism such as eco-tourism or cultural tourism and placing greater emphasis on man-made rather than natural attractions, which are less sensitive to weather conditions (Hanson et al., 2006). It is also likely that people will adapt autonomously and reactively by changing their recreation and travel behaviour in response to the new climatic conditions (Sievanen et al., 2005).

12.5.10 Property insurance

The insurance industry has several approaches for adapting to the growing climate-related risk to property. These include raising the cost of insurance premiums, restricting or removing coverage, reinsurance and improved loss remediation (Dlugolecki, 2001). Insurers are beginning to use Geographical Information Systems (GIS) to provide information needed to adjust insurance tariffs to climate-related risks (Dlugolecki, 2001; Munich Re, 2004) although the uncertainty of future climate change is an obvious problem in making these adjustments. Insurers are also involved in discussions of measures for climate change mitigation and adaptation, including measures such as more stringent control of flood-plain development and remedial measures for damages derived from weather action and extreme events (ABI, 2000; Dlugolecki and Keykhah, 2002).

An obvious adaptation measure against property damage is to improve construction techniques so that buildings and infrastructure are more robust to extreme climate events. However, even if building techniques are immediately improved, the benefits will not be instantaneous because current building stock has a long remaining lifetime. Hence these buildings would not be replaced for many years by more resilient structures unless they are retrofitted. While retrofitting can be an effective adaptation measure it also has drawbacks. Costs are often high, residents are disrupted and poor enforcement of building regulations and construction practices could lead to unsatisfactory results.

12.5.11 Human Health

Risks posed by weather extremes are the most important in terms of requiring society's preparedness (Ebi, 2005; Hassi and Rytkönen, 2005; Menne, 2005; Menne and Ebi, 2006). Primary adaptation measures to heatwaves include the development of health early warning systems and preventive emergency plans (Garssen et al., 2005; Nogueira et al., 2005; Pirard et al., 2005). Many European countries and cities have developed such measures, especially after the summer of 2003 (Koppe et al., 2004; Ministerio de Sanidad y Consumo, 2004; Menne, 2005; see also Chapter 8 Box 8.1). Other measures are aimed at the mitigation of 'heat islands' through urban planning, the adaptation of housing design to local climate and expanding air conditioning, shifts in work patterns and mortality monitoring (Keatinge et al., 2000; Ballester et al., 2003; Johnson et al., 2005; Marttila et al., 2005; Penning-Rowsell et al., 2005).

Principal strategies to lessen the risks of flooding include public flood warning systems, evacuations from lowlands, waterproof assembling of hospital equipment and the establishment of decision hierarchies between hospitals and administrative authorities (Ohl and Tapsell, 2000; Hajat et al., 2003; EEA, 2004b; WHO, 2004; Hedger, 2005; Marttila et al., 2005; Penning-Rowsell et al., 2005).

12.6 Case studies

12.6.1 Heatwave of 2003

A severe heatwave over large parts of Europe in 2003 extended from June to mid-August, raising summer temperatures by 3 to 5 °C in most of southern and central Europe (Figure 12.4). The warm anomalies in June lasted throughout the entire month (increases in monthly mean temperature of up to 6 to 7°C), but July was only slightly warmer than on average (+1 to +3°C), and the highest anomalies were reached between 1st and 13th August (+7°C) (Fink et al., 2004). Maximum temperatures of 35 to 40°C were repeatedly recorded and peak temperatures climbed well above 40°C (André et al., 2004; Beniston and Díaz, 2004).

Average summer (June to August) temperatures were far above the long-term mean by up to five standard deviations (Figure 12.4), implying that this was an extremely unlikely event under current climatic conditions (Schär and Jendritzky, 2004). However, it is consistent with a combined increase in mean temperature and temperature variability (Meehl and Tebaldi, 2004; Pal et al., 2004; Schär et al., 2004) (Figure 12.4). As such, the 2003 heatwave resembles simulations by regional climate models of summer temperatures in the latter part of the 21st century under the A2 scenario (Beniston, 2004). Anthropogenic warming may therefore already have increased the risk of heatwaves such as the one experienced in 2003 (Stott et al., 2004).

The heatwave was accompanied by annual precipitation deficits up to 300 mm. This drought contributed to the estimated 30% reduction in gross primary production of terrestrial ecosystems over Europe (Ciais et al., 2005). This

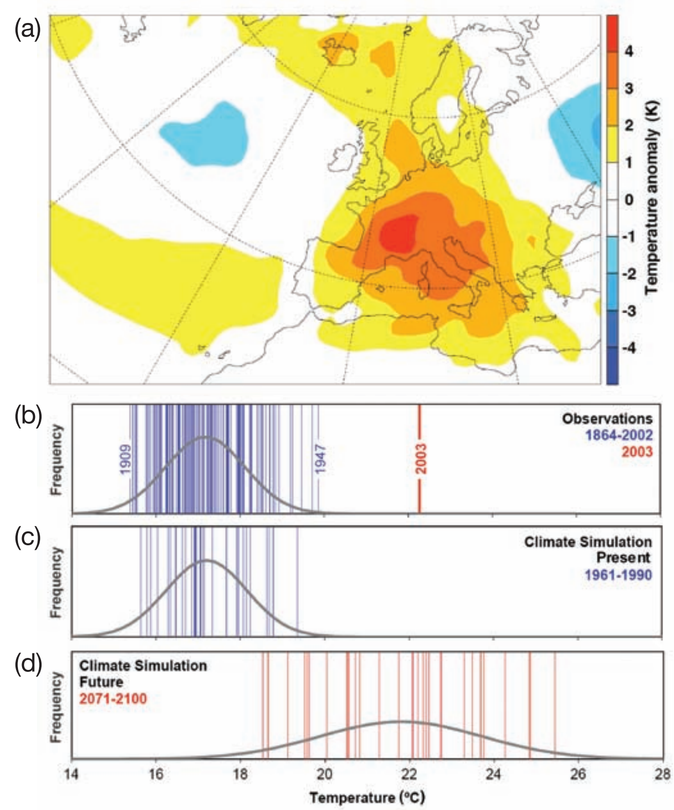

Figure 12.4. *Characteristics of the summer 2003 heatwave (adapted from Schär et al., 2004). (a) JJA temperature anomaly with respect to 1961 to 1990. (b) to (d): JJA temperatures for Switzerland observed during 1864 to 2003 (b), simulated using a regional climate model for the period 1961 to 1990 (c) and simulated for 2071 to 2100 under the A2 scenario using boundary data from the HadAM3H GCM (d). In panels (b) to (d): the black line shows the theoretical frequency distribution of mean summer temperature for the time-period considered, and the vertical blue and red bars show the mean summer temperature for individual years. Reprinted by permission from Macmillan Publishers Ltd. [Nature] (Schär et al., 2004), copyright 2004.*

reduced agricultural production and increased production costs, generating estimated damages of more than €13 billion (Fink et al., 2004; see also Chapter 5 Box 5.1). The hot and dry conditions led to many very large wildfires, in particular in Portugal (390,000 ha: Fink et al., 2004; see also Chapter 4 Box 4.1). Many major rivers (e.g., the Po, Rhine, Loire and Danube) were at record low levels, resulting in disruption of inland navigation, irrigation and power-plant cooling (Beniston and Díaz, 2004; Zebisch et al., 2005; see also Chapter 7 Box 7.1). The extreme glacier melt in the Alps prevented even lower river flows in the Danube and Rhine (Fink et al., 2004).

The excess deaths due to the extreme high temperatures during the period June to August may amount to 35,000 (Kosatsky, 2005), elderly people were among those most affected (WHO, 2003; Kovats and Jendritzky, 2006; see also Chapter 8 Box 8.1). The heatwave in 2003 has led to the development of heat health-watch warning systems in several European countries including France (Pascal et al., 2006), Spain (Simón et al., 2005), Portugal (Nogueira, 2005), Italy (Michelozzi et al., 2005), the UK (NHS, 2006) and Hungary (Kosatsky and Menne, 2005).

12.6.2 Thermohaline circulation changes in the North Atlantic: possible impacts for Europe

Earlier studies of the possible impacts of rapid change in Meridional Overturning Circulation (MOC), also known as the thermohaline circulation (THC), in the North Atlantic are now being updated (Vellinga and Wood 2002, 2006; Alley et al., 2003; Jacob et al., 2005; Rahmstorf and Ziekfeld, 2005; Stouffer et al., 2006; Schlesinger et al., 2007). Model simulations of an abrupt shut-down of the Atlantic MOC indicate that this is unlikely to occur before 2100 and that the impacts on European temperatures of any slowing in circulation before then are likely to be offset by the immediate effects of positive radiative forcings under increasing greenhouse gases (Arnell et al., 2005; Gregory et al., 2005; Vellinga and Wood, 2006; Meehl et al., 2007). Under slowing or full Atlantic MOC shut-down, temperatures on Europe's western margin would be most affected, together with further rises in relative sea level on European coasts (Vellinga and Wood, 2002, 2006; Jacob et al., 2005; Levermann et al., 2005; Wood et al., 2006; Meehl et al., 2007). Although there are no indications of an imminent change in the North Atlantic THC (Dickson et al., 2003; Curry and Mauritzen, 2005) it is recognised that MOC shut-down, should it occur, is likely to have potential socio-economic impacts for Europe and more widely (Table 12.3). Hence, it would be valuable to consider these impacts in developing climate policy (Defra, 2004c; Keller et al., 2004; Arnell et al., 2005; Schneider et al., 2007). Such policies are currently difficult to quantify (Manning et al., 2004; Parry, 2004). Assessment of the likely impacts of an abrupt Atlantic MOC shut-down on different economic and social sectors in Europe has been made using integrated assessment models, e.g., FUND (Tol, 2002, 2006; Link and Tol, 2004). Results suggest that the repercussions for socio-economic factors are likely to be less severe than was previously thought.

12.7 Conclusions: implications for sustainable development

The fraction of total plant growth or the net primary production appropriated by humans (HANPP) is a measure widely used to assess the 'human domination of Earth's ecosystems' (Haberl et al., 2002). Currently, HANPP in western Europe (WE) amounts to 2.86 tonnes carbon/capita/yr, which is 72.2% of its terrestrial net primary production. This exceeds, by far, the global average of 20% (Imhoff et al., 2004). The 'ecological footprint' (EF) is an estimate of the territory required to provide resources consumed by a given population (Wackernagel et al., 2002). In 2001, the EF of central and eastern Europe (CEE) was 3.8 ha/capita, and of WE 5.1 ha/capita (WWF, 2004). These values also far exceed the global average of 2.2 ha/capita (WWF, 2004). WE is one of the largest 'importers' of land, an expression of the net trade balance for agricultural products (van Vuuren and Bouwman, 2005). Globally, by 2050 the total EF is very likely to increase by between 70% (B2 scenario) and 300% (A1B scenario), thus placing an additional burden on a planet which some consider is already at an unsustainable level (Wackernagel et al., 2002; Wilson, 2002). Large changes in demand for land in regions with high population growth and changing consumption habits are expected, which is likely to result in a (need to) decrease WE imports (van Vuuren and Bouwman, 2005). The per capita EF of WE and CEE is projected to converge by the middle of this century, at which time values for WE become slightly lower (B2 scenario) or larger (A1B scenario) than current ones, and those of CEE increase to reach those of WE. In any case, European EF is very likely to remain much higher than the global average (van Vuuren and Bouwman, 2005).

Table 12.3. *Main types of impact for Europe following a rapid shut-down of the Meridional Overturning Circulation relative to the 'pre-industrial' climate (after: Arnell et al., 2005; Levermann et al., 2005; Vellinga and Wood, 2006).*

- Reductions in runoff and water availability in southern Europe; major increase in snowmelt flooding in western Europe.
- Increased sea-level rise on western European and Mediterranean coasts.
- Reductions in crop production with consequent impacts on food prices.
- Changes in temperature affecting ecosystems in western Europe and the Mediterranean (e.g., affecting biodiversity, forest products and food production).
- Disruption to winter travel opportunities and increased icing of northern ports and seas.
- Changes in regional patterns of increases versus decreases in cold- and heat-related deaths and ill-health.
- Movement of populations to southern Europe and a shift in the centre of economic gravity.
- Requirement to refurbish infrastructure towards Scandinavian standards.

Climate change in Europe is likely to have some positive effects (e.g., increased forest area, increased crop yield in northern Europe), or offer new opportunities (e.g., 'surplus land'). However, many changes are very likely to increase vulnerability due to reduced supply of ecosystem services (declining water availability, climate regulation potential or biodiversity), increase of climate-related hazards and disruption in productive sectors, among others (Schröter et al., 2005; Metzger et al., 2006) (Table 12.4). Therefore, additional pressures are very likely to be exerted upon Europe's environment, which is already subject to substantial pressures (EEA, 2003), and social and economic systems. Furthermore, climate change is likely to magnify regional differences in terms of Europe's natural resources and assets since impacts are likely to be unevenly distributed geographically, with the most negative impacts occurring in the south and east (Table 12.4). Adaptive capacity is high, although it varies greatly between countries (higher in the north than in the south and east) due to their different socio-economic systems (Yohe and Tol, 2002). Adaptive capacity is expected to increase in the future, yet, differences among countries will persist (Metzger et al., 2004, 2006). Hence, climate change is likely to create additional imbalances since negative impacts are likely to be largest where adaptive capacity is lowest.

The integration of sustainability goals into other sectoral policy areas is progressing, for instance, through national, regional and local sustainable development strategies and plans. However, these have not yet had a decisive effect on policies (EEA, 2003). Although climate change and sustainable development policies have strong linkages, they have evolved in parallel, at times they even compete with one another. Climate change is very likely to challenge established sustainability goals. Tools, such as integrated modelling approaches (Holman et al., 2005; Berry et al., 2006), integration frameworks (Tschakert and Olsson, 2005) and scenario build-up (Wiek et al., 2006) can help bridge the gap in the limited understanding we have on how climate change will ultimately affect sustainability. Pursuit of sustainable development goals might be a better avenue for achieving climate change policy goals than climate change policies themselves (Robinson et al., 2006).

12.8 Key uncertainties and research priorities

Uncertainties in future climate projections are discussed in great detail in Working Group I Section 10.5 (Meehl et al., 2007). For Europe, a major uncertainty is the future behaviour of the NAO and North Atlantic THC. Also important, but not specific to Europe, are the uncertainties associated with the still insufficient resolution of GCMs (e.g., Etchevers et al., 2002; Bronstert, 2003), and with downscaling techniques and regional climate models (Mearns et al., 2003; Haylock et al., 2006; Déqué et al., 2007). Uncertainties in climate impact assessment also stem from the uncertainties of land-use change and socio-economic development (Rounsevell et al., 2005, 2006) following European policies (e.g., CAP), and European Directives (Water Framework Directive, European Maritime Strategy Directive). Although most impact studies use the SRES scenarios, the procedures for scenario development are the subject of debate (Castle and Henderson, 2003a, b; Grübler et al., 2004; Holtsmark and Alfsen, 2005; van Vuuren and Alfsen, 2006). While current scenarios appear to reflect well the course of events in the recent past (van Vuuren and O'Neill, 2006), further research is needed to better account for the range of possible scenarios (Tol, 2006). This might be important for Europe given the many economies in transition.

Uncertainties in assessing future climate impacts also arise from the limitations of climate impact models including (i) structural uncertainty due to the inability of models to capture all influential factors, e.g., the models used to assess health impacts of climate change usually neglect social factors in the spread of disease (Kuhn et al., 2004; Reiter et al., 2004; Sutherst, 2004), and climate-runoff models often neglect the direct effect of increasing CO_2 concentration on plant transpiration (Gedney et al., 2006), (ii) lack of long-term representative data for model evaluation, e.g., current vector-monitoring systems are often unable to provide the reliable identification of changes (Kovats et al., 2001). Hence, more attention should be given to structural improvement of models and intensifying efforts of long-term monitoring of the environment, and systematic testing of models against observed data in field trials or catchment monitoring programmes (Hildén et al., 2005). Another way to address the uncertainty of deterministic models is to use probabilistic modelling which can produce an ensemble of scenarios, (e.g., Wilby and Harris, 2006; Araújo and New, 2007; ENSEMBLES project, http://ensembles-eu.metoffice.com/).

Until now, most impact studies have been conducted for separate sectors even if, in some cases, several sectors have been included in the same study (e.g., Schröter et al., 2005). Few studies have addressed impacts on various sectors and systems including their possible interactions by integrated modelling approaches (Holman et al., 2005; Berry et al., 2006). Even in these cases, there are various levels (supra-national, national, regional and sub-regional) that need to be jointly considered, since, if adaptation measures are to be implemented, knowledge down to the lowest decision level will be required. The varied geography, climate and human values of Europe pose a great challenge for evaluation of the ultimate impacts of climate change.

Although there are some good examples, such as the ESPACE-project (Nadarajah and Rankin, 2005), national-scale programmes, such as the FINADAPT project, studies of adaptation to climate change and of adaptation costs are at an early stage and need to be carried out urgently. These studies need to match adaptation measures to specific climate change impacts (e.g., targeted to alleviating impacts on particular types of agriculture, water management or on tourism at specific locations). They need to take into account regional differences in adaptive capacity (e.g., wide regional differences exist in Europe in the style and application of coastal management). Adaptation studies need to consider that in some cases both positive and negative impacts may occur as a result of climate change (e.g., the productivity of some crops may increase, while others decrease at the same location, e.g., Alexandrov et al., 2002). Key research priorities for impacts of climate change, adaptation and implications are included in Table 12.5.

Table 12.4. *Summary of the main expected impacts of climate change in Europe during the 21st century, assuming no adaptation.*

Sectors and Systems	Impact	Area: North	Atlantic	Central	Mediterr.	East
Water resources	Floods	↓↓	↓↓	↓↓	↓	↓↓↓
	Water availability	↑↑	↑↑	↓	↓↓↓	↓↓
	Water stress	↑↑	↑↑	↓	↓↓↓	↓↓
Coastal and marine systems	Beach, dune: low-lying coast erosional 'coastal squeeze'	↓↓↓	↓↓↓	na	↓↓	↓↓
	SLR- and surge-driven flooding	↓↓↓	↓↓	na	↓↓	↓↓↓
	River sediment supply to estuaries and deltas	↓↓	↓	na	↓↓↓	↓
	Saltwater intrusion to aquifers	↓	↓	na	↓↓	↓
	Northward migration of marine biota	↑	↑↑↑	na	↑	↑
	Rising SSTs, eutrophication and stress on biosystems	↓↓↓	↓↓	na	↓↓	↓
	Development of ICZM	↑↑	↑↑	na	↑↑	↑
	Deepening and larger inshore waters	↑↑	↑	na	↑	↑↑
Mountains, cryosphere	Glacier retreat	↓↓↓	↓	↓↓↓	↓↓↓	↓↓↓
	Duration of snow cover	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓
	Permafrost retreat	↓↓↓	↓	↓	na	↓
	Tree line upward shift	↑↑↑	↑↑↑	↑↑↑	↑	↑↑↑
	Nival species losses	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓
Forest, shrublands and grasslands	Forest NPP	↑↑↑	↑↑	↑ to ↓	↓	↑ to ↓
	Northward/inland shift of tree species	↑↑↑	↑↑	↑↑	↑ to ↓	↓↓
	Stability of forest ecosystems	↓↓	↓	↓	↓↓↓	↓↓↓
	Shrublands NPP	↑↑↑	↑↑↑	↑	↓↓↓	↓↓
	Natural disturbances (e.g., fire, pests, wind-storm)	↓	↓	↓	↓↓↓	↓↓
	Grasslands NPP	↑↑↑	↑↑	↑ to ↓	↓↓↓	↑
Wetlands and aquatic ecosystems	Drying/transformation of wetlands	↓↓	↓	↓	↓↓↓	↓↓↓
	Species diversity	↑ to ↓	↑	??	↓↓	↓
	Eutrophication	↓	↓↓	↓↓	↓↓↓	↓
	Disturbance of drained peatlands	↓↓↓	↓	↓↓	na	↓↓↓
Biodiversity	Plants	↓↓	↓↓	↓↓↓(Mt)	↓↓↓	↓
	Amphibians	↓↓	↓↓↓	↑↑	↓↓↓(SW) ↑↑(SE)	↑↑↑
	Reptiles	↓↓	↓↓	↑↑	↓↓↓(SW) ↑↑↑(SE)	↑↑↑
	Marine mammals	↓↓↓	??	na	↓↓↓	??
	Low-lying coastal birds	↓↓↓	↓↓↓	na	↓↓↓	??
	Freshwater biodiversity	↑ to ↓	??	??	↓↓↓	??
Agriculture and fisheries	Suitable cropping area	↑↑↑	↑↑	↑	↓↓	↓
	Agricultural land area	↓↓	↓↓	↓↓	↓↓	↓↓
	Summer crops (maize, sunflower)	↑↑↑	↑↑	↑	↓↓↓	↓↓
	Winter crops (winter wheat)	↑↑↑	↑↑	↑ to ↓	↓↓	↑
	Irrigation needs	na	↑ to ↓	↓↓	↓↓↓	↓
	Energy crops	↑↑↑	↑↑	↑	↓↓	↓
	Livestock	↑ to ↓	↓	↓↓	↓↓	↓↓
	Marine fisheries	↑↑	↑	na	↓	na
Energy and transport	Energy supply and distribution	↑	↑↑	↑	↓	↑
	Winter energy demand	↑↑	↑↑	↑	↑↑	↑
	Summer energy demand	↓	↓	↓↓	↓↓↓	↓↓
	Transport	↑	↓	↓	↓	↑
Tourism	Winter (including ski) tourism	↑↑	↓	↓↓↓	↑↑↑	↓↓
	Summer tourism	↑	↑↑	↑	↓↓	↑
Property insurance	Flooding claims	??	↓↓	↓↓	??	??
	Storms claims	↓	↓↓	↓↓	??	??
Human health	Heat-related mortality/morbidity	↓	↓↓	↓↓	↓↓↓	↓↓
	Cold-related mortality/morbidity	↑	↑↑	↑↑	↑	↑↑↑
	Health effects of flooding	↓	↓↓	↓↓	↓↓	↓↓
	Vector-borne diseases	↓	↓	↓	↓↓	↓↓
	Food safety/Water-borne diseases	↓	↓	↓	↓↓	↓↓
	Atopic diseases, due to aeroallergens	↓	↓	↓	↓	↓

Scoring has taken into account: a) geographical extent of impact/number of people exposed; b) intensity and severity of impact. The projected magnitude of impact increases with the number of arrows (one to three). Type of impact: positive (upward, blue); negative (downward, red); a change in the type of impact during the course of the century is marked with 'to' between arrows. na=not applicable; ??=insufficient information; North=boreal and Arctic; Central, Atlantic and Mediterranean as in Figure 12.3, including their mountains; East=steppic Russia, the Caucasus and the Caspian Sea; Mt=Mountains; SW=Southwest; SE=Southeast; SLR=Sea-Level Rise; ICZM=Integrated Coastal Zone Management; SST=Sea-Surface Temperature; NPP=Net Primary Productivity.

Table 12.5. *Key uncertainties and research needs.*

Impact of climate change
• Improved long-term monitoring of climate-sensitive physical (e.g., cryosphere), biological (e.g., ecosystem) and social sectors (e.g., tourism, human health).
• Improvement of climate impact models, including better understanding of mechanism of climate impacts, e.g., of heat/cold morbidity, differences between impacts due to short-term climate variability and long-term climate change, and the effects of extreme events, e.g., heatwaves, droughts, on longer-term dynamics of both managed and natural ecosystems.
• Simultaneous consideration of climatic and non-climatic factors, e.g., the synergistic effect of climate change and air pollution on buildings, or of climate change and other environmental factors on the epidemiology of vector-borne diseases; the validation and testing of climate impact models through the enhancement of experimental research; increased spatial scales; long-term field studies and the development of integrated impact models.
• Enhancement of climate change impact assessment in areas with little or no previous investigation, e.g., groundwater, shallow lakes, flow regimes of mountain rivers, renewable energy sources, travel behaviour, transport infrastructure, tourist demand, major biogeochemical cycles, stability, composition and functioning of forests, natural grasslands and shrublands), nutrient cycling and crop protection in agriculture.
• More integrated impact studies, e.g., of sensitive ecosystems including human dimensions.
• Better understanding of the socio-economic consequences of climate change for different European regions with different adaptive capacity.
Adaptation measures
• The comprehensive evaluation (i.e., of effectiveness, economy and constraints) of adaptation measures used in past in different regions of Europe to reduce the adverse impacts of climate variability and extreme meteorological events.
• Better understanding, identification and prioritisation of adaptation options for coping with the adverse effects of climate change on crop productivity, on the quality of aquatic ecosystems, on coastal management and the capacity of health services.
• Evaluation of the feasibility, costs and benefits of potential adaptation options, measures and technologies.
• Quantification of bio-climatic limitations of prevalent plant species.
• Continuation of studies on the regional differences in adaptive capacity.
Implementation
• Identification of populations at risk and the lag time of climate change impacts.
• Approaches for including climate change in management policy and institutions.
• Consideration of non-stationary climate in the design of engineering structures.
• Identification of the implications of climate change for water, air, health and environmental standards.
• Identification of the pragmatic information needs of managers responsible for adaptation.

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