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Climate change, impacts and vulnerability in Europe 2012

An indicator-based report

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Executive summary

Key messages

- Climate change (increases in temperature, changes in precipitation and decreases in ice and snow) is occurring globally and in Europe; some of the observed changes have established records in recent years.
- Observed climate change has already led to a wide range of impacts on environmental systems and society; further climate change impacts are projected for the future.
- Climate change can increase existing vulnerabilities and deepen socio-economic imbalances in Europe.
- Damage costs from natural disasters have increased; the contribution of climate change to these costs is projected to increase in the future.
- The combined impacts of projected climate change and socio-economic development can lead to high damage costs; these costs can be reduced significantly by mitigation and adaptation actions.
- The causes of the most costly climate impacts are projected to differ strongly across Europe.
- On-going and planned monitoring and research at national and EU level can improve assessments of past and projected impacts of climate change, thereby enhancing the knowledge base for adaptation.

This European Environment Agency (EEA) report presents information on past and projected climate change and related impacts in Europe, based on a range of indicators. The report also assesses the vulnerability of society, human health and ecosystems in Europe and identifies those regions in Europe most at risk from climate change. Furthermore, the report discusses the principle sources of uncertainty for the indicators and notes how monitoring and scenario development can improve our understanding of climate change, its impacts and related vulnerabilities.

Why such a report?

The United Nations Framework Convention on Climate Change (UNFCCC) has agreed to limit the increase in global mean temperature since pre-industrial times to less than 2 °C, in order to prevent the most severe impacts of climate change. Current global actions to reduce greenhouse gas emissions ('mitigation') are insufficient to constrain the temperature increase to 2 °C, and global warming could be well above 2 °C by 2100. Even if the 2 °C limit is kept, substantial impacts on society, human health and ecosystems are projected to occur. Adaptation to and mitigation of climate change are therefore both needed.

The European Commission has initiated various actions to integrate and mainstream adaptation into EU sectoral policies following the publication of the White Paper on adaptation to climate change in 2009. Furthermore, many countries in Europe have already adopted national adaptation strategies and some have followed up with specific action plans. The European Commission plans publishing its European Adaptation Strategy in 2013, which will include further proposals for adaptation actions across the EU.

This report aims at providing a strong knowledge base for the development and implementation of adaptation strategies and actions at both national and EU levels. The indicators presented here are also accessible via the EEA indicator management system and the European Climate Adaptation Platform (Climate-ADAPT; http://climate-adapt.eea.europa.eu). Early in 2013 the EEA will publish a dedicated report on adaptation, which will assess actions to adapt to climate change at European, national and sub-national levels.

Developing previous assessments further

This 2012 report follows earlier indicator-based assessments of climate change impacts and vulnerability published by the EEA in 2004 and 2008. The amount and quality of the information underlying the 2012 report has increased compared to the previous report of 2008.

New elements in the 2012 report include:

- use of a revised set of criteria for the selection of indicators, including policy relevance, strength of causal links between climate change and observed impacts, methodological soundness, data quality, availability of long periods of observations, and information on robustness and uncertainty;

- several new and extended indicators, for example on storms and storm surges, Baltic Sea ice, ocean acidification and ocean heat content, crop productivity, floods and health, and energy demand;

- information from several EU-funded projects that assess the impacts, vulnerability and costs of climate change across Europe considering also other socio-economic developments.

Where feasible, indicators cover the 32 member countries of the EEA. In some cases, indicators cover fewer countries due to the lack of European-wide data or to limited geographical relevance (e.g. glaciers). The indicators supporting the assessment cover a wide range of themes and sectors. They are based on data from in situ and satellite monitoring programmes, national and EU research programmes, and global initiatives.

Main findings of the report

Climate change (increases in temperature, changes in precipitation and decreases in ice and snow) is occurring globally and in Europe; some of these observed changes have established records in recent years

Compared to the preindustrial level (end of the 19th century), mean temperature and the frequency and length of heat waves have increased across Europe. The average temperature over land in Europe in the last decade was 1.3 °C warmer than the preindustrial level, which makes it the warmest decade on record. Over the same period precipitation has increased in northern and north-western Europe but it has decreased in southern Europe. Regarding storms, the observations do not show a clear trend. Storm frequency was increasing from the 1960s to 1990s, but followed by a decrease to the present.

The melting of the Greenland ice sheet has been accelerating since the 1990s. Exceptional melting was recorded in the summer of 2012. Arctic sea ice extent and volume have been decreasing much faster than previously projected. Record low sea ice cover was observed in 2007, 2011 and 2012 and can be equated to roughly half the size of the normal minimum extent in the 1980s. Snow cover has been decreasing, the vast majority of glaciers in Europe have been receding, and most permafrost soils have been warming.

Observed climate change has already led to a wide range of impacts on environmental systems and society

The following impacts of climate change have been observed:

- **Coasts and European seas**: overall rise in sea levels globally and across most of Europe's coasts (with variations due to local land movement and other factors); increase in ocean acidification; increase in sea surface temperature and ocean heat content; earlier seasonal appearance of various marine species; northward expansion of some fish and plankton species.

- **Freshwater systems**: decrease in river flows in southern and eastern Europe (in particular in summer) and increase in other regions (in particular in winter); increases in the reported number of flood events (mainly due to land-use changes and better reporting); increase in the frequency and intensity of droughts (in particular in southern Europe); increase in water temperature in rivers and lakes; northwards movement of cold-water species; earlier seasonal appearance of phytoplankton and zooplankton blooms.

- **Terrestrial biodiversity and ecosystems**: earlier occurrence of spring seasonal events and later occurrence of autumn seasonal events in plants and animals; lengthening of breeding seasons; northwards and uphill movement of many plant and animal species, but the migration rate of many species is insufficient to keep pace with the speed of climate change; establishment of warm-adapted alien plant species; many habitats of European interest (EU Habitats Directive) are potentially threatened by climate change over their natural range in Europe.

- **Agriculture:** northward expansion of areas suitable for several crops; earlier flowering and harvest dates in cereals; reduced yield of some crops due to heat waves and droughts (mostly in central and southern Europe), but increased yields of other crops (mostly in northern Europe); increased water demand for irrigation (in southern and south-western Europe).

- **Forests and forestry**: reduction in forest growth due to storms, pests and diseases in some central and western areas of Europe; increase in the number of forest fires in the Mediterranean region between 1980 and 2000 and a decrease thereafter.

- **Energy**: reduced demand for heating (particularly in northern and north-western Europe) but increased demand for cooling (particularly in southern Europe).

- **Human health**: tens of thousands of premature deaths due to the extreme 2003 summer heat-wave; thousands of premature deaths per year due to tropospheric ozone (but the contribution of climate change is difficult to quantify); increased number of people affected by river and coastal flooding; northward and upward movement of tick species and related increased risk of transmission of vector-borne diseases.

Further climate change impacts are projected for the future

Observed impacts of climate change are projected to continue due to further climate change. The level of future impacts depends on the magnitude of climate change and on socio-economic and environmental factors. Socio-economic developments can either aggravate or reduce the projected impacts of climate change. Future impacts can be substantially reduced by an ambitious global mitigation policy and by targeted adaptation actions.

Climate change can increase existing vulnerabilities and deepen socio-economic imbalances in Europe

Existing socio-economic vulnerabilities may be exacerbated by the impacts of climate change. There are significant differences in the economic, technical, and institutional capacity to cope with and adapt to climate change across Europe. When impacts of climate change affect regions with low adaptive capacity, the consequences can be severe. An integrated assessment of European regions' vulnerability to climate change suggests that climate change may negatively affect the territorial cohesion in Europe by deepening existing socio-economic imbalances.

Damage costs from natural disasters have increased; the contribution of climate change to these costs is projected to increase in the future

Hydro-meteorological events such as floods and storms account for around two thirds of the damage costs of natural disasters, and these costs have increased since 1980. The observed increase in damage costs from extreme weather events is mainly due to increases in population, economic wealth and human activities in hazard-prone areas and to better reporting. The contribution of climate change to the damage costs from natural disasters is expected to increase in the future due to the projected increase in the intensity and frequency of extreme weather events in many regions.

The combined impacts of projected climate change and socio-economic development can lead to high damage costs

Potentially large damage costs are projected for Europe due to the combined impacts of socio-economic developments and climate change, such as increases in coastal and river flooding, heat waves and energy demand for cooling. Cost estimates for various key sectors (infrastructure, built environment, tourism, transport, and forestry) are either unavailable or fragmentary. There is no consensus on cost estimates for biodiversity and ecosystem services due to the challenge of proper economic valuation. Estimates of the total costs of future climate change on the European economy are currently not available.

The causes of the most costly climate impacts are projected to differ strongly across Europe

The most costly impacts in southern Europe are projected to be increases in energy demand and heat waves, in western Europe coastal flooding and heat waves, in northern Europe coastal and river floods, and in eastern Europe river floods.

The damage costs from climate impacts can be reduced significantly by mitigation and adaptation actions

Significant reductions in damage costs can be achieved by global and European mitigation policies, consistent with the UNFCCC 2 °C objective, in combination with adaptation actions.

On-going and planned monitoring and research at national and EU level can improve assessments of past and projected impacts of climate change, thereby enhancing the knowledge base for adaptation

Improved information on past and projected climate impacts and on the vulnerability of environmental and social systems is crucial for the planning and implementation of effective adaptation measures. Climate-ADAPT provides a platform for sharing this information with policymakers at the European, national and subnational level.

Longer time series and greater spatial coverage of climate data could be achieved through improved monitoring of Essential Climate Variables from in situ stations and satellites, and reanalysis of European climate data.

The availability of consistent and comparable socio-economic scenarios at the European level could improve integrated climate change vulnerability assessments. The availability of such scenarios, and the use of comparable methods, could also improve the comparability of national impact and vulnerability assessments.

The indicators informing this assessment are based mainly on EU-wide research and on global databases. In the future some indicators on climate impacts and adaptation may be based on data collected from member countries.

Technical summary

Table TS.1 summarises the observed and projected changes for the following indicators:

- changes in the climate system (key climate variables and cryosphere);
- climate impacts on environmental systems (oceans and marine environment, coastal zones, freshwater quantity and quality, terrestrial ecosystems and biodiversity, and soil);
- climate impacts on socio-economic systems and human health (agriculture, forests and forestry, fisheries and aquaculture, human health, energy, transport services and infrastructure, and tourism).

Table TS.1 Observed and projected climate change and impacts on environmental and socio-economic systems and human health

	What is already happening	What could happen
Changes in the climate system		
Key climate variables		
Global temperature (C)	Three independent long records of global average (land and ocean) annual temperature show that the decade between 2002 and 2011 was 0.77 °C to 0.80 °C warmer than the pre-industrial average. The Arctic has warmed significantly more than the globe as a whole.	The further rise in global average temperature is projected to be between 1.1–6.4 °C by 2100 taking climate model uncertainties into account. The EU target of limiting global average temperature increase to 2 °C above pre-industrial levels is projected to be exceeded during the second half of this century and likely around 2050 for scenarios that assume no global mitigation policy. The Arctic is projected to warm more than the globe.
European temperature (C)	The average temperature for the European land area for the last decade (2002–2011) is 1.3 °C above the pre-industrial level, which makes it the warmest decade on record. Heat waves have increased in frequency and length.	Land temperature in Europe is projected to increase between 2.5 °C and 4.0 °C by 2071–2100. The largest temperature increases during the 21st century are projected over eastern and northern Europe in winter and over southern Europe in summer. Heat waves are projected to become more frequent and last longer across Europe over the 21st century.
Precipitation (C)	Precipitation changes across Europe show more spatial and temporal variability than temperature. Since the mid-20th century, annual precipitation has been generally increasing across most of northern Europe, most notably in winter, but decreasing in parts of southern Europe. In Western Europe intense precipitation events have significantly contributed to the increase. There are no widespread significant trends in the number of either consecutive dry or wet days across Europe.	Most climate model projections show continued precipitation increases in northern Europe (most notably during winter) and decreases in southern Europe (most notably during summer). The number of days with high precipitation is projected to increase.
Storms (C)	Observations of storm location, frequency and intensity show considerable variability across Europe during the 20th century. Storm frequency shows a general increasing trend from the 1960s to 1990s, followed by a decrease to the present.	Available climate change projections show no clear consensus in either the direction of movement or the intensity of storm activity.

Table TS.1 Observed and projected climate change and impacts on environmental and socio-economic systems and human health (cont.)

	What is already happening	What could happen
Cryosphere		
Snow cover (C)	Snow cover extent in the Northern Hemisphere has fallen by 7 % in March and 11 % in April during the past four decades. In winter and autumn no significant changes have occurred. Snow mass in Europe has decreased by 7 % in March from 1982 to 2009.	Model simulations project widespread reductions in the extent and duration of snow cover in Europe over the 21st century.
Greenland ice sheet (C)	The Greenland ice sheet changed in the 1990s from being in near mass balance to losing about 100 billion tonnes of ice per year. Ice losses have since then more than doubled to 250 billion tonnes a year averaged over 2005 to 2009. The recent melting of the Greenland Ice Sheet is estimated to have contributed up to 0.7 millimetres a year to global sea-level rise (about one quarter of the total sea-level rise).	Model projections suggest further declines of the Greenland ice sheet in the future but the processes determining the rate of change are still poorly understood.
Glaciers (C)	The vast majority of glaciers in the European glacial regions are in retreat. Glaciers in the European Alps have lost approximately two thirds of their volume since 1850, with clear acceleration since the 1980s.	Glacier retreat is expected to continue in the future. The volume of European glaciers has been estimated to decline between 22 and 66 % compared to the current situation by 2100 under a business-as-usual emission scenario.
Arctic (C) and Baltic sea ice (N)	The extent and volume of Arctic sea ice has declined rapidly since 1980, especially in summer. Record low sea ice cover in September 2007, 2011 and 2012 was roughly half the size of the normal minimum extent in the 1980s.The decline in summer sea ice appears to have accelerated since 1999. The maximum sea ice extent in the Baltic sea has been decreasing since about 1800.	Arctic Sea ice is projected to continue to shrink in extent and thickness and may even disappear completely at the end of the summer melt season in the coming decades. It is expected that there will still be substantial ice in winter. Baltic Sea ice, in particular the extent of the maximal cover, is projected to shrink further.
Permafrost (C)	In the past 10–20 years European permafrost has shown a general warming trend, with greatest warming in Svalbard and Scandinavia. The active layer thickness (i.e. the thawing depth) has increased at some European permafrost sites.	Present and projected atmospheric warming is projected to lead to wide-spread warming and thawing of permafrost.
Climate impacts on environmental systems		
Oceans and marine environment		
Ocean acidification (N)	Surface-ocean pH has declined from 8.2 to 8.1 over the industrial era due to the growth of atmospheric CO_2 concentrations. This decline corresponds to a 30 % increase in oceanic acidity. Observed reductions in surface-water pH are nearly identical across the global ocean and throughout Europe's seas. Ocean acidification in recent decades is occurring a hundred times faster than during past natural events over the last 55 million years. Ocean acidification already reaches into the deep ocean, particularly in the high latitudes.	Average surface-water pH is projected to decline further to 7.7 or 7.8 by the year 2100, depending on future CO_2 emissions. This decline represents a 100 to 150 % increase in acidity relative to present conditions. Ocean acidification may affect many marine organisms within the next 20 years and could alter marine ecosystems and fisheries.
Ocean heat content (N)	Heat increases in the world's oceans accounts for approximately 93 % of the warming of the earth system during the last six decades. An increasing trend in the heat content in the uppermost 700 m of the world's oceans is evident over the last six decades. Recent observations show substantial warming of the deeper ocean (between 700 and 2 000 m depth).	Further warming of the oceans is expected with projected climate change, but quantitative projections of ocean heat content are not available.
Sea surface temperature (C)	Sea surface temperature in European seas is increasing more rapidly than in the global oceans. The rate of increase in sea surface temperature in all European seas during the past 25 years is the largest ever measured in any previous 25-year period.	Global sea surface temperature is projected to rise more slowly than atmospheric temperature.
Phenology of marine species (C)	Many marine organisms in European seas appear earlier in their seasonal cycles than in the past. Some plankton species have advanced their seasonal cycle by four to six weeks in recent decades.	Projections of the phenological responses of individual species are not available, but phenological changes are expected to continue with projected further climate change.

Table TS.1 Observed and projected climate change and impacts on environmental and socio-economic systems and human health (cont.)

	What is already happening	What could happen
Distribution of marine species (C)	A major northward expansion of warmer-water plankton in the north-east Atlantic and a northward retreat of colder-water plankton has taken place. The northerly movement is about 10 ° latitude (1 100 km) over the past 40 years, and it seems to have accelerated since 2000. Sub-tropical species are occurring with increasing frequency in European waters and sub-Arctic species are receding northwards.	Further changes in the distribution of marine species are expected, with projected further climate change, but quantitative projections are not available.
Coastal zones		
Global and European sea-level rise (C)	Tide gauges show a global mean sea-level rise of around 1.7 mm/year over the 20th century. Satellite measurements show a rise of around 3 mm/year over the last two decades. Sea level is not rising uniformly at all locations, with some locations experiencing much greater than average rise. Coastal impacts also depend on the vertical movement of the land, which can either add to or subtract from climate-induced sea-level change, depending on the location.	Projections of global mean sea-level rise in the 21st century range between 20 cm and about 2 m by the end of the century. Modelling uncertainty contributes at least as much to the overall uncertainty as uncertainty about future greenhouse gas emission scenarios. It is likely that 21st century sea-level rise will be greater than during the 20th century. Current projections suggest that it is more likely to be less than 1 m than to be more than 1 m.
Storm surges (N)	Several large storm surge events have caused loss of life and damage to property in Europe during the past century. Extreme coastal water levels have increased at many locations around the European coastline, mainly due to increases in mean local sea level rather than to changes in storm activity. Large natural variability and lack of good quality long observational records makes detecting long-term changes in trends in extreme coastal sea levels difficult.	Projections of changes in storms and storm surges for the European region have a high uncertainty. Increases in extreme coastal water levels will likely be dominated by increases in local relative mean sea level, with changes in the surge component being less important at most locations.
Coastal erosion (C)	About one quarter of the European coastline for which data is available is currently eroding, due partly to increasing human activities in the coastal zone.	Projections for coastal erosion are not available. Future climate change, in particular rising sea levels, is expected to accelerate coastal erosion.
Freshwater quantity and quality		
River flow (C)	Climate change induced long-term trends in river flows are difficult to detect due to substantial natural variability and modifications from water abstractions, man-made reservoirs and land-use changes. Nevertheless, increased river flows during winter and lower river flows during summer have been recorded since the 1960s in large parts of Europe.	Climate change is projected to result in strong changes in the seasonality of river flows across Europe. Summer flows are projected to decrease in most of Europe, including in regions where annual flows are projected to increase.
River floods (C)	More than 325 major river floods have been reported for Europe since 1980, of which more than 200 have been reported since 2000. The rise in the reported number of flood events over recent decades results mainly from better reporting and from land-use changes.	Global warming is projected to intensify the hydrological cycle and increase the occurrence and frequency of flood events in large parts of Europe. Pluvial floods and in particular flash floods, which are triggered by local intense precipitation events, are also likely to become more frequent throughout Europe. In regions with projected reduced snow accumulation during winter (e.g. north-eastern Europe), the risk of early spring flooding could decrease. However quantitative projections for flood frequency and intensity are uncertain.
River flow drought (C)	Europe has been affected by several major droughts in recent decades, such as the catastrophic drought associated with the 2003 summer heat wave in central parts of the continent and the 2005 drought in the Iberian Peninsula. Severity and frequency of droughts appear to have increased in parts of Europe, in particular in southern Europe.	Regions most prone to an increase in drought hazard are southern and south-eastern Europe, but minimum river flows are also projected to decrease significantly in many other parts of the continent, especially in summer.
Water temperature (C)	Water temperature in major European rivers and lakes has increased by 1–3 °C over the last century.	Lake and river surface water temperatures are projected to increase with further increases in air temperature.
Lake and river ice cover (C)	The duration of ice cover on European lakes and rivers has shortened at a mean rate of 12 days per century over the last 150–200 years.	A further decrease in the duration of lake ice cover is projected.

Table TS.1 Observed and projected climate change and impacts on environmental and socio-economic systems and human health (cont.)

	What is already happening	What could happen
Freshwater ecosystems and water quality (C)	Cold-water species have been observed to move northwards or to higher altitudes. Changes in life cycle events (phenology) have been observed. Phytoplankton and zooplankton blooms in several European lakes are now occurring one month earlier than 30–40 years ago. Biological invasions of species (including toxic species) that originate in warmer regions have been observed.	The observed changes are projected to continue with further projected climate change. Increases in nutrient and dissolved organic carbon concentrations in lakes and rivers may occur, but management changes can have much larger effects than climate change.
Terrestrial ecosystems and biodiversity		
Plant and fungi phenology (C)	The timing of seasonal events in plants is changing. 78 % of leaf unfolding and flowering records show advancing trends in recent decades whereas only 3 % show a significant delay. Between 1971 and 2000, the average advance of spring and summer was between 2.5 and 4 days per decade. The pollen season starts on average 10 days earlier and is longer than 50 years ago.	Trends in seasonal events are projected to advance further as climate change proceeds.
Animal phenology (C)	Many animal groups have advanced their life cycles in recent decades, including frogs spawning, birds nesting and the arrival of migrant birds and butterflies. The breeding season of many thermophilic insects (such as butterflies, dragonflies and bark beetles) has been lengthening, allowing more generations to be produced per year.	The observed trends are expected to continue in the future but quantitative projections are rather uncertain.
Distribution of plant species (C)	Several European plant species have shifted their distribution northward and uphill. Mountain ecosystems in many parts of Europe are changing as plant species expand uphill.	Cold-adapted species are projected to lose climatically suitable areas in mountains. By the late 21st century, European plant species are projected to shift several hundred kilometres to the north, forests are likely to contract in the south and expand in the north, and about half of the mountain plant species may face extinction. The rate of climate change is expected to exceed the ability of many plant species to migrate, especially as landscape fragmentation may restrict movement.
Distribution and abundance of animal species (C)	There is a clear poleward trend of butterfly distributions from 1990 to 2007 in Europe. Nevertheless, the migration of many species is lagging behind the changes in climate, suggesting that they are unable to keep pace with the speed of climate change.	Distribution changes are projected to continue. Suitable climatic conditions for Europe's breeding birds are projected to shift nearly 550 km northeast by the end of the 21st century under a scenario of 3 °C warming, with the average range size shrinking by 20 %. Habitat use, fragmentation and other obstacles are impeding the migration of many animal species. The difference between required and actual migration rate may lead to a progressive decline in European biodiversity.
Soil		
Soil organic carbon (C)	On average, soils in Europe are most likely accumulating carbon. Soils under grassland and forest are a carbon sink, whereas soils under arable land are a smaller carbon source.	Climate change is expected to have an impact on soil carbon in the long term, but changes in the short term will more likely be driven by land management practices and land use change.
Soil erosion (C)	About 130 million ha of land in the EU is affected by soil erosion by water, of which almost 20 % shows soil loss in excess of 10 t/ha/year. 42 million ha of land is affected by wind erosion, of which around 1 million ha is severely affected.	Increased variations in rainfall pattern and intensity are expected to make soils more susceptible to water erosion and increased aridity would make finer-textured soils more vulnerable to wind erosion. However reliable quantitative projections are not available.
Soil moisture (C)	There is no clear indication on past trends for water retention across the EU due to a lack of systematic and harmonised data.	Projections suggest a reduction in summer soil moisture over most of Europe, significant reductions in the Mediterranean region, and increases in the northeastern part of Europe.

Table TS.1 Observed and projected climate change and impacts on environmental and socio-economic systems and human health (cont.)

	What is already happening	What could happen
Climate impacts on socio-economic systems and human health		
Agriculture		
Growing season for agricultural crops (C)	The thermal growing season of a number of agricultural crops in Europe has lengthened by 11.4 days on average from 1992 to 2008. The delay in the end of the growing season was more pronounced than the advance of its start.	The growing season is projected to increase further throughout most of Europe which would allow a northward expansion of warm-season crops to areas that are currently not suitable.
Agrophenology (C)	Flowering of a several perennial crops has advanced by about two days per decade in recent decades. These changes are affecting crop production and the relative performance of different crop species and varieties.	The shortening of crop growth phases in many crops is expected to continue. The shortening of the grain filling phase of cereals and oilseed crops can be particularly detrimental to yield.
Water-limited crop productivity (N)	Yields of several crops (e.g. wheat) are stagnating and yields of other crops (e.g. maize in northern Europe) are increasing, partly due to climate change. Extreme climatic events, including droughts and heat waves, have negatively affected crop productivity during the first decade of the 21st century.	Future climate change can lead to yield decreases or increases, depending on crop type and with considerable regional differences across Europe. Yield variability is expected to further increase under projected future climate change (including increased intensity and frequency of extreme events).
Irrigation water requirement (C)	In Italy and the Iberian Peninsula, an increase in the volume of water required for irrigation from 1975 to 2010 has been estimated, whereas parts of south-eastern Europe have recorded a decrease.	In southern Europe suitability for rain-fed agriculture is projected to decrease and irrigation requirements are projected to increase, under future climate change.
Forests and forestry		
Forest growth (C)	Forest biomass and the area covered by forests and other wooded land have increased over the past decades. In some central and western forest areas of Europe, forest growth has been reduced in the last 10 years due to storms, pests and diseases.	Forest growth is projected to increase in northern Europe and to decrease in southern Europe under projected future climate change.
Forest fires (C)	The number of fires in the Mediterranean region has increased over the period from 1980 to 2000 and decreased thereafter. The impact of fire events is particularly strong on already degraded ecosystems in southern Europe.	In a warmer climate, more severe fire weather and, as a consequence, an expansion of the fire-prone area and longer fire seasons are projected, but with considerable regional variation.
Fisheries and aquaculture (N)	Wild fish stocks seem to be responding to changing temperatures and food supply by changing their geographical distribution.	Future projected climate change is likely to lead to an increased catch potential in the Arctic, and to a decreased or constant catch potential in other European seas. Climate change can influence where aquaculture is possible, which species are raised, and the efficiency of the production.
Human health		
Floods and health (N)	River and coastal flooding affect millions of people in Europe each year. Effects include drowning, heart attacks, injuries, infections, psychosocial consequences, health effects of chemical hazards, and disruption of services.	Increases in health risks associated with river and coastal flooding are projected in many regions of Europe due to projected increases in extreme precipitation events and sea level.
Extreme temperatures and health (C)	Mortality and morbidity increase, especially in vulnerable population groups, and general population well-being decreases during extreme cold spells and heat-waves, as well as above and below local and seasonal comfort temperatures, with different temperature thresholds in Europe. Heat-waves over the last decade have caused tens of thousands of premature deaths in Europe.	Length, frequency, and intensity of heat-waves are very likely to increase in the future. This increase can lead to a substantial increase in mortality over the next decades, especially in vulnerable groups, unless adaptation measures are taken. Cold-related mortality is projected to decrease in many countries due to climate change as well as better social, economic, and housing conditions.
Air pollution by ozone and health (C)	Excessive exposure to ground-level ozone is estimated to cause about 20 000 premature deaths per year in Europe. Attribution of observed changes in ozone exceedances to climate change is difficult.	Future projected climate change is expected to increase ozone concentrations but this effect will most likely be outweighed by reduction in ozone levels due to expected future emission reductions.

Table TS.1 Observed and projected climate change and impacts on environmental and socio-economic systems and human health (cont.)

	What is already happening	What could happen
Vector-borne diseases (C)	The transmission cycles of vector-borne diseases are sensitive to climatic factors but also to land use, vector control, human behaviour, and public health capacities. Climate change is the main factor behind the observed northward and upward move of the tick species *Ixodes ricinus* in parts of Europe.	Climate change is projected to lead to further northward and upward shifts in the distribution of *Ixodes ricinus*. It is also expected to affect the habitat suitability for a wide range of disease vectors, including Aedes albopictus and the phlebotomine species of sandflies.
Water- and foodborne diseases (C)	It is not possible to assess whether climate change has already affected water- and food-borne diseases in Europe.	Climate change is projected to increase the risk of food- and water-borne diseases in many parts of Europe. Projected increased temperatures could increase the risk of salmonellosis. Where precipitation or extreme flooding is projected to increase in Europe, the risk of campylobacteriosis and cryptosporidiosis could increase.
Energy		
(N)	The number of heating degree days has decreased by an average of 16 per year since 1980. This decrease helps reduce the demand for heating, particularly in northern and north-western Europe. Cooling degree days are increasing but time series are not available.	Climate change is projected to reduce demand for heating in northern and north-western Europe and to strongly increase energy demand for cooling in southern Europe, which may further exacerbate peaks in electricity supply in the summer. Further increases in temperature and droughts may limit the availability of cooling water for thermal power generation in summer.
Transport		
(N)	Land-based and water-based transport infrastructure and operation is sensitive to changes in climate. Data on past climate-related impacts on transport are restricted to individual extreme events, and attribution to climate change is generally not possible.	Climate change is projected to have both beneficial and adverse impacts on transport, depending on the region and the transport mode. Rail transport is projected to face the highest percentage increase in costs from extreme weather events. The British Isles, central Europe, eastern Europe, France and Scandinavia are projected to be most adversely impacted.
Tourism		
(C)	Climatic suitability for general tourism activities is currently best in southern Europe.	Touristic attractiveness in northern and Central Europe is projected to increase in most seasons. The suitability of southern Europe for tourism is projected to decline markedly during the key summer months but improve in other seasons. Projected reductions in snow cover will negatively affect the winter sports industry in many regions, in particular regions close to the low elevation limit for winter sport. Economic consequences for regions where tourism is an important economic sector can be substantial, but this is strongly determined by non-climatic factors, such as the ability of tourists to adjust the timing of their holidays.

Note: Letters in brackets compare information in the 2012 report with the 2008 report: (C) = broadly consistent; (N) = new information.

Regional impacts and vulnerability

Overview

Human systems and ecosystems in Europe are vulnerable to major climate change impacts such as river floods, droughts or coastal flooding. In various regions, a combination of different types of these impacts can exacerbate vulnerabilities. Vulnerabilities differ across Europe depending on local conditions.

A summary of regional impacts and vulnerabilities is presented (see also Map TS.1 and Table TS.2).

Socio-economic developments (e.g. population and wealth growth leading to increasing exposed systems such as houses and other infrastructures) are a key driver (in addition to climate change) of projected increases in climate change impacts. There are significant differences in adaptive capacity across Europe. When major climate change impacts affect regions with a low adaptive capacity, the consequences are severe. An integrated assessment of European regions' vulnerability to climate change suggests that climate change could deepen existing socio-economic imbalances in Europe and may negatively affect the territorial cohesion.

The Arctic

The Arctic faces major changes including a higher than average temperature increase, a decrease in summer sea ice cover and thawing of permafrost. The reduction of ice cover is accelerating and projected to continue to impact the local natural and human systems. It also opens up business opportunities that could put an additional burden on the environment such as extensive oil and gas exploration and the opening of new shipping routes. Thawing of permafrost has the potential to seriously affect human systems, by, for example, creating infrastructural problems. The fragile Arctic ecosystems have suffered significantly from above average temperature increases and these impacts are expected to continue.

Northern Europe

Projections suggest less snow and lake and river ice cover, increased winter and spring river flows in some parts (e.g. Norway) and decreases in other parts (e.g. Finland), and greater damage by winter storms. Climate change could offer opportunities in northern Europe, at least in the short and medium terms. These include increased crop variety and yields, enhanced forests growth, higher potential for electricity from hydropower, lower energy consumption for heating and possibly more summer tourism. However, more frequent and intense extreme weather events in the medium to long term might adversely impact the region, for example by making crop yields more variable.

North-western Europe

Coastal flooding has impacted low-lying coastal areas in north-western Europe in the past and the risks are expected to increase due to sea-level rise and an increased risk of storm surges. North Sea countries are particularly vulnerable, especially Belgium, Denmark, Germany, the Netherlands and the United Kingdom. Higher winter precipitation is projected to increase the intensity and frequency of winter and spring river flooding, although to date no increased trends in flooding have been observed.

Central and eastern Europe

Temperature extremes are projected to be a key impact in central and eastern Europe. Together with reduced summer precipitation this can increase the risk of droughts, and is projected to increase energy demand in summer. The intensity and frequency of river floods in winter and spring (in various regions) is projected to increase due to increases in winter precipitation. Climate change is also projected to lead to higher crop-yield variability and increased occurrence of forest fires.

Mediterranean region

The Mediterranean region has been subject to major impacts over recent decades as a result of decreased precipitation and increased temperature, and these are expected to worsen as the climate continues to change. The main impacts are decreases in water availability and crop yields, increasing risks of droughts and biodiversity loss, forest fires and heat waves. Increasing irrigation efficiency in agriculture can reduce irrigation water withdrawals to some degree but will not be sufficient to compensate for climate-induced increases in water stress. In addition the hydropower sector will be increasingly affected by lower water availability and increasing energy demand, while the tourism industry will face less favourable conditions in summer. Environmental flows, which are important for the healthy maintenance of aquatic ecosystems, are threatened by climate change impacts and socio-economic developments.

Cities and urban areas

In previous years, increasing urban land take and urban population growth have in many places increased the exposure of European cities to different climate impacts such as heat waves, flooding and droughts. The impacts of extreme events such as the flooding of the river Elbe (2002) or the urban drainage flood in Copenhagen (2011) demonstrate the high vulnerability of cities to extreme weather events, even though it is not possible to attribute these specific events to anthropogenic climate change. In the future, on-going urban land take, growth and concentration of population in cities, and an aging population, contribute to increase further the vulnerability of cities to climate change. Urban design, urban management and enhancing green infrastructure may partly address these effects.

Mountain areas

The increase in temperature is particularly high in many mountain regions, where loss of glacier mass, reduced snow cover, thawing of permafrost and changing precipitation patterns, including less precipitation falling as snow, have been observed and are expected to increase further. This could lead to an increase in the frequency and intensity of floods in some mountain areas (e.g. in parts of Scandinavia) that can impact people and the built environment. Additional projected impacts include reduced winter tourism, lower energy potential from hydropower in southern Europe, a shift in vegetation zones and extensive biodiversity loss. Plant and animal species living close to mountain tops face the risk of becoming extinct due to the inability to migrate to higher regions.

The retreat of the vast majority of glaciers also affects water availability in downstream areas.

Damage costs

Damage costs from weather and climate-related disasters

Hydro-meteorological events (storms, floods, and landslides) account for 64 % of the reported damage costs due to natural disasters in Europe since 1980; climatological events (extreme temperatures; droughts and forest fires) account for another 20 %. It is, however, difficult to determine accurately the proportion of damages that are attributable to climate change. Damages from extreme weather events have increased from EUR 9 billion in the 1980s to more than EUR 13 billion in the 2000s. The increased in damages is primarily due to increases in population, economic wealth and human activities in hazard-prone areas and to better reporting. The contribution of climate change to the damage costs from natural disasters is expected to increase due to the projected changes in the intensity and frequency of extreme weather events.

Projected costs of climate change impacts

Projections suggest potentially large costs of combined climate change impacts and socio-economic developments in Europe, particularly due to increases in coastal and river flooding, heat waves and energy demand (for cooling). The most costly impacts differ strongly across Europe. In southern parts of Europe the most costly impacts are increases in energy demand and heat waves, in western Europe coastal flooding and heat waves, in northern Europe coastal and river floods and in eastern Europe river floods. Significant reductions in costs can be achieved by global and European mitigation policies, consistent with the UNFCCC 2 °C objective, in combination with adaptation actions.

Cost estimates have a medium to good coverage at European level for coastal and river flooding, water supply, energy demand, agriculture and human health, but for various key sectors cost estimates are fragmentary or unavailable (infrastructure, built environment, tourism, transport, forestry). For biodiversity and ecosystem services cost estimates are difficult to prepare due to the challenge of proper valuation. Estimates of the total costs of future climate change on the European economy are currently not available.

Data availability and needs

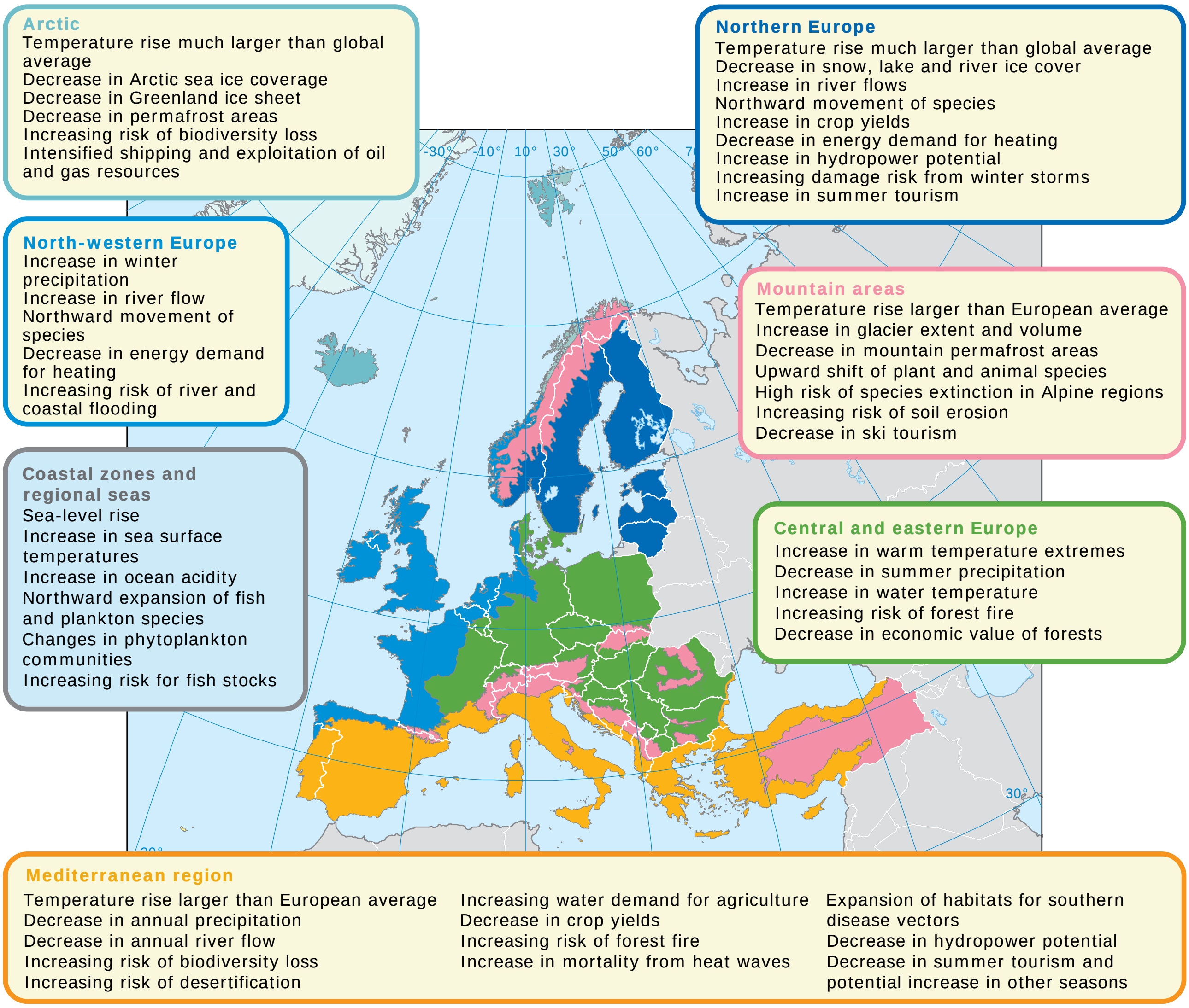
The available data and indicators show that climate change is occurring and causes a multitude of different impacts. Longer time series and greater spatial coverage of both climate change and its impacts can provide greater insights into processes of change and a more diversified picture across Europe. Actions being undertaken globally and in Europe to improve monitoring of Essential Climate Variables (ECVs) from both in situ stations and using satellites are expected to enhance the knowledge base. In addition on-going and planned actions on reanalysis of European climate data will improve the understanding of climate change. It is important that the planned actions are implemented. Currently there is a lack of sufficient observations of impacts of climate change on various environmental and socio-economic systems and on human health. Properly including climate change impact aspects in existing monitoring systems can improve the knowledge base needed to develop evidence based adaptation policies and actions.

European wide integrated climate change vulnerability assessments apply different methodologies, and the underlying datasets have important limitations. The availability of consistent and comparable information at EU level on scenarios for key socio-economic and physical variables is incomplete. Also European wide projections of cost estimates of impacts, including damages of extreme weather events, can be improved. On-going and planned EU funded research is expected to improve this situation.

Many European countries have performed national and sub-national climate change vulnerability and risk assessments while several countries have not yet done so. The comparability of national assessments, including the national impact indicators, may be improved in future for example by using comparable methods and climate and socio-economic projections.

Climate change impacts indicators are currently only to a very limited extent included within existing and emerging European thematic and sectoral indicator sets, but this should be considered in future improvements of these indicator sets. The indicators informing this assessment are based on EU-wide research and on global databases. Some selected indicators may in the future be based on data collected from member countries, e.g. through the European Climate Adaptation Platform Climate-ADAPT (http://climate-adapt.eea.europa.eu) and/or through reporting of indicators by Member States to the European Commission and the EEA.

Map TS.1 Key observed and projected climate change and impacts for the main regions in Europe



Note: Information covers both observed and projected changes (see text and Table TS.2 for details).

Table TS.2 Key observed (O) and projected (P) climate change and impacts for the main regions in Europe

			Northern Europe (incl. Arctic)		North-western Europe		Central and eastern Europe		Medi-terranean region		European average	
Section	**Indicator / topic**	**Variable**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**
2	**Changes in the climate system**											
2.2	**Key climate variables**											
2.2.2	Global and European Temperature	Temperature	+	+	+	+	+	+	+	+		
2.2.3	Temperature extremes (Warm)	Frequency	+	+	+	+	+	+	+	+		
2.2.3	Temperature extremes (Cold)	Frequency	–	–	–	–	–	–	–	–		
2.2.4	Mean precipitation	Precipitation	+	+	+	(+)	o	(+)	–	–		
2.2.5	Precipitation extremes (Wet)	Duration/Amount	(+)	+	(+)	+	o	+	(–)	+		
2.2.5	Precipitation extremes (Dry)	Duration	±		(+)		o		(+)			
2.2.6	Storms	Wind speed	+	(+)	+	(+)	(+)	(+)	o	(–)		
2.3	**Cryosphere**											
2.3.2	Snow cover	Duration/amount	±	±	–	–	(–)	(–)	(–)	–		
2.3.3	Greenland ice sheet	Mass	–	–								
2.3.4	Glaciers	Mass	±	(–)			–	–	–	–		
2.3.5	Permafrost	Active layer depth	+	+			+		+			
2.3.6	Arctic and Baltic sea ice	*See below*										
3	**Climate impacts on environmental systems**											
3.1	**Oceans and marine environment**	*See below*										
3.2	**Coastal zones**											
3.2.2	Sea-level rise	Mean sea level (excl. land movement)	+	+	+	+	+	+	(+)	(+)		
3.2.3	Storm surges	Surge height (in addition to mean sea level)	(+)	(+)	o	(+)	o	(+)	o	–		
3.3	**Inland waters**											
3.3.2	River flow	Mean flow	+	+	(+)	+	±	±	–	–		
3.3.3	River floods	Maximum flow		±	+	+		±		±		
3.3.4	River flow drought	Minimum flow	o	+	o	–	o	±	o	–		
3.3.5	Water temperature	Temperature	+	+	+	+	+	+	+	+		
3.3.6	Lake and river ice cover	Duration	–	–	–	–	–	–	–	–		
3.4	**Terrestrial ecosystems and biodiversity**											
3.4.2	Plant and fungi phenology	Day of year (spring/summer)									–	–
3.4.3	Animal phenology	Day of year (spring/summer)									–	–
3.4.4	Distribution of plant species	Latitude and altitude									+	+
3.4.5	Distribution and abundance of animal species	Latitude and altitude									+	+
3.5	**Soil**											
3.5.2	Soil organic carbon	Carbon content									+	
4	**Climate impacts on socio-economic systems and health**											
4.1	**Agriculture**											
4.1.2	Growing season for agricultural crops	Duration	(+)		+		(+)		(+)			+
4.1.3	Agrophenology	Day of year	–	–	–	–	–	–	–	–		
4.1.4	Water-limited crop productivity	Yield	+	+	±	±		±	–	(–)		
4.1.5	Irrigation water requirement	Water requirement	(–)		o		(+)		±	(+)		

Table TS.2 Key observed (O) and projected (P) climate change and impacts for the main regions in Europe (cont.)

			Northern Europe (incl. Arctic)		North-western Europe		Central and eastern Europe		Medi-terranean region		European average	
Section	**Indicator / topic**	**Variable**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**P**
4.2	**Forests and forestry**											
4.2.2	Forest growth	Biomass		+		+		±		(–)	+	
4.2.3	Forest fires	Area							(+)			+
4.3	**Fisheries and aquaculture**	*See below*										
4.4	**Human health**											
4.4.3	Floods and health	People flooded				+						+
4.4.4	Extreme temperatures and health	Mortality								+		+
4.4.5	Air pollution by ozone and health	Ozone levels	(+)	–	o		(+)		(+)	+		
4.4.6	Vector-borne diseases	People infected										(+)
4.5	**Energy**											
4.5.2	Heating degree days	Heating demand	–	–	–	–	–	–	(–)	(–)		
4.5.3	Electricity demand	Electricity demand		–						+		
4.5.3	Electricity production	Electricity production		+		–		–		–		
4.6	**Transport**											
4.6.3	Impacts of changes in weather extremes	Costs					+					±
4.7	**Tourism**											
4.7.2	General tourism	Attractivity		+		+		±		(–)		
4.7.3	Winter sport tourism	Attractivity		(–)				(–)				
5	**Vulnerability to climate change**											
5.5	**Damage costs related to climate change**											
5.5.1	Damages from weather and climate-related events	Damage costs									+	+
5.5.2	Projected costs of climate change	Costs										+
			Arctic ocean		**Atlantic and North Sea**		**Baltic Sea**		**Medi-terranean Sea**		**All European seas**	
2.3.6	Arctic and Baltic sea ice	Duration/extent	–	–			–	–				
3.1	**Oceans and marine environment**											
3.1.2	Ocean acidification	Acidity									+	+
3.1.3	Ocean heat content	Heat content									+	+
3.1.4	Sea surface temperature	Temperature									+	+
3.1.5	Phenology of marine species	Day of year			+							
3.1.6	Distribution of marine species	Latitude			+							
4.3	**Fisheries and aquaculture**	Catch potential		+								

Legend: +: Increase in variable throughout (most of the) region

–: Decrease in variable throughout (most of the) region

±: Increases as well as decreases in the variable in the region

o: Only small changes in variable

(): Increase or decrease only in some parts of the region

Green: Beneficial change

Red: Adverse change

Note: Information refers to different time horizons, emissions scenarios and socio-economic scenarios. Some observations and projections have lower levels of confidence than others.

1 Introduction

1.1 Purpose and outline

This report presents an indicator-based assessment of past and projected climate changes, their observed and projected impacts, and the associated vulnerability ([1]) of and risks to society, human health and ecosystems in Europe. The report can be regarded as an updated and extended version of the 2008 report 'Impacts of Europe's changing climate — 2008 indicator-based assessment' ([2]).

The main objectives of this 'climate change, impacts and vulnerability' report are to:

- present past and projected climate change and impacts through indicators;
- identify sectors and regions most at risk;
- highlight the need for adaptation actions;
- identify main sources of uncertainty;
- demonstrate how monitoring and scenario development can improve the knowledge base.

This report is structured as follows. This chapter

- describes the links to other reports (Section 1.2);
- presents the relevant international and EU policy frameworks (Section 1.3);
- discusses the role of indicators on climate change, impacts, vulnerability and adaptation (Section 1.4);
- explains the emissions scenarios and socio-economic scenarios underlying projections for the future (Section 1.5);
- outlines how uncertainty is addressed in this report (Section 1.6);
- explains the use of the terms 'vulnerability' and 'risk' in this report as well as in the underlying literature (Section 1.7).

Chapters 2, 3 and 4 constitute the main part of this report. They describe observed and projected climate change and its impacts in Europe by means of about 40 indicators. These indicators will also be included and presented in the European Environment Agency (EEA) indicator management system ([3]) and the European Climate Adaptation Platform (Climate-ADAPT) (see Section 1.2.5).

Chapter 2 presents information on the climate system:

- Overview of the climate system and the human influence on it (Section 2.1);
- Key climate variables (Section 2.2);
- Cryosphere: glaciers, snow and ice (Section 2.3).

Chapter 3 presents information on climate change impacts on environmental systems:

- Oceans and marine environment (Section 3.1);
- Coastal zones (Section 3.2);
- Freshwater quantity and quality (Section 3.3);
- Terrestrial ecosystems and biodiversity (Section 3.4);
- Soil (Section 3.5).

([1]) For an explanation of the terms 'vulnerability' and 'risk', and their use in this report, see Section 1.7.
([2]) See http://www.eea.europa.eu/publications/eea_report_2008_4.
([3]) See http://www.eea.europa.eu/themes/climate/indicators#c7=all&c5=all&c10=&c13=20&b_start=0.

It should be noted that mountains are not covered in a separate section, but relevant information is included within some of the abovementioned sections (e.g. on biodiversity).

Chapter 4 presents information on climate change impacts on socio-economic sectors and systems, and on human health:

- Agriculture (Section 4.1);
- Forests and forestry (Section 4.2);
- Fisheries and aquaculture (Section 4.3);
- Human health (Section 4.4);
- Energy (Section 4.5);
- Transport services and infrastructure (Section 4.6);
- Tourism (Section 4.7).

The selection of socio-economic sectors and systems covered in this report is based on several criteria, including the relevance of climate change, the availability of EU-wide quantitative information, and the importance of EU policies. Mainly due to lack of such information some sectors, systems and issues are not covered, including industry and manufacturing, insurance, infrastructure (except for transport infrastructure), livestock production and cultural heritage. However, hard-to-quantify and immaterial impacts of climate change (such as aesthetic changes and changes in personal well-being) are not systematically covered because meaningful indicators are not available. Also, information on changes in migration of people within and to the EU due to climate change is not included because of a lack of evidence.

The indicators in Chapters 2, 3 and 4 provide information on climate changes and their impacts and give an indication of where, to what extent and in which sectors Europe is vulnerable to climate change, now and in the future. An important question is to which future climate change the EU should adapt. Since future levels of greenhouse gas (GHG) emissions and associated global climate change are uncertain, this report provides impact projections for a range of emissions scenarios, where available. This allows the user of the report to interpret which impacts may need to be avoided. The projections shown are for different time horizons in the 21st century depending on available information for each indicator (for details see Table 1.3).

Information for each indicator comprises key messages, an explanation of its environmental and policy relevance, and an analysis of past trends and future projections, where available. Data quality issues and main uncertainties are generally discussed for a group of indicators together. Some sections also present relevant information on climate impacts on specific sectors even though data availability and quality does not currently allow developing an EEA indicator based on this information.

Chapter 5 presents information on the current and projected vulnerability ([4]) of regions and sectors to climate change, also taking into account future changes in demography and socio-economic conditions. It also covers vulnerability in cities. In addition, selected information on economic losses from past weather and climate-related events and from projected climate change is presented. Information in Chapter 5 is generally not presented in the form of EEA indicators.

Chapter 6 identifies indicator and data needs and presents key actions and programmes aimed at addressing these needs.

Finally, Chapter 7 presents the abbreviations and acronyms used throughout this report.

This report was prepared with contributions from many experts and organisations including the World Health Organization Regional Office for Europe (WHO/Europe), the European Centre of Disease Prevention and Control (ECDC), the European Commission's Joint Research Centre (JRC), and various European Topic Centres (ETCs), funded by the EEA (European Topic Centre on Climate Change impacts, vulnerability and Adaptation, ETC/CCA; European Topic Centre on Inland, Coastal and Marine waters, ETC/ICM; ETC on Biological Diversity, ETC/BD).

([4]) For an explanation of the terms 'vulnerability' and 'risk', and their use in this report, see Section 1.7.

1.2 Scope and link to other EU and EEA activities and products

1.2.1 Scope

This report provides comprehensive indicator-based information covering all main categories of climate impacts (with some exceptions as described above in Section 1.1). Where feasible, indicators cover all of Europe (the 32 member countries of the EEA). However, for some indicator categories for which no Europe-wide data were available (e.g. for ecosystem-related indicators), indicators have been selected and presented for fewer countries. Furthermore, some indicators have only limited geographical relevance (e.g. glaciers) and in such cases the aim was for full coverage of the relevant countries.

Key terms used to assess and communicate the effects of climate change emphasise adverse impacts (e.g. vulnerability and risk; see Section 1.7), which may wrongly suggest that all impacts are adverse, while in fact some impacts may be beneficial. The emphasis in this report on adverse impacts has two reasons. Firstly, and most importantly, adverse and beneficial impacts have rather different policy implications. Adverse impacts generally call for anticipatory, planned adaptation (e.g. increasing risk management efforts in order to maintain current risk levels under *projected* climate change), whereas the benefits of climate change can often be brought in by reactive adaptation (e.g. reducing risk management efforts that turn out to be no longer needed after *observing* climate change). Secondly, on balance most climate change impacts presented in this report are projected to be adverse. However, the level of the impacts depends on the time horizon and scenario.

1.2.2 Data sources

There is no reporting of climate change impacts and vulnerability data and information from EU Member States to the European Commission or EEA. Some information is available in national communications to the United Nations Framework Convention on Climate Change (UNFCCC), but this cannot be used for preparing comparable quantitative indicators across EEA member countries (see also Section 1.3.1). Thus the indicators presented in this report are based on data from in situ and satellite monitoring programmes, from national and EU research programmes and from a few global databases.

Various EU research programmes (e.g. Sixth and Seventh Framework Programmes (FP6 and FP7, respectively) ([5])) have developed knowledge over the past years and information from these programmes has been included to the extent feasible in this report. However, there are still many gaps in the data and coverage across Europe and over time. Chapter 6 gives an overview of main data gaps and needs. Section 7.2 provides an (incomplete) overview of those research projects that have contributed significantly to the indicators presented in this report.

1.2.3 Links to other reports

The report builds on various previous EEA reports, including the 'State of the Environment and Outlook report 2010' and its thematic assessments on climate change and on impacts, vulnerability and adaptation (EEA, 2010a; b), a technical report on natural (and technological) disasters (EEA, 2011) and various reports from the JRC, WHO/Europe and ECDC.

Furthermore, this report is consistent with the following EEA reports published in 2012:

- *Urban adaptation to climate change in Europe* (EEA, 2012);
- 'Water resources in Europe in the context of vulnerability' (to be published autumn 2012);
- 'State of coasts in Europe' (in preparation).

The report furthermore aims to achieve consistency, to the extent feasible, with the Intergovernmental Panel on Climate Change (IPCC) Special Report on 'Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)' (IPCC, 2012), the IPCC Fifth Assessment Report (AR5) (see Box 1.1), a 'PESETA II' report from JRC (which however was not yet published by autumn 2012), a follow-up from 'PESETA I' (Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis) (Ciscar et al., 2009, 2011), and a forthcoming WHO/Europe report on 'The health effects of climate change in the European Union: evidence for action' ([6]).

([5]) See http://ec.europa.eu/research/environment/index_en.cfm?pg=climate.
([6]) See http://ec.europa.eu/health/indicators/other_indicators/environment/index_en.htm.

Box 1.1 The IPCC Fifth Assessment Report

The IPCC Fourth Assessment Report (IPCC, 2007a; b; c; d) was published in 2007. The Intergovernmental Panel on Climate Change (IPCC) is currently producing its Fifth Assessment Report (AR5), which consists of four volumes to be published in 2013 and 2014 ([7]).

The IPCC Working Group I (The Physical Science Basis) will publish its assessment in September 2013, while the IPCC Working Group II (Impacts, Adaptation and Vulnerability) will publish its assessment in March 2014. The report contains, amongst others, chapters addressing regions and thus in particular the WGII report's chapter on Europe is relevant.

Regarding the Arctic several major assessment reports on the impacts of climate change and on biodiversity have been published over the past years. These include the report 'Snow, Water, Ice and Permafrost in the Arctic' (AMAP, 2011) and the report 'Arctic Biodiversity Assessment — Arctic Biodiversity Trends 2010: Selected indicators of change' (Barry et al., 2010). Therefore, this EEA report does not provide a comprehensive assessment of climate change impacts in the Arctic and refers to these existing assessments, although the report does contain a few relevant indicators (e.g. on Arctic sea ice).

1.2.4 Report on adaptation in Europe

In parallel to this report, a second report is published by EEA, covering adaptation in Europe. Adaptation is understood as anticipating the adverse effects of climate change and taking appropriate action to prevent or minimise the damage they can cause. This second report presents the emerging European, national and subnational adaptation actions across Europe. The report will include case studies of implemented adaptation measures to illustrate the size of the adaptation challenge, provide examples of successful actions at various scales and lessons to be learned on adaptation actions at the European level. It also includes a brief comparison on transnational and national adaptation strategies and actions in Europe.

1.2.5 European Climate Adaptation Platform (Climate-ADAPT)

The information in the two EEA reports on climate change, impacts and vulnerability and on adaptation is supported by information in Climate-ADAPT ([8]), which is a publicly accessible, web-based platform, designed to support policymakers at EU, national, regional and local levels in the development of climate change adaptation measures and policies.

Climate-ADAPT is hosted and managed by the EEA, in collaboration with the European Commission. The website will be continuously updated with new information, for example from EU research projects, transnational projects, and national and local authorities. Climate-ADAPT is related to other relevant European information systems including the Biodiversity Information System for Europe ([9]), the Water Information System for Europe ([10]) and the land use data centre ([11]).

1.3 Background and policy framework

1.3.1 Global climate change mitigation and adaptation policies

The threat of climate change is being addressed globally by the UNFCCC. Its long-term objective is 'to stabilise atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.'

The UNFCCC has agreed, through the Copenhagen Accord of December 2009, to limit the global mean temperature increase since pre-industrial times ([12]) to less than 2 °C (the '2 °C target'). The 2 °C target will be reviewed in 2015, based on new scientific insights, to consider a possible goal of limiting the

([7]) See http://www.ipcc.ch/activities/activities.shtml.
([8]) See http://climate-adapt.eea.europa.eu.
([9]) See http://biodiversity.europa.eu.
([10]) See http://water.europa.eu.
([11]) See http://www.eea.europa.eu/highlights/themes/landuse/dc.
([12]) Pre-industrial being defined as 1850–1899.

global temperature increase to 1.5 °C (UNFCCC, 2009).

To achieve the '2 °C target substantial global reductions are needed of GHG emissions ('climate change mitigation'). However, with the currently implemented and planned global and European actions to reduce GHG emissions the average temperature increase could be well above + 2 °C by 2100. Even with achievement of the + 2 °C goal, many impacts are projected to occur globally and in Europe. Thus adaptation to climate change is needed in addition to mitigation of climate change.

The UNFCCC Copenhagen Accord of December 2009 recognised the need for enhanced action on adaptation to reduce vulnerability and build resilience in the most vulnerable developing countries. In a Fast Start Finance programme developed countries pledged to provide new and additional resources approaching USD 30 billion for the period 2010–2012 with balanced allocation between mitigation and adaptation. Long-term finance of USD 100 billion annually by 2020 from the developed countries was also agreed. The EU has pledged to contribute EUR 2.4 billion/year in 2010–2012 and with its fair share in the longer term international financing by 2020.

The Cancún Agreements, adopted at the UN Climate Conference in Mexico (December 2010), established a Green Climate Fund through which much of the funding will be channelled. A Cancún Adaptation Framework (UNFCCC, 2011) was established with the objective of enhancing action on adaptation, and has a specific focus on developing countries. The EU encourages the Adaptation Framework to enable Least Developed Countries (LDCs) to formulate and implement national adaptation plans.

The 'Durban Platform for Enhanced Action', adopted at the United Nations (UN) conference in South Africa (UNFCCC, 2012), agreed on a roadmap towards a new 'protocol, another legal instrument or an agreed outcome with legal force' by 2015, applicable to all Parties to the UN climate convention. It also foresees a second commitment period of the Kyoto Protocol, starting in 2013. Agreement was reached on the design and governance arrangements for the new Green Climate Fund. It also agreed on the composition (including the EU) and a list of activities for the Adaptation Committee.

The Nairobi work programme (NWP ([13])) of the UNFCCC has as its objective to assist all countries, but in particular developing countries, to improve their understanding and assessment of impacts, vulnerability and adaptation to climate change, and to make decisions on practical adaptation actions and measures on a sound scientific, technical and socio-economic basis. The EU supports the programme.

The UNFCCC requires all Parties to prepare and report 'National Communications' every three to five years ([14]). On climate change impacts, vulnerability and adaptation the current guidance for developed countries includes reporting on actions within the country, assistance to developing country Parties, and on research and systematic observation. The guidance on reporting leaves, however, much flexibility. EU Member States as well as the EU (prepared by the European Commission) have reported their fifth NC ([15]). However, since there was limited quantitative and comparable (across Europe) information in these reports on climate change impacts and vulnerability these have not been used for the preparation of this report.

1.3.2 EU White Paper on Adaptation and follow-up process

The rationale for a need to take action on climate change adaptation at the EU level is:

- many climate change impacts and adaptation measures have cross-border dimensions;
- climate impacts and adaptation affect single market and common policies;
- climate change vulnerabilities and adaptation trigger a new framework for solidarity;
- EU programmes could complement Member States' resources for adaptation;
- potential economies of scale can be significant for capacity building, research, information and data gathering, and knowledge transfer.

The Adaptation White Paper (2009) focused on four pillars to reduce the EU's vulnerability and improve its resilience:

([13]) See http://unfccc.int/adaptation/nairobi_work_programme/items/3633.php.
([14]) See http://unfccc.int/national_reports/annex_i_natcom_/items/1095.php.
([15]) See http://unfccc.int/national_reports/annex_i_natcom/submitted_natcom/items/4903.php.

1. develop and improve the knowledge base at regional level on climate change impacts, vulnerabilities mapping, costs and benefits of adaptation measures to inform policies at all levels of decision-making;

2. integrate adaptation into EU policies;

3. use a combination of policy instruments — market-based instruments, guidelines and public-private partnerships (PPPs) — to ensure effective delivery of adaptation;

4. work in partnership with the Member States and strengthen international cooperation on adaptation by mainstreaming adaptation into the EU's external policies.

A range of concrete initiatives have taken place since 2009 to integrate and mainstream adaptation into EU sectoral policies, for example related to water resources; marine environment; coastal areas; biodiversity; agriculture; forestry; infrastructure, urban environment, environmental assessment and disaster risk reduction. In the EEA report on adaptation in Europe these mainstreaming actions are described in detail. In addition, the European Climate-ADAPT provides an overview of main policy developments to integrate adaptation into EU sector policies ([16]).

The European Commission is working on a European Adaptation Strategy, due in 2013, which is further described in the EEA adaptation report. Mainstreaming of climate change is also a critical element of the draft 2014–2020 Multi-annual Financial Framework, which includes a proposal for increasing the share of climate-related expenditure (i.e. for climate change mitigation and adaptation as a whole) to at least 20 % of the EU budget (about EUR 200 billion) ([17]).

Indicators of climate change impacts and vulnerability and analyses of adaptation are needed to support mainstreaming adaptation in EU sector policies and in developing, implementing and evaluating adaptation policy actions and instruments. The two EEA reports (on climate change impacts and vulnerability and on adaptation) aim to be relevant for EU policy development and implementation but also for national and regional authorities and stakeholders being involved in either planning adaptation or implementing actions.

1.4 Climate change, impact, vulnerability and adaptation indicators

1.4.1 Types and definitions of indicators

The indicators presented in this report have broadly different main purposes (see Table 1.1), and are in different stages of development and usage, due to methodological challenges and often large uncertainties.

Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2007a).

Climate change impacts refer to the observed or projected effects of climate change on natural and human systems. In the case of projected effects, these projections often refer to 'potential impacts', which are those impacts that may occur given a projected change in climate, without considering adaptation.

The Impact Assessment to the European Commission's 2009 White Paper on Adaptation ([18]) describes the purpose and scope of indicators, as to 'build a structured information dataset to better

Table 1.1 Type of indicator and main purpose

Type of indicator	Main purpose
Climate change (Chapter 2)	Understanding the causes of impacts of climate change
Climate change impacts (Chapters 3 and 4)	Understanding consequences of climate change and determining vulnerability to climate change
Social, economic, health and ecological vulnerability (Chapters 4 and 5)	Monitoring and understanding vulnerability, identifying adaptation needs, evaluating adaptation strategies and action

([16]) See http://climate-adapt.eea.europa.eu/web/guest/eu-sector-policy/general.
([17]) See http://ec.europa.eu/budget/reform.
([18]) See http://ec.europa.eu/clima/policies/adaptation/index_en.htm.

understand the territorial and sectoral distribution of vulnerability to climate change impacts. Vulnerability is defined as a function of 1) the exposure to climate change impacts,
2) the sensitivity and 3) the adaptive capacity of a system or territory)'.

For a further discussion of the use of the concepts *vulnerability* and *risk*, the reader is referred to Section 1.7.

1.4.2 Criteria for indicator selection and changes since the 2008 report

The selection of indicators for this report was guided by a number of criteria and documented in an ETC/CCA technical paper ([19]). This technical paper used 13 criteria grouped into the following themes:

1. Policy relevance;
2. Causal links to climate change;
3. Methodological and data quality, and data accessibility;
4. Robustness and known uncertainty;
5. Acceptance and intelligibility.

Some criteria were adapted to address the specific characteristics of those parts of indicators addressing 'observed change' and 'future projections'. The final selection of indicators was done in consensus with the authors, considering all criteria mentioned above as well as the opinions of the external Advisory Group.

The number and quality of the underlying information on climate change impacts, vulnerability and risks relevant for Europe has increased since the publication of the previous climate change indicator report of 2008. In the 2012 report several new indicators have been included, and some indicators have been extended to include additional information. A few indicators have been dropped because they do not fulfil the updated criteria for EEA indicators (see Section 1.4.2), but information on these topics is still presented in this report.

Table 1.2 shows the main changes in indicators covered in the 2012 report compared to the 2008 report. Changes in the names of indicators without major changes in content and movements of indicators from one section to another are not reported in this table.

Table 1.2 Changes in indicators 2008–2012

Section	New or modified indicator in 2012	Replaced or removed indicator from 2008 report
Key climate variables	Storms	Storms and storm surges in Europe
Cryosphere	Permafrost	Mountain permafrost
	Arctic and Baltic sea ice	Arctic sea ice
Oceans and marine environment	Ocean acidification	
	Ocean heat content	
Coastal zones	Storm surges	
Freshwater quantity and quality		Freshwater biodiversity and water quality
Soil	Soil erosion	Soil erosion by water
	Land degradation and desertification	
Agriculture	Water-limited crop productivity	Crop yield variability
		Agriculture and forestry
Human health	Floods and health	Heat and health
	Extreme temperatures and health	Air pollution by ozone
	Air pollution by ozone and health	Water- and food-borne diseases
Energy	Heating degree days	
Economic sectors		Direct losses from river flood disasters
		Coastal areas

([19]) ETC/CCA Technical paper on evaluation of climate change state, impact and vulnerability indicators (draft 2011).

1.4.3 Overview of main EU indicator developments

In the EU a number of indicator sets exist or are being developed for various policy purposes. These initiatives do not yet explicitly take climate change impact, vulnerability and adaptation aspects into account, although the indicator global temperature increase is included in a few sets (either as contextual or as key indicator).

The following main EU policy processes and related indicators exist:

- European Commission (including Eurostat):
    - Europe 2020 indicators ([20]);
    - A resource efficient Europe by 2020 ([21]);
    - GDP and beyond ([22]);
    - Structural indicators ([23]);
    - Sustainable Development Indicators (SDI) ([24]);
    - Annual Environment Policy Review ([25]);
- Environmental Accounts ([26]) (Eurostat and EEA);
- EEA core set of indicators (CSI) ([27]) and EEA environmental and sectoral indicators;
- The JRC develops and maintains a range of indicators (e.g. on soil, forests).

The EEA hosts about 225 indicators across 12 environmental and sectoral themes, including for example on water, biodiversity, marine and various sectors and also the 2008 indicator set on climate change, impacts and vulnerability. In 2011/2012 the EEA has reviewed its indicators, including the EEA core set (of 37 indicators). The EEA core set contains two indicators related to climate change: GHG concentration in the atmosphere (not presented in this report) and global/European temperature (see Section 2.2.2). The EEA, together with the European Commission and interested member countries, will discuss proposals for further prioritisation of indicators until the end of 2013. This report on climate change impact and vulnerability indicators will be an important input to this process. Further details on EU indicator sets and their relevance for climate change are presented in Chapter 6.

1.4.4 National initiatives on indicators

An important part of the adaptation to climate change is local or national. There is therefore a need to develop climate change impact and vulnerability indicators at national and subnational levels. To allow sharing of good practice and comparative analysis that can inform policymaking at the European level it is desirable to achieve, as far as possible, consistency in methodologies and data collection, across countries.

Several countries have started developing indicator sets. Here two examples are mentioned. The United Kingdom (United Kingdom) published its first Climate Change Risk Assessment (CCRA) in January 2012 (Defra, 2012). It contains a range of indicators on projected climate change impact and vulnerability that are similar to those covered in this report, but an in-depth comparison has not yet taken place. The adaptation sub-committee (ASC) of the independent Climate Change Committee published a second and third report of the United Kingdom's preparedness (ASC, 2011; 2012) that sets out a range of indicators against which the United Kingdom's progress can be measured. The UK government will in future undertake a study of the Economics of Climate Resilience, focusing on policy options for the key risks identified, towards a future National Adaptation Programme. The ASC will continue to develop and implement their indicator framework for measuring progress on preparing for climate change in the United Kingdom and develop a more comprehensive set of indicators across the priority areas for adaptation, including those not covered so far (emergency planning, managing natural resources and other infrastructure sectors).

In 2008 Germany adopted the 'German Strategy for Adaptation to Climate Change' (DAS) (Deutsche Bundesregierung, 2008). It was followed by the 'Adaptation Action Plan (APA) of the German Adaptation Strategy' (Deutsche Bundesregierung, 2011) adopted in August 2011. The 'Adaptation Action Plan' sets strategic priorities including the expansion of the knowledge base on climate change impacts for all sectors, the subsequent prioritisation of climate risks and, based on this, the definition of key areas for actions or priority measures of the Federal Government (some of the measures in joint

([20]) See http://ec.europa.eu/europe2020/index_en.htm and http://epp.eurostat.ec.europa.eu/portal/page/portal/europe_2020_indicators/headline_indicators.
([21]) See http://ec.europa.eu/resource-efficient-europe/.
([22]) See http://epp.eurostat.ec.europa.eu/portal/page/portal/gdp_and_beyond/introduction.
([23]) See http://epp.eurostat.ec.europa.eu/portal/page/portal/structural_indicators/introduction.
([24]) See http://epp.eurostat.ec.europa.eu/portal/page/portal/sdi/indicators.
([25]) See http://ec.europa.eu/environment/policyreview.htm.
([26]) See http://epp.eurostat.ec.europa.eu/portal/page/portal/environmental_accounts/introduction.
([27]) See http://www.eea.europa.eu/data-and-maps/indicators#c7=all&c5=&c0=10&b_start=0&c10=CSI.

responsibility with the Federal states). A supplement Adaptation Action Plan is planned for 2014. It will rely on an updated comprehensive vulnerability assessment for Germany. An initial evaluation report on DAS and APA is projected for the end of 2014. An indicator concept ('Establishment of an Indicator Concept for the German Strategy on Adaptation to Climate Change') (Schönthaler et al., 2010) is currently being developed and agreed upon, underpinned by various ongoing studies. The 2010 report contains an initial set of indicators for adaptation at federal level and a structure for a national report on indicators. In 2011 another report on indicators was published (Schönthaler et al., 2011). The indicators will be consolidated in the coming years.

1.5 Emissions and socio-economic scenarios for projections

Section 1.5.1 presents the global emissions scenarios underlying projections of climate and climate impact indicators in Chapters 2, 3 and 4 as well as assessments of vulnerability to climate change in Chapter 5. Section 1.5.2 presents additional demographic and socio-economic scenarios for Europe that have been used in the vulnerability assessments in Chapter 5.

1.5.1 Emissions scenarios

The projected indicators in this report are based on a wide range of studies published in peer-reviewed academic papers and reports of international organisations. Many of these refer to or use generally available emissions and/or climate scenarios, but there is inevitably variation in the choice and use of emissions scenarios and climate model runs for the assessments of individual indicators.

Most climate projections use the storylines and the associated emissions scenarios published by the IPCC in 2000 in the Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000). These scenarios, often called the SRES scenarios, represent the outcome of different assumptions about the future course of economic development, demography and technological change. The SRES scenarios are 'baseline' (or 'reference') scenarios, which means that they do not take into account specific agreements or policy measures aimed at limiting the emission of GHG emissions (e.g. the Kyoto Protocol to the UNFCCC). The SRES emissions scenarios are organised into families, which contain scenarios that are based on similar assumptions regarding demographic, economic and technological development. The six families of emissions scenarios discussed in the IPCC's Third Assessment Report (TAR) and Fourth Assessment Report (AR4) are A1FI ('fossil intensive'), A1B ('base'), A1T ('technology'), A2, B1 and B2 (see Box 1.2).

Box 1.2 The IPCC Special Report on Emissions Scenarios (SRES)

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

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

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

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

Source: Nakicenovic and Swart, 2000.

The next generation of scenarios to support climate change research and assessments are called Representative Concentration Pathways (RCPs). These scenarios prescribe trajectories for the concentrations (rather than the emissions) of GHGs and therefore are not simply updates of the SRES emissions scenarios (van Vuuren et al., 2011). The RCPs provide a consistent set of greenhouse concentration trajectories that are intended to serve as input for climate modelling, pattern scaling and atmospheric chemistry modelling. They are named from RCP 2.6 to RCP 8.5 according to their radiative forcing level in the year 2100. Unlike SRES, the RCPs cover the full range of stabilisation, mitigation and baseline emissions scenarios available in the scientific literature and thus facilitate the mapping of all plausible climate evolutions

Table 1.3 explains which emissions scenarios and climate models were used in the projections of indicators presented in this report. Some vulnerability and risk assessments in Chapter 5

Table 1.3 Emissions scenarios and climate models used in projections ([a])

Section	Indicator	Emissions scenario(s)	Climate model(s) ([b])	Time period(s) ([c])
2.2.2	Global and European temperature	*Global:* A1B, A2, B1 *European:* A1B	 GCM ensemble RCM ensemble based on 5 GCMs	 21st century 2030s, 2080s
2.2.3	Temperature extremes	A1B	6 RCM ensemble	2030s, 2080s
2.2.4	Mean precipitation	A1B	RCM ensemble based on 5 GCMs	2080s
2.2.5	Precipitation extremes		Single RCM nested in 6 GCMs	2080s
2.2.6	Storms	A1B	9 GCM and 11 RCM ensemble	2080s
2.3.2	Snow cover	A1B	6 RCM ensemble	2050s
2.3.4	Glaciers	A1B	10 GCM ensemble	21st century
3.2.2	Global and European sea-level rise	*Global:* Various scenarios	*Global:* Various sources	*Global:* 2100
3.3.2	River flow	A1B	12 RCM ensemble	2050s
3.3.3	River floods	A1B	12 RCM ensemble	2050s
3.3.4	River flow drought	A1B	12 RCM ensemble	2050s
3.4.4	Distribution of plant species	S550E stabilisation and IMAGE baseline scenario	HadCM2	2100
3.4.5	Distribution and abundance of animal species	*Levinsky* et al.*:* A2, B1 *ALARM project:* A2	 Unspecified HadCM3	 2080s 2030s, 2060s
3.4.6	Species interactions	A2	HadCM3	2060s
4.1.3	Agrophenology	A1B	RACMO, HadRCM3	2031-2050
4.1.4	Water-limited crop productivity	A1B A1B A1B	RACMO, HadRCM3 12 RCM ensemble ECHAM5, HadCM3	2031–2050 2050s 2030s
4.1.5	Water requirement	A1B	HIRHAM (DMI) RCM	2080s
4.2.3	Forest fires	A1B	RACMO2 driven by ECHAM5	2080s
	The information below is not presented in indicator format in this report			
4.7.2	Tourism climatic index	A2	5 RCM ensemble (PRUDENCE)	2080s
5.2	River flooding, water scarcity and droughts	A2, B2	GCM/RCM ensemble	2050s
5.3	Coastal flooding	A2, B1	Uniform sea-level rise	2100
5.4	Integrated vulnerability assessment	A1B	CCLM RCM	2080s

Note: ([a]) The table only lists quantitative projections of future changes in the form of graphs or maps. National or subnational projections shown in numbered text boxes are not considered.

([b]) Unless otherwise specified, RCM ensemble projections are derived from the ENSEMBLES FP6 project (http://www.ensembles-eu.org).

([c]) If a decade is specified by an ending 's', this stands for the 30-year period centred on this decade (e.g. '2030s' refer to 2021–2050 and '2080s' to 2071–2100).

consider climate change along with other socio-economic developments. The underlying socio-economic and demographic projections are explained in Section 1.5.2.

1.5.2 Socio-economic scenarios

The risks and vulnerabilities of regions, sectors and population groups are determined by changes in climatic conditions as well as by demographic, social, economic, political, technological and environmental changes. (For notational convenience, the following text refers to the full range of non-climatic developments simply as 'socio-economic developments'.) Several studies assessing future consequences of climate change use complex models and other methods that incorporate assumptions and scenarios for socio-economic developments in addition to climate projections. On the one hand, the integration of climatic and socio-economic scenarios allows for a more realistic assessment of future consequences of climate change, in particular if future socio-economic developments are fairly well known (e.g. demographic changes). They also facilitate estimates of the relative importance of various changes, such as rising sea level versus population migration, in climate-sensitive risks (but such analyses are not always done). On the other hand, the inclusion of uncertain socio-economic scenarios may further increase the uncertainty of projections, which may make them less amenable to decision-makers.

Socio-economic developments have a significant (and often dominant) role in the exposure and vulnerabilities of regions, sectors or population groups to climatic and other hazards. The social, technological, economic, environmental and political developments determine the socio-economic context within which climate change is experienced, and can therefore strongly influence climate change-related risks and vulnerabilities ([28]). Key socio-economic variables include: economic wealth and commodity prices developments; sectoral developments and technological innovation; population dynamics (e.g. growth, ageing and spatial distribution); consumption patterns and lifestyles; settlement patterns (e.g. urban growth and sprawl); infrastructure developments; land cover and land use. Strong inter-linkages and feedbacks exist between the different drivers of socio-economic change, which require a consistent and comprehensive consideration in scenario studies.

Most recent integrated assessments of climate change in Europe, including those presented in this report, are based on the IPCC SRES (see Section 1.5.1). The SRES scenarios provide internally consistent socio-economic storylines and GHG emissions scenarios for four world regions that can support climate change and climate impact assessments. The studies supporting the indicators presented in Chapters 2, 3 and 4 of this report generally rely on the SRES emissions scenarios (see Table 1.3 for details). The projects presented in the chapter on vulnerability to climate change (Chapter 5) use a range of SRES socio-economic and climate scenarios.

Recently, alternative socio-economic scenarios have been developed globally and at the European scale in connection with the IPCC AR5 (see Box 1.1). In Europe, this has occurred, for example, in connection with the study on 'Climate adaptation — modelling water scenarios and sectoral impacts' (ClimWatAdapt) ([29]). Section 5.2 presents selected results for floods and for water scarcity and droughts. The ClimWatAdapt project and its predecessor SCENES envisaged an iterative participatory process to develop (both qualitative and quantitative) scenarios of Europe's freshwater up to 2050, entitled 'Economy First (EcF)', 'Fortress Europe (FoE)', 'Policy Rules (PoR)' and 'Sustainability Eventually (SuE)'.

The next generation of emissions and socio-economic scenarios will serve IPCC's AR5. (Moss et al., 2010) describes in detail the process by which they are being developed to take advantage of the latest scientific advances on the response of the Earth system to changes in radiative forcing as well as knowledge on how societies respond through changes in technology, economies, lifestyle and policy. The research community took up the task of developing new scenarios by departing from the sequential approach of the latest set of SRES scenarios from the IPCC. Their approach includes the parallel development of new climate scenarios (based on the four representative concentration pathways or RCPs (van Vuuren et al., 2011) and new socio-economic scenarios with a more regional approach that enable exploration of important socio-economic uncertainties affecting both adaptation and mitigation.. The new scenarios

([28]) See Section 1.7 for a discussion of the terms 'vulnerability' and 'risk' and their use in this report.
([29]) See http://www.climwatadapt.eu.

assume there are policy actions to mitigate climate change and are expected to factor in the economic recession. Integration of the climate and socio-economic scenarios (in 2013/2014) is expected to provide insights into the costs, benefits and risks of different climate futures, policies and socio-economic development pathways.

The availability of EU-wide and disaggregated (e.g. NUTS3 level) future scenarios for key socio-economic variables is limited until new results in relation to the IPCC AR5 become available (this is expected in late 2012). This difficulty is illustrated by the fact that the projects presented in Chapter 5 of this report apply a variety of scenarios to study different aspects of vulnerability to climate change in Europe.

The ESPON-DEMIFER ('Demographic and Migratory Flows Affecting European Regions and Cities') project recently provided population projections for Europe until 2050 at NUTS2 level for a series of indicators (De Beer et al., 2010). Other initiatives addressed specifically the economic and social consequences of demographic change on regional and urban development (Hungarian EU Presidency, 2011) or link European socio-economic developments to global trends (EEA, 2010c) along the social, technological, economic, environmental and political dimensions.

Some relevant demographic and economic projections for Europe from a recent report of the European Commission are summarised below (EC, 2011).

- *Fertility rates rise slightly*. EU total fertility rate is projected to rise from 1.59 in 2010 to 1.64 by 2030 and further to 1.71 by 2060.

- *Further life expectancy gains are projected*. In the EU, life expectancy at birth for males is projected to increase from 76.7 in 2010 to 84.6 in 2060 and for females from 82.5 in 2008 to 89.1 in 2060.

- *Inward net migration to the EU continues, but decelerates*. Annual net inflows are projected to increase from about 1 018 000 people in 2010 (equivalent to 0.2 % of the natural EU population) to 1 217 000 by 2020 and thereafter declining to 878 000 people by 2060.

- *EU population is projected to increase up to 2040 and decline thereafter*. EU population is projected to increase (from 501 million in 2010) up to 2040 by almost 5 %, when it will peak (at 526 million). Thereafter, a steady decline occurs and the population in 2060 will be slightly higher than in 2010, at 517 million.

- *EU population will undergo significant changes in its age structure*. The proportion of young people (aged 0–14) is projected to remain fairly constant by 2060 (around 15 %), while those aged 15–64 will become a substantially smaller share, declining from 67 % to 56 %. Those aged 65 and over will become a much larger share (rising from 18 % to 30 % of the population), and those aged 80 and over (rising from 5 % to 12 %) will become almost as numerous as the young population in 2060.

- *The old-age dependency ratio in the EU will double*. The demographic old-age dependency ratio (people aged 65 or above relative to those aged 15–64) is projected to increase from 26 % to 52.5 % in the EU as a whole over the projection period. This entails that the EU would move from having 4 working-age people for every person aged over 65 years to 2 working-age persons.

- *Labour supply will decline because of the projected population trends*. Total labour supply in the EU-27 is projected to increase by 1.4 % from 2010 to 2020 (age group 20–64), mainly due to the increase in women's labour supply. During the period 2020 to 2060 the total labour force is projected to decrease by 11.8 %.

- *Markedly lower potential economic growth rates are projected for the EU*. The annual average potential gross domestic product (GDP) growth rate is projected to remain quite stable over the long term. After an average potential growth of 1.5 % up to 2020, a slight rebound to 1.6 % is projected in the period 2021–2030 while over the remainder of the projection period (2031–2060) a slowdown to 1.3 % emerges. Following the largest economic crisis in many decades, potential GDP growth has been revised downwards in 2010 and the surrounding years, compared with the earlier baseline projection published in 2009.

The study shows furthermore that regarding these demographic and macro-economic projections there is a wide diversity across and within countries.

The ESPON-DEMIFER projections for 2050 are similar to the abovementioned projections. For example, they conclude that if economic conditions are poor, if activity rates will not increase and if immigration will be low, 55–70 % of the NUTS2 regions in Europe will experience a decline of the labour force by 10 % or more. In most regions in eastern and southern parts of Europe, the labour force may even decrease by more than 30 %. Use of such detailed demographic and macro-economic projections within future EU-wide climate change vulnerability assessments could potentially improve the quality and consistency of such assessments.

1.6 Uncertainty in observations and projections

Data on observed and projected climate change and its impacts is always associated with some uncertainty. This section discusses the main sources of uncertainty relevant for this report, and how uncertainties are addressed and communicated in this report, in particular in the key messages. Note that the term 'uncertainty' is used by scientists to refer to partial, or imperfect, information. Thus, the direction or even the approximate magnitude of a phenomenon may be known although the exact magnitude is not known. For example, a scientific projection of global mean temperature for a given emissions scenario may report a best estimate of 3 °C, with an uncertainty range of 2–4.5 °C. The uncertainty interval reflects the impossibility to forecast *exactly* what will happen. However, knowing that it is virtually certain that the Earth will continue to warm and that the future warming is likely within a certain range still provides highly relevant information to decision-makers concerned with climate change mitigation as well as adaptation.

1.6.1 Sources of uncertainty

Uncertainties in indicators presented in this report arise primarily from the following sources. Note that some sources of uncertainty can be quantified whereas others cannot. Furthermore, some of them can in principle be reduced by further research whereas others cannot.

1. *Measurement errors* resulting from imperfect observational instruments (e.g. rain gauges) and/or data processing (e.g. algorithms for estimating surface temperature based on satellite data).

2. *Aggregation errors* resulting from incomplete temporal and/or spatial data coverage. Most indicators presented in this report combine measurement from a limited number of locations (e.g. meteorological observation stations) and from discrete points in time to make aggregate statements on large regions and for whole time periods. Such an aggregation introduces uncertainties, in particular when the measure network is scarce and when the phenomenon exhibits large variations across space and/or time.

3. *Natural climate variability* resulting from unpredictable natural processes either within the climate system (e.g. atmospheric and oceanic variability) or outside the climate system (e.g. future volcanic eruptions).

4. *Future emissions of greenhouse gases* determine the magnitude of the human influence on the climate system and therefore the magnitude and rate of future climate change. Controlling (net) GHG emissions is the only way, besides highly controversial geo-engineering, to limit global climate change.

5. *Uncertainties in climate models* resulting from an incomplete understanding of the Earth system (e.g. dynamic ice sheet processes or methane release from permafrost areas and methane hydrates) and/or from the limited resolution of climate models (e.g. hampering the explicit resolution of cloud physics). These uncertainties are particularly relevant in the context of positive and negative feedback processes.

6. *Complex interaction of climatic and non-climatic factors*. This complex cause-effect web hampers the attribution of observed environmental or social changes to past changes in climate as well as the projection of future climate impacts.

7. *Future changes in socio-economic, demographic and technological factors as well as in societal preferences and political priorities*. Changes in non-climatic variables interact with climate change to determine the impacts on environment and society. Changes in preferences affect whether a certain 'climate impact' (e.g. a decrease in biodiversity) is seen as a small or big problem; such changes are particularly relevant in the formulation of long-term adaptation policies.

The relative importance of the various sources of uncertainty depends on the target system, the climate and non-climate factors it is sensitive to, and the time horizon of the assessment. For example, uncertainty about future emissions of long-lived GHGs becomes the dominant source of uncertainty for changes in global mean temperature on time scales of 50 years or more but it is of limited importance for short-term climate change projections (Cox and Stephenson, 2007; Hawkins and Sutton, 2009; Yip et al., 2011).

Another source of uncertainty not explicitly mentioned in the list above is the downscaling of climate or climate impact projections. Most projections in this report cover all of Europe (i.e. EEA member and cooperating countries). Such a broad coverage necessarily limits the level of detail at which regional climatic, environmental and other features can be considered, and the spatial resolution at which projections can be presented. Decisions on the management of climate-sensitive resources at the national, regional and local levels require more detailed projections at a higher spatial resolution than can be presented in this report. A key element of providing such detailed projections is the downscaling of climate projections (see Chapter 2), which constitutes another important element of uncertainty in climate and climate impact projects at the national and subnational levels.

Further information on sources of uncertainty can be found in the uncertainty guidance of Climate-ADAPT ([30]).

1.6.2 Addressing and communicating uncertainty

The lack of perfect information is a common feature in all areas of policymaking. Uncertainties must not prevent taking decisions but it is in the interest of decision-makers to be aware of the degree of uncertainty associated with specific data sources so that they can consider the range of plausible developments in their decisions. The importance of uncertainties about climate change and its impacts for a particular decision depends on factors such as the time horizon and reversibility of the decision, the importance of climate factors for the decision, and the costs of buffering the decision against uncertain developments. For example, when uncertainties are very large, it is often (but not always) prudent to focus on 'no regrets' and 'win-win' adaptation strategies that address adaptation to (uncertain) climate change jointly with other societal goals, thereby limiting the additional cost of the adaptation component. This topic is addressed in more detail in the parallel report on Adaptation in Europe (see Section 1.2.4).

Compared to the 2008 report, increased efforts were made in this report to describe the accuracy and robustness of data underlying indicators as clearly as possible. The approach followed in this report was inspired by the considerable experience of the IPCC in communicating uncertainties (Mastrandrea et al., 2010) and by the NUSAP approach (Funtowicz and Ravetz, 1990). Over a period of 10 years, the IPCC has developed and refined a 'calibrated language' to express the confidence in and/or likelihood of specific findings, which is applied in most key messages of IPCC reports. However, following the IPCC uncertainty guidance in this report is not feasible because the small number of experts involved in producing this report prohibits quantitative expert assessments of confidence and uncertainty.

In this report uncertainty is addressed by:

1. choosing carefully the type of statement, making clear the specific context and possibilities for generalisation;

2. choosing the appropriate level of precision, from the existence of an effect to a precise value;

3. reporting the pedigree of a statement, including main factors known to affect the confidence that can be put in a specific data set or conclusion.

These three main elements of addressing uncertainties in this report are outlined below.

Appropriate choice of type of statement

Several different types of statements can be distinguished in this report:

1. observation of a climate variable;

2. observation of a statistically significant (change in) trend of a climate variable;

3. projection of a climate variable into the future;

4. observation of a climate-sensitive 'impact' variable (i.e. a change in an environmental or social phenomenon that is sensitive to changes in climate);

5. observation of a significant (change in) trend of a climate-sensitive 'impact' variable;

6. attribution of a change in a climate-sensitive 'impact' variable to (anthropogenic) climate change;

([30]) See http://climate-adapt.eea.europa.eu/uncertainty-guidance.

7. projection of a climate-sensitive 'impact' variable;

8. identification of adaptation needs.

Different types of statements are subject to different sources of uncertainty. As a general rule, the (sources of) uncertainty increases from observations to attributions and projections, and from climate variables to climate impacts and adaptation needs (see Figure 1.1). For example, observations of a climate or climate impact variably (numbers 1 and 4 above) can be made for short time series whereas statements about statistically significant trends (numbers 2 and 5 above) require longer time series and the consideration of natural interannual variability. With respect to projections, the future trajectory of GHG emissions is a relevant source of uncertainty for long-term climate and climate impact projections but not for observations of the past. Also, near-term projections (e.g. up to 30 years) show limited sensitivity to future GHG emissions scenarios due to the long residence time of most GHGs and the large thermal inertia of the climate system.

Key messages are formulated so that it is clear what type of statement they make. Note that the type of statement supported by a particular dataset may depend on the spatial scale. For example, a significant climate trend may be detectable at the continental scale (where year-to-year variability is low) but not in each region (where year-to-year variability is higher and regional factors may be important). For the sake of clarity, the combination of different types of statements in a single message is generally avoided.

Appropriate choice of the level of precision

It is useful to consider several different levels of precision (or quantification) in key messages, which are ordered here from least to most precise (see also the IPCC uncertainty guidance (IPCC, 2005):

1. existence of effect (but the direction is ambiguous or unpredictable);

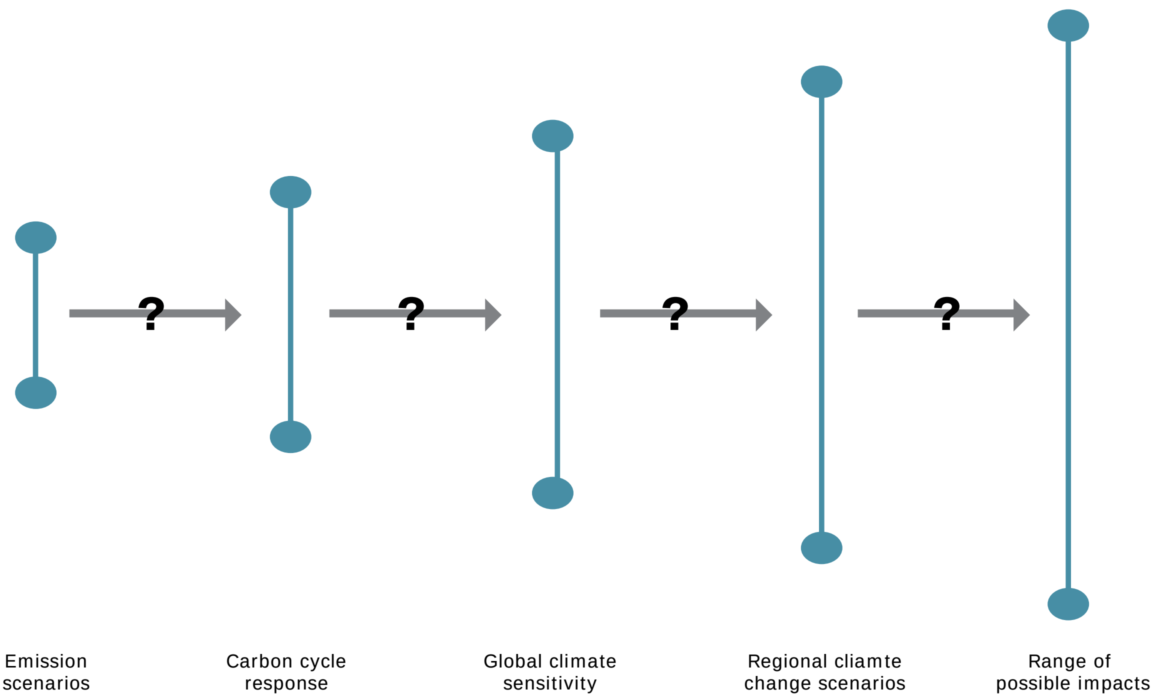
2. direction of change or trend;

3. order of magnitude of a change (e.g. indicated by a semi-quantitative verbal statement);

4. range or confidence interval;

5. single value (implying confidence in all significant digits).

Figure 1.1 Cascade of uncertainties in climate impact assessments



Note: The length of the bars represents the magnitude of the uncertainty.

Source: Ahmad et al., 2007, figure 2–2.

As a general rule, key messages are formulated at the highest level of precision that is justified by the underlying data. Furthermore, related statements with different levels of precision (e.g. observation vs. projection) are clearly separated to indicate the precision of each individual statement.

Explicit information on the pedigree of information and uncertainty

Key messages make explicit whether and how key sources of uncertainty have been considered in the underlying dataset wherever relevant and feasible. For example, a key message on future climate change would indicate how many emissions scenarios and climate models were considered to produce the dataset.

1.7 Definition of vulnerability and risk

1.7.1 Diverse use of terms

The terms vulnerability and risk are often used to describe the potential (adverse) effects of climate change on ecosystems, infrastructure, economic sectors, social groups, communities and regions. These terms are attractive because they are both intuitively understandable to a large audience and rooted in several scholarly communities contributing to climate change impact, vulnerability and risk assessments. However, the fact that these terms are used rather differently across, and sometimes within these scholarly communities, can give rise to misunderstandings (Füssel, 2007; O'Brien et al., 2007). In general, use of the terms vulnerability and risk is unproblematic if they are applied in a rather generic, intuitive sense. However, whenever one of these terms is used quantitatively (e.g. to compare the vulnerability of different regions or population groups) or to advise on suitable actions to reduce vulnerability or risk, it is necessary to specify clearly how the term is understood.

This EEA report includes contributions that use the term vulnerability according to its use in the climate change, disaster risk and public health communities. The distinction between the various concepts is explained below and also in the IPCC SREX (IPCC, 2012).

The EEA accepts the existence of various definitions and interpretations of vulnerability and risks in climate change science and policy. The approach in this report was therefore not to choose one specific definition of vulnerability and risk over others but to provide further clarification where needed. Hence, the use of these terms in this report always follows the underlying literature, and further explanation is provided where needed.

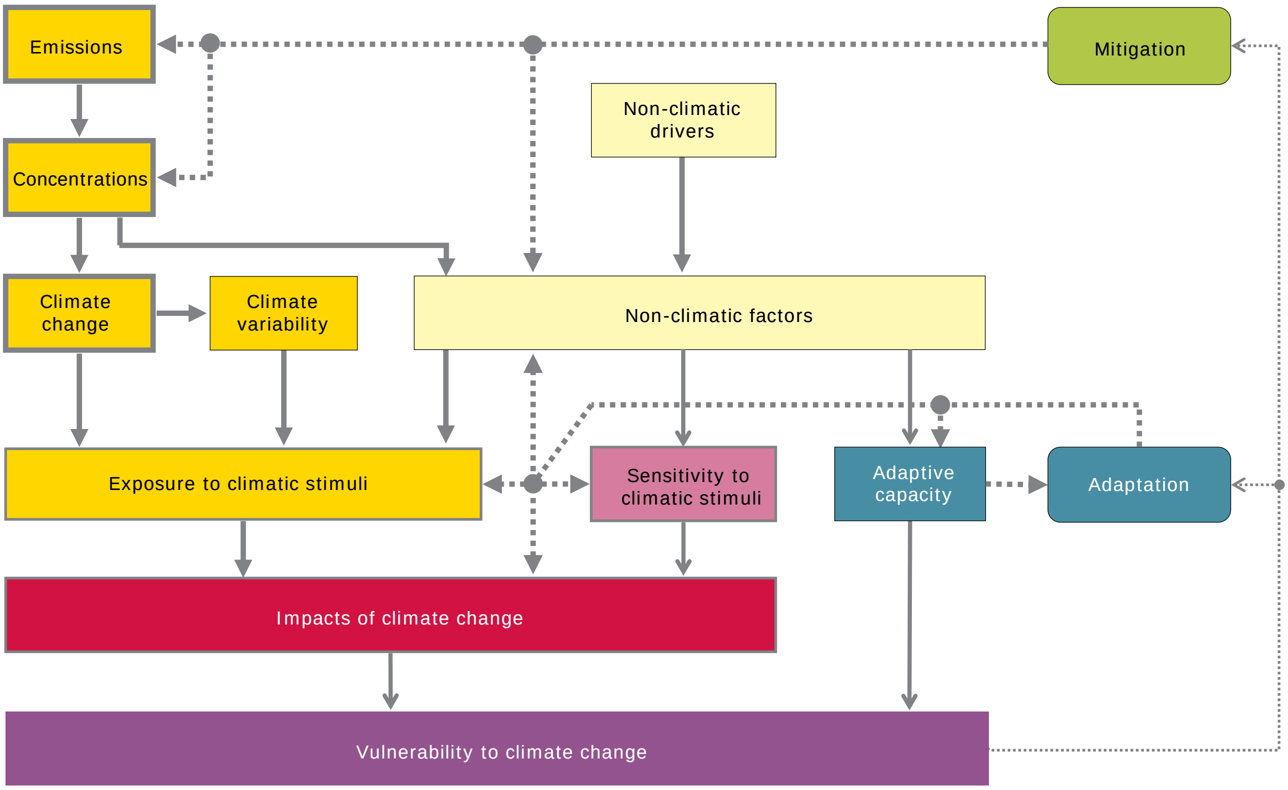
The term vulnerability is generally used to describe that a valued characteristic of a system (e.g. the income basis of a community or the carbon stock of a forest ecosystem) is threatened due to exposure to one or more stressors (e.g. extreme weather events or long-term climate change). Different uses of vulnerability in the climate change context are distinguished by the following factors:

- whether they consider only internal characteristics of the vulnerable system or also characteristics of the external stressor(s) it is exposed to;
- whether they refer to human systems, natural systems, coupled human-environment systems and/or built infrastructure;
- whether they consider only short-onset events (e.g. tropical cyclones) or also continuous changes (e.g. long-term changes in mean temperature);
- whether they consider climate change in isolation or together with other environmental and/or socio-economic developments;
- the level of aggregation and the extent of value judgements required for doing so (e.g. for aggregating market and non-market impacts, for aggregating impacts affecting different groups of people at different points in time, and for aggregating impact projections associated with different levels of uncertainty);
- the level of quantification (e.g. high/medium/ low vs. exact numbers).

1.7.2 'Outcome' interpretation of vulnerability to climate change

The IPCC in its AR4 defined vulnerability (to climate change) as follows: '*Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.*' (IPCC, 2007b, p. 883) (see Figure 1.2). According to this definition, vulnerability is an integrated measure of the expected magnitude of adverse effects to a system caused by a given level of certain external stressors, taking into account feasible adaptation.

Figure 1.2 IPCC vulnerability assessment framework



Source: Adapted from Füssel and Klein, 2006.

This definition highlights that the consequences of climate change for a system, in particular for a social system or community, are determined by factors that determine the potential impacts of climate change (e.g. the magnitude of sea-level rise and the morphology of a coastline) as well as by factors that determine the adaptive capacity and coping capacity of the affected population (e.g. the level of disaster preparedness and the availability of financial resources).

Vulnerability to climate change as defined in the IPCC AR4 is the final outcome of an assessment that considers biogeophysical as well as socio-economic factors (where relevant). However, the concept of vulnerability is used differently in several scientific disciplines contributing to climate change assessments, including natural hazards research, ecology, public health, poverty and development, and sustainability science.

The 'outcome interpretation' of vulnerability to climate change has been used in several studies attempting to quantify vulnerability to climate change at the European level, including ClimWatAdapt (see Section 5.2), Regions 2020 and ESPON Climate (see Section 5.3). It also underlies the EU White Paper on Adaptation (EC, 2009) and the UNFCCC.

1.7.3 Vulnerability and risk in disaster risk assessment

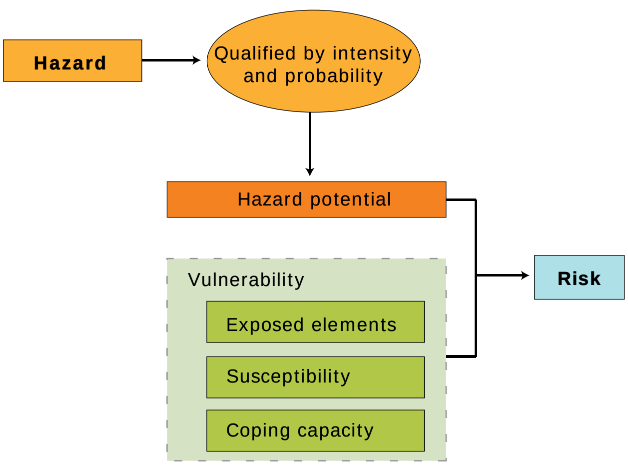
Standard applications of disaster risk assessment are primarily concerned with short-term (discrete) natural hazards, assuming known hazards and present (fixed) vulnerability (Downing et al., 1999). In contrast, key characteristics of anthropogenic climate change are that it is long term and dynamical, it is global but spatially heterogeneous, and it involves multiple climatic hazards associated with large uncertainties. In a nutshell, the hazard events considered in disaster risk assessment are limited in time and space and rather well known (even though their probability may be very uncertain) whereas anthropogenic climate change is a continuous stressor of global extent that involves unprecedented climate conditions.

The term risk is also interpreted in different ways (Coburn et al., 1994; Adams, 1995; Cardona, 2003). It is not defined in the IPCC AR4 even though it is used occasionally. The risk concept most relevant in the present context, which is sometimes referred to as disaster risk or outcome risk, is defined as 'expected losses […] due to a particular hazard for a given area and reference period' (UNDHA, 1993).

A key aspect of the approach applied by the disaster risk community is the clear distinction between two factors that determine the risk to a particular system: the hazard, which is a 'potentially damaging physical event, phenomenon or human activity characterised by its location, intensity, frequency and probability', and the vulnerability, which denotes the 'relationship between the severity of hazard and the degree of damage caused' to an exposed element (UNDHA, 1993; Coburn et al., 1994; United Nations, 2004). If a risk assessment considers several potentially exposed elements in different locations, their differential exposure to hazards has to be considered as well (see Figure 1.3).

It has been argued that the indicators used for determining vulnerability in the disaster risk context are often in practice quite similar to those describing the 'sensitivity' of the system's components to climatic stimuli in the climate change community, and that vulnerability in the climate change community is sometimes used similar to risk in the disaster risk community (Costa and Kropp, 2012). Note also that in practice there appear to be few systematic differences between national-level climate change assessments denoted as vulnerability and risk assessments, such as those in Germany (Zebisch et al., 2005), Austria (Balas et al., 2010), the United Kingdom (Defra, 2012), and Switzerland (Holthausen et al., 2011).

Figure 1.3 The concepts of risk, hazard and vulnerability in the risk-hazard framework



Note: The exposure of various elements is shown here as part of the vulnerability of the group of elements but exposure assessment may also be regarded as separate from vulnerability assessment (as shown in Figure 1.4).

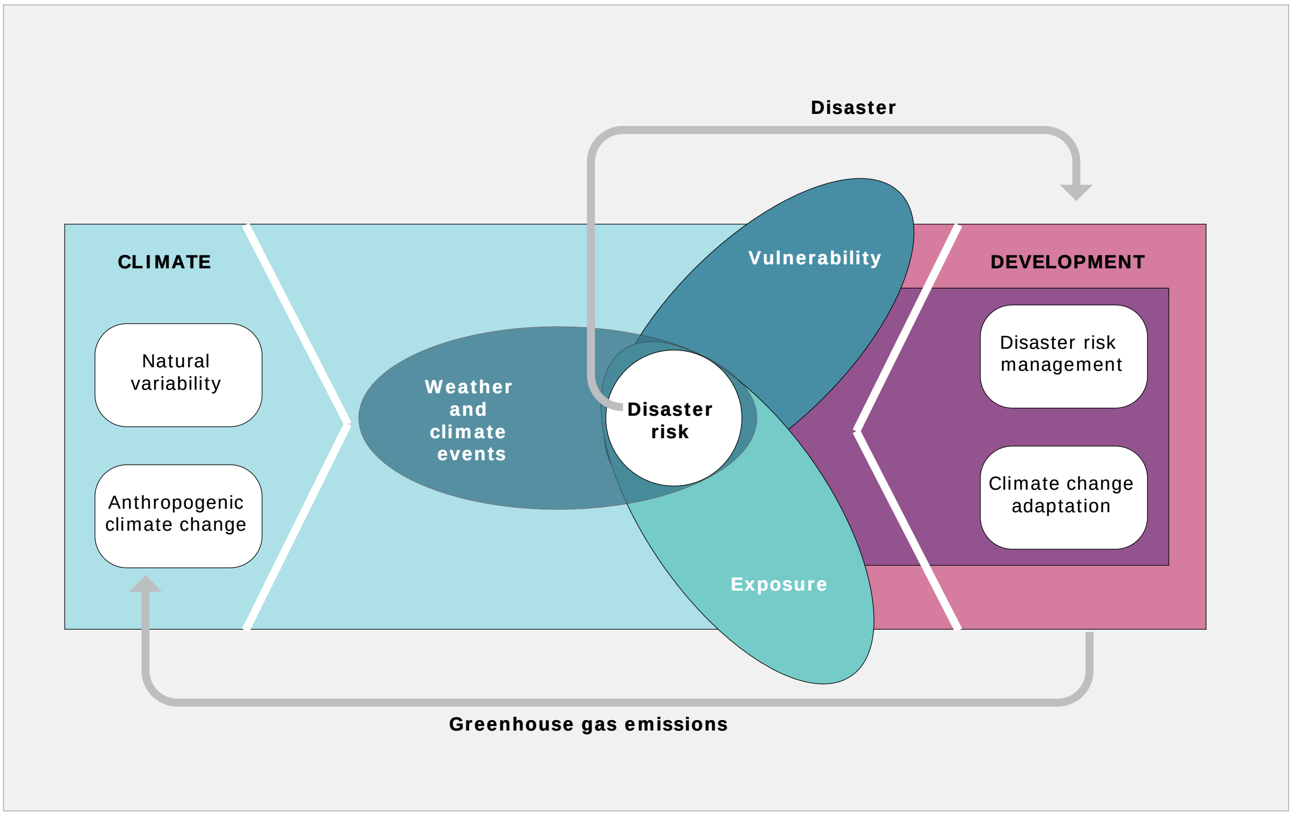
The vulnerability concept of the disaster risk community has been applied in this report in the section on transport (Section 4.6) and generally also in the section on cities and urban areas (Section 5.4).

The definition of vulnerability in the public health community is closely related to that of the disaster risk community. It emphasises characteristics of a population group (such as age, gender, nutritional status and pre-existing diseases) that determine their susceptibility to a specific health hazard (Stafoggia et al., 2006). In this report it has been applied in the section on human health (Section 4.4).

1.7.4 Partial integration of both approaches in the IPCC SREX

The IPCC recently published the Special Report SREX (IPCC, 2012), which focuses on the interconnections between extreme weather events, climate change and disasters. This report no longer uses the vulnerability definition of the IPCC AR4 but follows largely the concept of vulnerability as understood by the disaster risk community: 'Vulnerability is defined generically in this report as the propensity or predisposition to be adversely affected. Such predisposition constitutes an internal characteristic of the affected element. In the field of disaster risk, this includes the characteristics of a person or group and their situation that influences their capacity to anticipate, cope with, resist, and recover from the adverse effects of physical events.' (IPCC, 2012). However, the SREX expands existing concepts of the disaster risk community by emphasising how climate change and development can affect both the climatic hazards that a system or community is exposed to as well as its vulnerability (see Figure 1.4).

Figure 1.4 Links between climate change and disaster risk



Source: IPCC, 2012.

2 Changes in the climate system

2.1 Human influence on the climate system

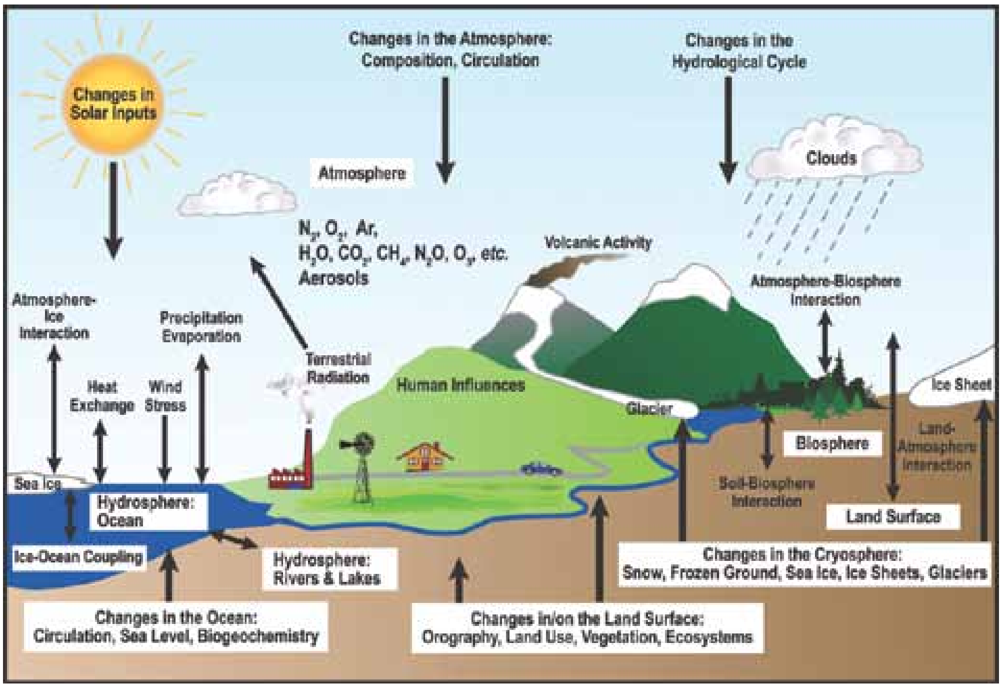
2.1.1 The climate system

Climate denotes the statistics (average conditions and variability) of the day-to-day weather over a long time period (usually 30 years). In contrast, weather denotes the state of the atmosphere at any given time, such as the day-to-day temperature and precipitation activity.

The Earth's climate system is a complex system consisting of several closely linked subsystems: the atmosphere, the hydrosphere (oceans, lakes and rivers), the cryosphere (snow and ice), and the lithosphere (soils). The climate system is closely linked to the other components of the Earth system, such as the biosphere (see Figure 2.1).

The climate system is influenced by many factors, such as solar activity, the Earth's orbit around the Sun, atmospheric composition and volcanic activity. Climate has always been changing as a result of changes in these factors. For example, the transitions between ice ages and intermediate warm phases (interglacials) during the last one million years were triggered by predictable changes in the position of the Earth's axis with respect to the Sun, followed by an amplification of the initial changes through feedback mechanisms in the climate system. In addition to the long-term changes, the climate is characterised by substantial variability on multiple time scales. Examples include daily and seasonal cycles but also more irregular multi-year and multi-decadal phenomena such as ENSO (El Niño-Southern Oscillation), NAO (North Atlantic oscillation), PDO (Pacific decadal oscillation), and the Arctic and Antarctic oscillations.

Figure 2.1 Components of the climate system, their processes and interactions

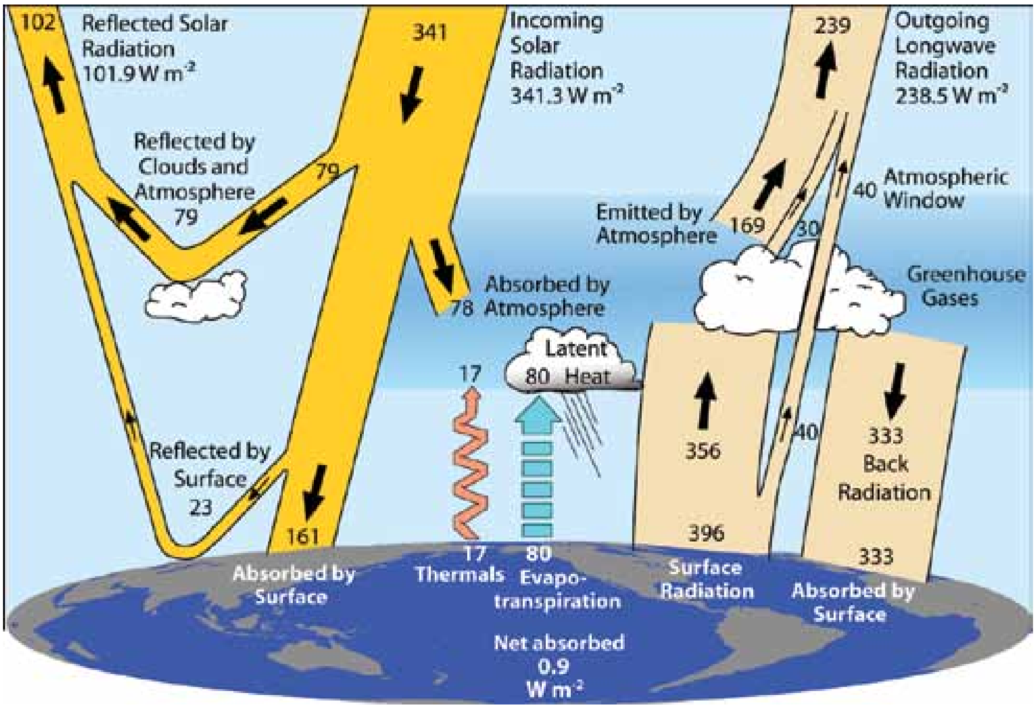


Source: IPCC, 2007 (FAQ 1.2, Figure 1).

Humans have over time exerted an increasingly important influence on the climate system. Early human activities affected the climate on a local to regional scale only. For example, the large-scale deforestation in the Mediterranean region during the Roman period altered the regional water cycle and may have caused drying of the region. With the industrial revolution, however, human activities began to alter the composition of the atmosphere thereby changing the Earth's climate on a global scale.

The main pathway along which humans are affecting the global climate is by increasing the concentration of so called long-lived GHGs. These gases let visible light pass through but absorb part of the infrared radiation from the Earth, thereby keeping the heat in the system (see Figure 2.2). The most important GHG in the atmosphere is water vapour; the most important anthropogenic GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and a number of halocarbons. The atmospheric concentrations of these gases are now far higher than at any time during the last 800 000 years. This is a result of the burning of fossil fuels, deforestation, and to a lesser extent the raising of cattle and the use of synthetic fertilisers. The current concentration of CO_2, the most important anthropogenic GHG, is 392 ppm (parts per million) (NOAA, 2012), compared to a historical range of 180 to 300 ppm as measured by air bubbles from the last 800 000 years captured in deep ice cores ([31]). Further human activities that warm the Earth are the emission of short-lived ozone (O_3) precursors (nitrogen oxides (NO_X), carbon monoxide (CO), and hydrocarbons) and the emission and deposition of black carbon aerosols (i.e. soot) on snow and ice, which reduces its reflectivity. Human activities affect also several other aspects of the climate system, e.g. through agriculture, land-use change, and the

Figure 2.2 The Earth's energy balance



Note: The magnitudes of various energy flows in this figure are associated with some uncertainties. Please consult the original reference for further information.

Source: Trenberth et al., 2009, figure 1. © American Meteorological Society. Reprinted with permission.

([31]) Note that carbon dioxide emissions have two major impacts. One part ends up in the atmosphere where it increases the greenhouse effect and thus warms the planet. Another part ends up in the oceans where it increases their acidity. Ocean acidification has potentially severe consequences for marine ecosystems, such as coral reefs (see Section 3.1). It is sometimes denoted as 'The other CO_2 problem'.

damming of rivers and lakes. Some human activities have a cooling effect, in particular the emission of aerosols (i.e. sulphates, smoke, dust and haze) that reflect part of the incoming sunlight and certain land-use changes that increase the reflectivity of the land surface (see Figure 2.2).

2.1.2 Observed climate change and its attribution

The IPCC AR4 (IPCC, 2007) concludes with very high confidence that human activities have contributed to the warming of the global climate since at least 1750. It estimates that the total warming effect of human activities is at least 10 times larger than that of natural factors, in particular changes in solar activity. The AR4 further concludes that the warmth since the mid-20th century is exceptional in at least the last 1 300 years, and that the observed rapid increase in global average temperatures since the mid-20th century is very likely due to the observed increase in GHG concentrations due to human activities. In other words, humans have now become the dominating cause of changes in global climate on decadal and centennial time scales.

The observed increasing trend in land surface temperature worldwide is the most obvious aspect of anthropogenic climate change. The global mean temperature has increased by about 0.8 °C since the industrial revolution, whereby the largest warming has occurred in Polar regions (see Section 2.2.2). Many other climate variables have changed as well. Observations show increases in ocean temperature to depths of at least 3 000 m, in atmospheric water content, and in sea level since at least 1950. At the same time, the Greenland ice sheets, Arctic sea ice, mountain glaciers and snow cover in both hemispheres are declining rapidly. Significant changes have also been observed in precipitation amounts, ocean salinity and wind patterns. Changes in some weather and climate extremes have also been detected in some regions since 1950, in particular increases in daily temperature extremes and heat waves (IPCC, 2012).

2.1.3 Future climate change

Projections of future climate change are derived from simulations with general circulation models and regional climate models using different emission scenarios for GHGs and aerosols (see Box 2.1 for further information). These models agree that past human activities will continue to warm the climate and raise sea levels for many decades to come. This future climate change commitment is due to the long lifetime of anthropogenic GHGs in the atmosphere (typically decades to centuries) and to the large inertia of the climate system (in particular the oceans). However, the pace and magnitude of future climate change depends on the level of global GHG emissions and other human activities. The best estimates of further warming (relative to the 1980–1999 average) provided in the IPCC AR4 are 1.8 °C for a low emissions scenario (SRES B1) (Nakicenovic and Swart, 2000) and 4.0 °C for a high emissions scenario (SRES A1FI). When uncertainties in climate modelling are considered, the likely range for 21st century global warming based on the six SRES marker emission scenarios extends to 1.1–6.4 °C ([32]). For comparison, the difference in global mean temperature between the present warm phase and the coldest phase of the last ice age (around 22 000 years ago) is about 5–6 °C.

Future warming of the Earth will affect other aspects of the climate system as well, leading to increasing sea levels, changing precipitation patterns, and changes in weather and climate extremes. The spatial pattern of climate change in the coming decades is expected to be largely similar to the pattern of recent changes, which shows a particularly strong warming in high latitudes, increasing precipitation in most tropical and high latitude regions, and decreasing precipitation in most sub-tropical regions.

([32]) Climate projections in the IPCC AR5 will be based on so-called representative concentration pathways (RCPs) rather than the SRES emissions scenarios. A summary of these simulations will only be publicly available in 2013 even though many individual results are already available through the CMIP5 website (http://cmip-pcmdi.llnl.gov/cmip5/).

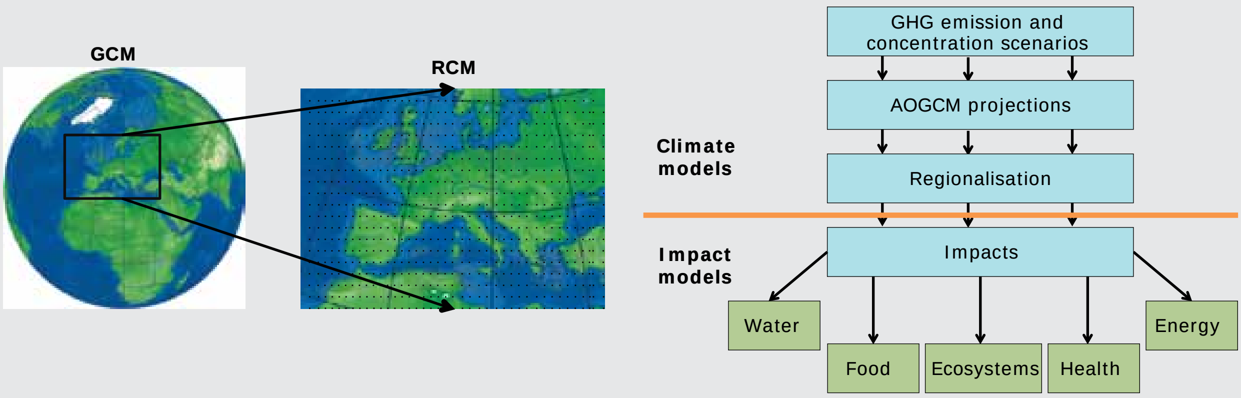
Box 2.1 General circulation models (GCMs) and regional climate models (RCMs)

General circulation models (GCMs) are numerical models that represent key physical and chemical processes in all components of the global climate system (see Figure 2.1). GCMs are the most advanced tools for simulating the response of the global climate system to different emissions scenarios for GHGs and aerosols. GCMs depict the climate using a three-dimensional (3D) grid over the globe. The GCMs used in the IPCC AR4 typically simulate atmospheric processes at a horizontal resolution of between 100 and 300 km, with 20 to 60 vertical layers. Ocean processes were simulated at a horizontal resolution of between 20 and 200 km, with up to 30 vertical layers. Some more recent GCMs have a somewhat finer horizontal resolution but their resolution is still quite coarse relative to the scale of exposure units in most climate impact assessments.

Regional climate models (RCMs) can be used to bridge the coarse-resolution outputs from GCMs with the high-resolution climate data needs of regional impact assessments. RCMs cover a limited area of interest, such as Europe or an individual country (see Figure 2.3). They are embedded into GCMs, which prescribe the large-scale climate features. RCMs typically have a horizontal resolution of between 5 and 50 km. Their higher resolution allows for a better representation of topographic features (e.g. mountain ranges) and of regional-scale climate phenomena. As a result they can provide better projections of changes in regional precipitation patterns and in certain weather extremes. RCMs have been used to relate future climate change in specific locations to the current variability of climate within Europe. For example, simulations with two RCMs have suggested that the climate of the city of London at the end of the 21st century under a high emissions scenario (SRES A2) would be similar to the current climate in south-west France or northern Portugal, respectively (Kopf et al., 2008).

Global and regional climate models have recognised weaknesses. Their simulations of past and current climate show some deviation from the observed climate. Furthermore, different models provide somewhat different climate projections when forced with the same emissions scenario (see Section 2.1.4). Nevertheless, the scientific community is confident that climate models provide credible quantitative estimates of future climate change since these models are based on fundamental physical laws and are able to reproduce the key features of observed climate change.

Figure 2.3 Components needed for modelling climate change and its impacts



Source: Blaz Kurnik (EEA).

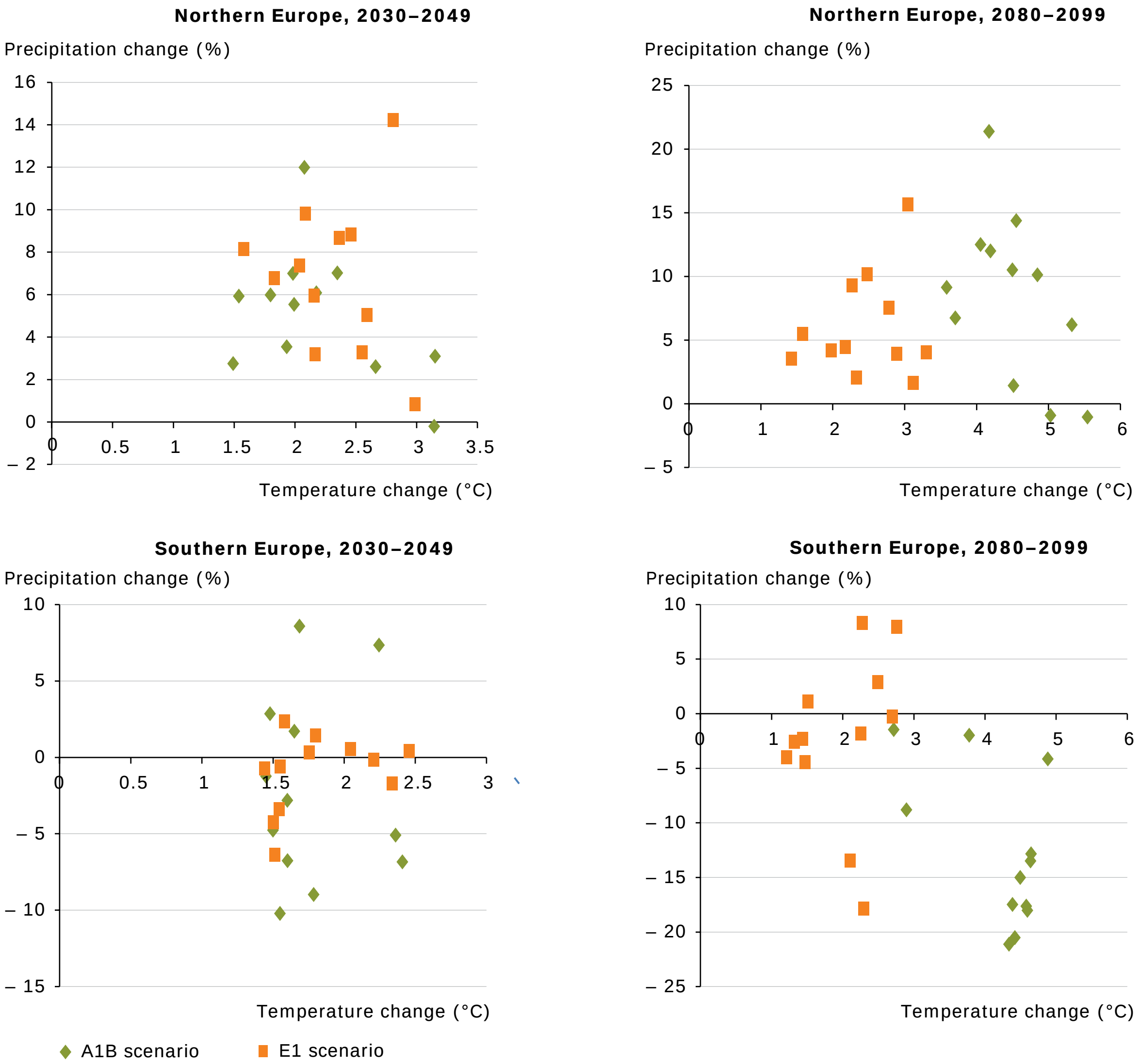
Downscaling of climate projections may be obtained by RCMs and the empirical-statistical downscaling modelling (ESDM). ESDM can effectively correct or refine climate variable projections provided by GCMs or RCMs and reduce the spread of projections given by a GCM/RCM ensemble. Application of ESDM is particularly beneficial to support local-scale climate projections and adaptation in mountain regions where many different precipitation regimes may exist within a GCM/RCM grid cell.

2.1.4 Robustness and uncertainty of climate change projections

Despite substantial progress in understanding and modelling the climate system, there will always be substantial uncertainties [33] about future climate change, in particular at the regional and local levels. The evolution of climate is determined by the highly complex interaction of the atmosphere, oceans and other elements of the global climate system (see Figure 2.1).

Uncertainty about future climate change has many sources (see also Section 1.6). One important factor is the level of future GHG and aerosol emissions, which depends on demographic, socio-economic and technological development as well as the implementation of mitigation policies. Further sources of uncertainty are the incomplete understanding of some climate processes (e.g. regarding cloud physics and rapid ice dynamics), insufficient spatial and temporal resolution of global climate models, and the lack of

Figure 2.4 Projections for combined changes in temperature and precipitation



Note: Annual changes in temperature and precipitation in northern (top panels) and southern Europe (bottom panels) for the periods 2030–2049 (left panels) and 2080–2099 (right panels) relative to 1961–1990. GCM simulations for the SRES A1B scenario, which assumes rather high population and economic growth and a balanced use of energy sources, are shown with green points. Comparable simulations for the ENSEMBLES E1 mitigation scenario are shown with orange points.

Source: Johns et al., 2011.

([33]) See the introduction of Section 1.6 for the scientific use of the term uncertainty, which differs somewhat from its use in everyday language.

long-term observations of key components of the climate system (in particular from the oceans). Some of these sources of uncertainty can be reduced by further research and data collection but they will never be fully eliminated. Assessments of climate impacts on human communities and ecosystems are further complicated by the need to consider relevant changes in economic, demographic, technical, institutional and cultural factors. Finally, the climate system exhibits substantial natural variability, in particular on the regional level.

In general, uncertainties about future climate change are smaller for changes in temperature than for precipitation and other climate variables, for changes at global and continental scales than at regional scale, and for changes in mean climate than for extreme events. The importance of different sources of climate uncertainty also varies over time. Natural climate variability and model uncertainty is the dominating factor in the short term. On time scales of 50 years and longer, scenario uncertainty becomes the main source of the uncertainty about temperature change whereas model uncertainty remains the main source of uncertainty for precipitation (Cox and Stephenson, 2007; Hawkins and Sutton, 2009; 2011).

Providing the best available scientific information to decision-makers, including a characterisation of uncertainties, helps narrowing the range of possible future conditions that policies need to address. For example, Figure 2.4 depicts key aspects of future climate change in northern and southern Europe for two future periods (see Section 2.2 for further information on observed and projected climate change in Europe). Key uncertainties are depicted by showing the results for two different emissions scenarios and for several climate models separately. One robust conclusion is that both regions are expected to warm further, whereby the details depend on the region, emissions scenario, climate model and time horizon. Furthermore, (almost) all climate models agree that northern Europe will become substantially wetter annually averaged and in particular in winter (see Section 2.2). All models agree that southern Europe will become drier towards the end of the 21st century under a business-as-usual precipitation scenario annually averaged and in particular in summer (see Section 2.2). Projected precipitation changes in the first half of the 21st century and for a mitigation scenario are less certain. Finally, differences between emissions scenarios increase over time.

2.2 Key climate variables

2.2.1 Overview

Relevance

Anthropogenic emissions of GHGs are the dominating cause of the observed rapid increases in global average temperature over recent decades. Natural factors like volcanoes and solar activity can explain a large portion of the temperature variability up to the middle of the 20th century but can only explain a small part of the warming trend over the past 50 years. Changes in precipitation and storminess have been more varied than the temperature trend but they can also exert major impacts on natural and social systems.

Key messages: 2.2 Key climate variables

- Three independent records show long-term warming trends of global and European average annual temperature since the end of the 19th century, with most rapid increases in recent decades. The last decade (2002–2011) was the warmest on record globally and in Europe. Heat waves have also increased in frequency and length. All these changes are projected to continue at an increased pace throughout the 21st century.
- Precipitation changes across Europe show more spatial and temporal variability than temperature. Since the mid-20th century, annual precipitation has been generally increasing across most of northern Europe, most notably in winter, but decreasing in parts of southern Europe. In western Europe intense precipitation events have provided a significant contribution to the increase. Most climate model projections show continued precipitation increases in northern Europe (most notably during winter) and decreases in southern Europe (most notably during summer). The number of days with high precipitation is projected to increase.
- Observations of storm location, frequency and intensity show considerable variability across Europe during the 20th century. Storm frequency shows a general increasing trend from the 1960s to 1990s, followed by a decrease to the present. Available climate change projections show no clear consensus in either the direction of movement or the intensity of storm activity.

Selection of indicators

This section presents the following indicators on the key atmospheric climate variables temperature, precipitation and storminess.

- *Global and European temperature:* Global average temperature is the key climate variable to track anthropogenic climate change. It is also the only climate variable for which a political target exists (see Section 1.3). European average temperature is more relevant for assessing impacts of climate change in Europe, and for informing adaptation planning.
- *Temperature extremes:* This indicator presents information on heat and cold extremes in Europe. Heat extremes are one of the most deadly and expensive climatic hazards in Europe.
- *Precipitation:* This indicator presents information on average annual and seasonal precipitation in Europe. Precipitation is a key climate variable with major importance for all ecosystems and social systems.
- *Precipitation extremes:* This indicator presents information on daily precipitation extremes and dry spells, which is import to inform flood protection and drought management.
- *Storminess:* Storms are one of the most important weather hazards in Europe.

Data quality and data needs

The presented key atmospheric climate variables are a subset of the Essential Climate Variables (ECVs) defined through the Global Climate Observing System (GCOS) ([34]). Spatial and temporal coverage of the observed climate variables varies significantly across the globe; it is generally best over Europe and North America.

Regular instrumental measurements of temperature and precipitation started around 1850; since then monthly information about global temperature and precipitation have become available. A dense network of stations across the globe, and particularly in Europe, now provide regular monitoring of key atmospheric climate variables, using standardised measurements, quality control and homogeneity procedures at European level. However, even where sufficient data are available, several problems can limit their use for analysis. These problems are mainly connected with 1) limitations of distributing data in high spatial and temporal resolution by many countries, 2) unavailability of data in easy-to-use digital format, and 3) lack of data homogeneity. The situation in Europe is improving since several EU-funded projects (such as ECA&D ([35]) and EURO4M ([36])) have started to collect, digitalise and homogenise additional time series of the Essential Climate Variables. In addition, EUMETNET ([37]) initiated an optional programme, EUMETGRID ([38]), which aims to develop and maintain a sustainable common data infrastructure for access to and distribution of gridded climate information in Europe and establish recommendations of best practices for establishing national and European gridded datasets.

([34]) See http://www.wmo.int/pages/prog/gcos/index.php.
([35]) See http://eca.knmi.nl.
([36]) See http://www.euro4m.eu.
([37]) EUMETNET is a grouping of 29 European National Meteorological Services that provides a framework to organise cooperative programmes between its members in the various fields of basic meteorological activities (http://www.eumetnet.eu).
([38]) See http://eumetgrid.met.no.

2.2.2 Global and European temperature

Relevance

This indicator summarises changes in average near-surface temperature for the globe and for a region covering the 39 EEA member and cooperating countries ([39]). Near-surface air temperature gives one of the clearest and most consistent signals of global and regional climate change. A dense network of stations across the globe, and particularly in Europe, provide regular monitoring of temperature, using standardised measurements, quality control and homogeneity procedures. Time series extend back for many decades or even centuries at some locations.

This indicator directly refers to the following policy-relevant questions ([40]):

- Will the global average temperature increase stay within the EU and UNFCCC policy target of 2.0 °C above pre-industrial levels?
- Will the rate of global average temperature increase stay below the target of 0.2 °C increase per decade?

Global average annual temperature is expressed here relative to a 'pre-industrial' period between 1850 and 1899, which coincides with the beginning of widespread instrumental temperature records. During this time, anthropogenic GHGs from the industrial revolution (between 1750 and 1850) are considered to have had a relatively small influence on climate compared to natural influences. However, it should be noted that there is no rigorous scientific definition of the term 'pre-industrial climate' because the climate has also changed prior to 1850 due to internal and forced natural variability.

Key messages: 2.2.2 Global and European temperature

Global:

- Three independent long records of global average near-surface (land and ocean) annual temperature show that the decade between 2002 and 2011 was 0.77 to 0.80 °C warmer than the pre-industrial average.
- In recent decades, the rate of change in global average temperature has been close to the indicative limit of 0.2 °C per decade.
- The Arctic has warmed significantly more than the globe, and this is projected to continue into the future.
- The best estimate for the further rise in global average temperature is between 1.8 and 4.0 °C for the lowest and highest SRES marker scenarios (IPCC SRES) that assume no additional political measures to limit emissions. When climate model uncertainties are taken into account, the likely range increases to 1.1–6.4 °C.
- The EU target of limiting global average temperature increase to 2 °C above pre-industrial levels is projected to be exceeded during the second half of this century and likely around 2050, for all six IPCC SRES emissions scenarios.

Europe:

- Annual average temperature across European land areas has warmed more than global average temperature, and slightly more than global land temperature. The average temperature for the European land area for the last decade (2002–2011) is 1.3 °C above the pre-industrial level, which makes it the warmest decade on record.
- Annual average land temperature over Europe is projected to continue increasing by more than global average temperature during the 21st century. Increases in land temperature in Europe for the SRES A1B emission scenario are projected between 1.0 and 2.5 °C by 2021–2050, and between 2.5 and 4.0 °C by 2071–2100.
- The largest temperature increases during the 21st century are projected over eastern and northern Europe in winter and over southern Europe in summer.

([39]) In this section, EEA Europe is defined as the area between 35 °N to 70 °N and 25 °W to 30 °E, plus the area from 35 °N to 40 °N and 30 °E to 45 °E (including also the Asian part of Turkey).

([40]) The European Council proposed in its Sixth Environmental Action Programme (EC, 2002) that the global average temperature increase should be limited to not more than 2 °C above pre-industrial levels (about 1.3 °C above current global mean temperature). This limit was reaffirmed by the Environment Council and the European Council in 2005. Furthermore, the UNFCCC 15th Conference of the Parties (COP15) recognised, in the Copenhagen Accord (UNFCCC, 2009) the scientific evidence for the need to keep global average temperature increase below 2 °C above pre-industrial levels (see Section 1.3). In addition, several studies have proposed to limit the rate of anthropogenic warming to 0.2 °C per decade (WBGU, 2003; van Vliet and Leemans, 2005).

Past trends

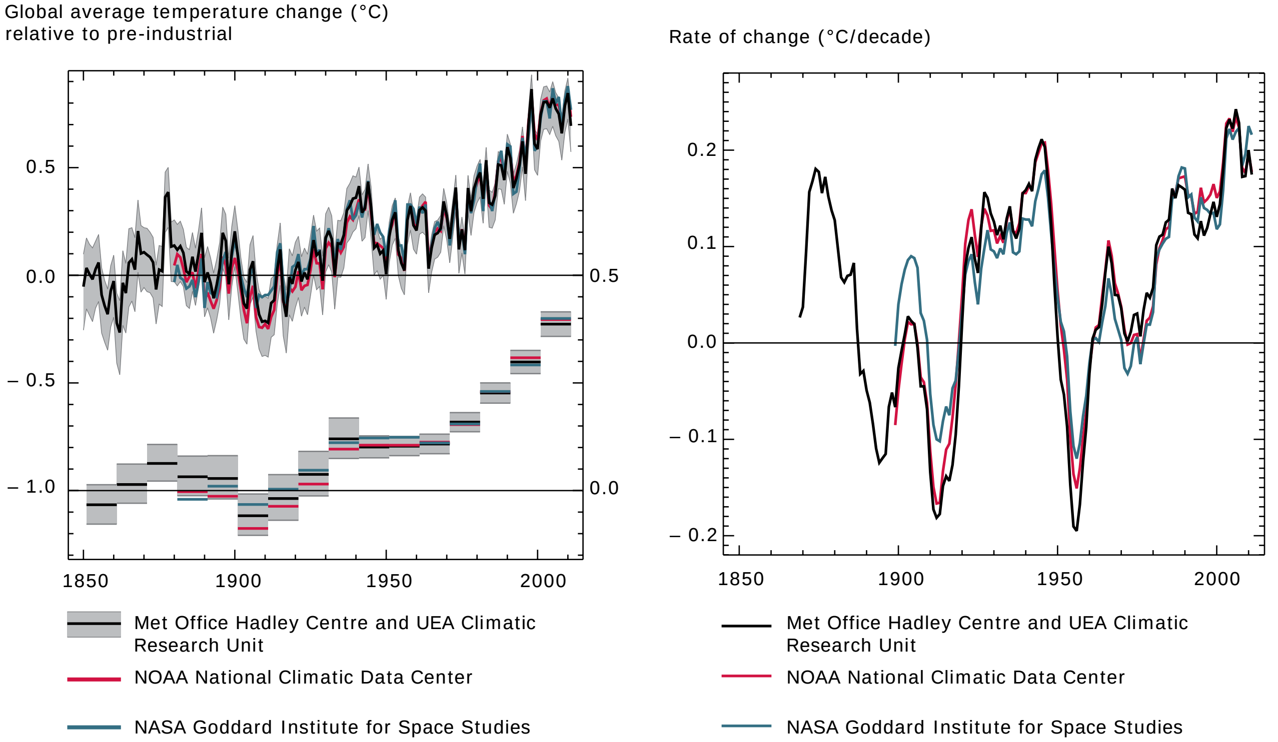
Global:

Since the end of the 19th century, records of global average temperature have shown long-term warming trends which have been especially rapid in the most recent decades. Relative to pre-industrial temperatures (taken here to be comparable with the earliest observations at the end of the 19th century), three independent analyses of global average temperature using near-surface observation records — HadCRUT3 (Brohan et al., 2006); NOAA-NCDC (Smith et al., 2008); and NASA-GISS (Hansen et al., 2010) — show similar amounts of warming by the 2002 to 2011 decade of 0.77 °C, 0.78 °C and 0.80 °C, respectively (Figure 2.5 left). This magnitude of warming corresponds to more than one third of the 2 °C warming permitted under the global climate stabilisation target of the EU and UNFCCC.

Figure 2.5 (left) shows estimates (based on instrumental measurements) of air temperatures at 2 m height over land, and sea surface temperatures observed from ships and buoys. The various estimates differ slightly because the underlying sources differ in their methods for analysing the data and filling data gaps. Another independent method that can be used to estimate changes in global average temperature is through 'Climate reanalysis' (see Box 2.2).

The rate of change in global average temperature during the last century was on average around 0.07 °C per decade (for all three analyses shown in Figure 2.5). The rate of change increased to around 0.15 °C per decade averaged over the past 50 years, and between 0.17 and 0.22 °C over the last 20 years (Figure 2.5 right). This rate is close to the indicative limit of 0.2 °C per decade proposed by some scientific studies (WBGU, 2003; van Vliet and Leemans, 2005).

Figure 2.5 Change in global average temperature from three sources (1850–2011)



Note: Change (left) and rates of change, based on 10-year running average (right) in global average air temperature. Temperature is expressed in degrees Celsius (°C) relative to a pre-industrial baseline period. The upper time series on the left graph shows annual anomalies and the lower time series shows decadal average anomalies for the same datasets.

Source: 1) Black line — HadCRUT3 from the UK Met Office Hadley Centre and University of East Anglia Climate Research Unit, baseline period 1850–1899 (Brohan et al., 2006). The grey area represents the 95 % confidence range.
2) Red line — MLOST from the US National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center, baseline period 1880–1899 (Smith et al., 2008).
3) Blue line — GISSTemp from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies, baseline period 1880–1899 (Hansen et al., 2010).

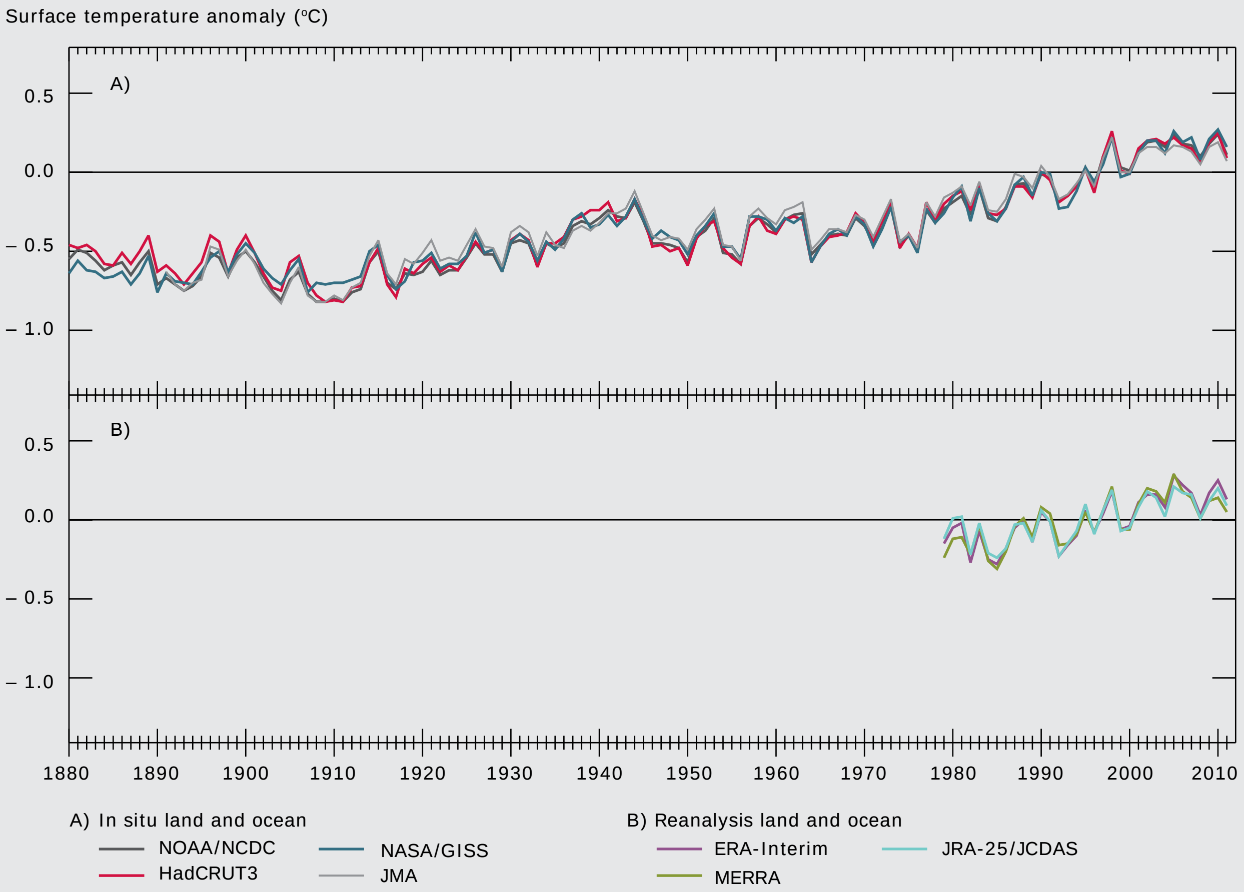
Box 2.2 Climate reanalyses

Reanalysis is a method to reconstruct the past state of the atmosphere and oceans in a coherent way by combining available observations with numerical models. These reconstructions are created with model-based data assimilation methods which are similar to those used for numerical weather prediction. Using this approach it is possible to extract useful information about rainfall using temperature and humidity observation from satellites, or to infer large-scale features of the global circulation in the early 20th century using only surface pressure observations available at that time (Compo et al., 2011). Reanalysis is a rapidly evolving field, and new reanalysis products benefit from recent modelling capabilities, improved techniques in data assimilation, in the latest observation techniques (i.e. from satellite measurements), and newly digitalised historical datasets (Blunden et al., 2011). Reanalyses also allow the user to estimate temperature, humidity, wind and precipitation over regions where in situ observations are not available (e.g. Polar regions, or large areas of Africa). In recent years, datasets from reanalyses have been widely used for research in the atmospheric and ocean sciences and in climate services.

Global average surface temperature anomalies from in situ temperature measurements and from various reanalyses are presented in Figure 2.6. In situ temperature anomalies use temperature measurements over land and sea. While they differ in their methods, which can lead to differences in ranking years, all time series are close in agreement. Global average temperature datasets from reanalyses have larger spread than those obtained from in situ observations due to complex construction of the reanalyses.

Reanalyses are explicitly and implicitly used in various sections of this report.

Figure 2.6 Global average surface temperature anomalies from in situ observations and from reanalysis



Note: For the in situ datasets near-surface (2 m) air temperature is used over land and sea surface temperature over the oceans. For the reanalyses a 2 m temperature is used over the whole globe. In situ datasets use the 1961–1990 base period whereas all other reanalysis datasets use the 1989–2008 base period. However, to aid comparison, all time series have been adjusted such that they give a mean of zero over the common period 1989–2001.

Source: Blunden et al., 2011.

Europe:

The decadal average temperature over European land areas increased by approximately 1.3 °C (± 0.11 °C) between pre-industrial times and the decade of 2002 to 2011 (Figure 2.7 upper). The interannual temperature variability over Europe is generally much higher in winter (Figure 2.7 middle) than in summer. The relatively rapid warming trend since the 1980s is most clearly evident in the summer (Figure 2.7 lower).

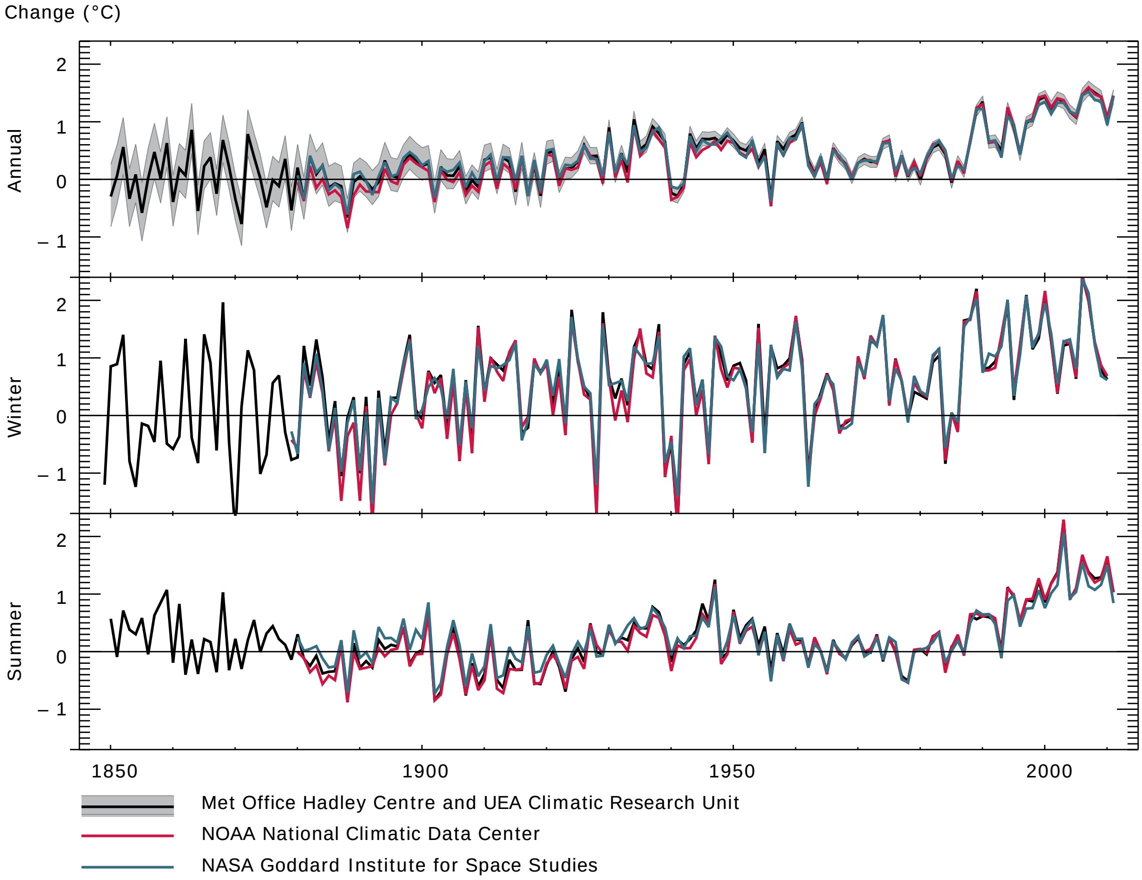
Particularly large warming has been observed in the past 50 years over the Iberian Peninsula, across central and north-eastern Europe, and in mountainous regions. Over the past 30 years, warming was the strongest over Scandinavia, especially in winter, whereas the Iberian Peninsula warmed mostly in summer (Haylock et al., 2008) (Map 2.1).

Projections

Global:

The global average temperature will continue to increase throughout the 21st century as a result of projected further increases in GHG concentrations (Figure 2.8). Forced by a range of future possible emissions scenarios (IPCC SRES scenarios (Nakicenovic and Swart, 2000)), the central estimate for the warming averaged for the near future (2011–2030) compared to 1980–1999 is between + 0.64 °C and + 0.69 °C (Solomon et al., 2007). By the mid-century (2046–2065), projected increases of between + 1.3 °C and + 1.8 °C for the same models and scenarios were noted, and by the late 21st century (2090–2099), these ranged between + 1.8 °C and + 4.0 °C. When model uncertainty is included, the likely range extends to 1.1 to 6.4 °C, as shown by the grey bars to the right of Figure 2.8.

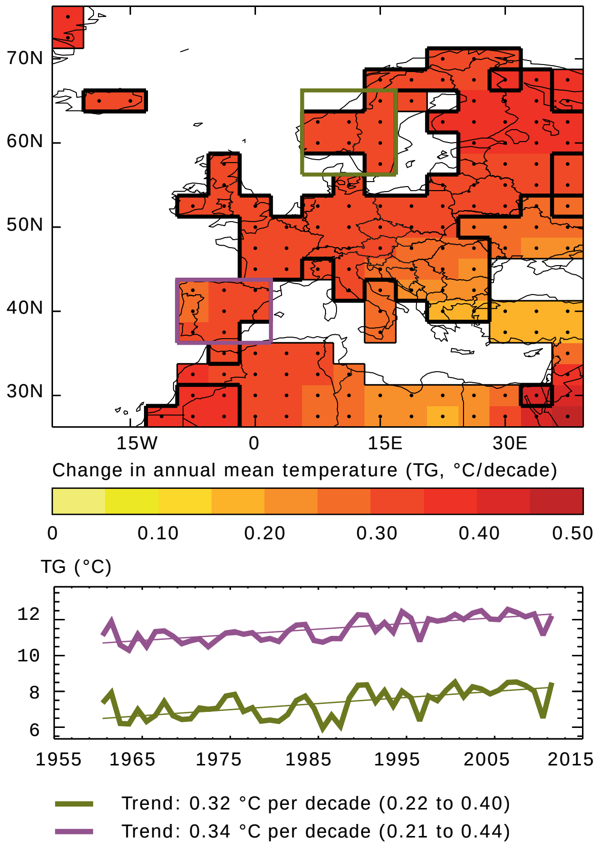
Figure 2.7 European average temperature (1850–2011) over land areas for annual (upper), winter (middle) and summer (lower) periods



Note: Datasets, pre-industrial periods and techniques are the same as for Figure 2.5.

Source: 1) Black line — HadCRUT3 from the UK Met Office Hadley Centre and University of East Anglia Climate Research Unit, baseline period 1850–1899 (Brohan et al., 2006). The grey area represents the 95 % confidence range.
2) Red line — MLOST from the US National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center, baseline period 1880–1899 (Smith et al., 2008).
3) Blue line — GISSTemp from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies, baseline period 1880–1899 (Hansen et al., 2010).

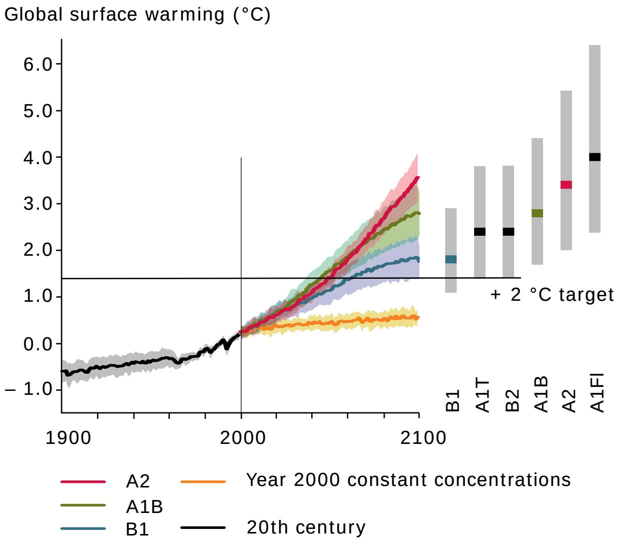
Map 2.1 Trend in annual temperature across Europe (1960–2012)



Note: Grid boxes outlined in solid black contain at least three stations and so are likely to be more representative of the grid box. High confidence in the long-term trend is shown by a black dot. (In the map above, this is the case for all grid boxes.) Area averaged annual time series of percentage changes and trend lines are shown below each map for one area in northern Europe (green line, 5.6 ° to 16.9 °E and 56.2 ° to 66.2 °N) and one in south-western Europe (purple line, 350.6 ° to 1.9 °E and 36.2 ° to 43.7 °N).

Source: ECA&D dataset (Klein Tank and Wijngaard, 2002).

Figure 2.8 Projected changes in global average temperature based on multi-model simulations



Note: Solid lines are multi-model global averages of surface warming (relative to 1980–1999; add 0.6 °C to estimate warming relative to the pre-industrial period) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ± 1 standard deviation range of individual model projections. The orange line is for an experiment where GHG concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the Atmosphere-Ocean Global Circulation Models (AOGCM) in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.

Source: IPCC, 2007a.

None of the SRES emissions scenarios includes specific policies to limit GHG emissions. The range results from the uncertainties in future socio-economic development and in climate models. The EU and UNFCCC target of limiting global average warming to not more than 2.0 °C above pre-industrial levels is projected to be exceeded around 2050 for all SRES scenarios considered here. The future projections show greatest warming over land (roughly twice the global average warming) and at high northern latitudes. These trends are consistent with the observations during the latter part of the 20th century (Solomon et al., 2007).

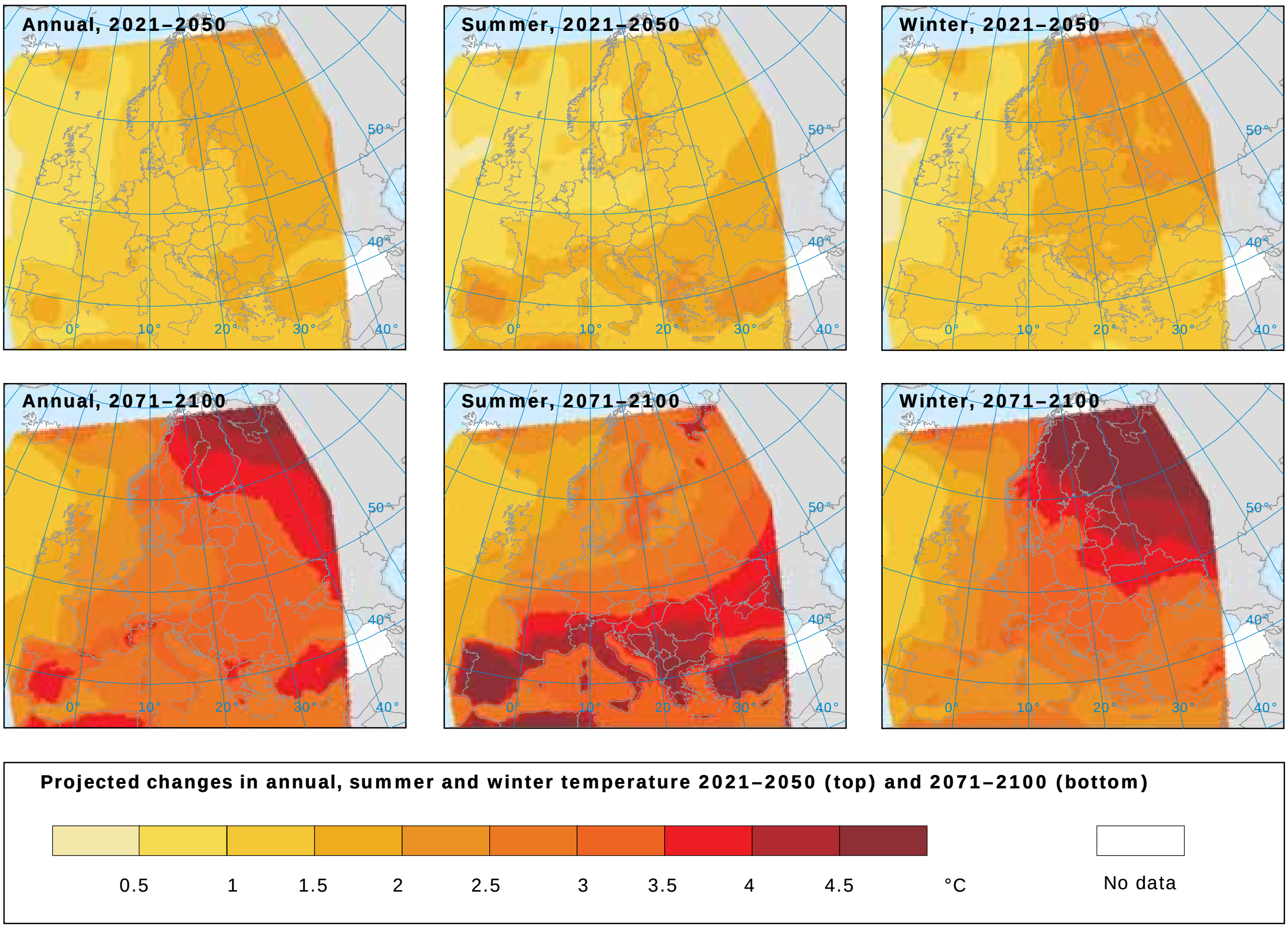
Four representative concentration pathways (RCPs) have been developed recently to succeed the IPCC SRES emissions scenarios (see Section 1.5.1). RCPs aim to span the whole range of plausible emission scenarios, including mitigation scenarios, until 2100. RCPs will be the basis of the climate projections in the forthcoming IPCC Fifth Assessment Report.

Several studies have applied global climate models to estimate the warming associated with different RCPs. These studies project an increase in global mean temperature by 2100, relative to preindustrial levels (1850–1900), of 1.5–2.3 °C for the lowest RCP (RCP2.6) to 4.5–5.8 °C for the highest RCP (RCP8.5) (Arora et al., 2011; Meinshausen et al., 2011; Meehl et al., 2012). The RCPs have been extended until 2300 by the so-called extended concentration pathways (ECPs). Simulations using the ECPs suggest best estimates for global mean temperature increase by 2300, relative to preindustrial levels, of 1.1 °C for the extension of RCP2.6 to 8.0 °C for the extension of RCP8.5 (Meinshausen et al., 2011).

Europe:

The average temperature over Europe is projected to continue increasing throughout the 21st century. According to results from the ENSEMBLES project (van der Linden and Mitchell, 2009) the annual average land temperature over Europe is projected to increase by more than global land temperature. The annual temperature for Europe is projected to increase by 1.0 °C to 2.5 °C (between periods 2021–2050 and 1961–1990) and 2.5 °C to 4.0 °C (between periods 2071–2100 and 1961–1990). The warming is projected to be the greatest in north-eastern Europe and Scandinavia in winter and over southern Europe in summer (Map 2.2). Note that maps about trends and projections are not directly comparable because complex processes, variability and feedbacks mean that past trends cannot be assumed to continue at the same rate into the future.

Map 2.2 Projected changes in annual, summer and winter temperature across Europe



Note: Projected changes in annual (left), summer (JJA; centre), and winter (DJF; right) near-surface air temperature (°C) for the period 2021–2050 (above) and 2071–2100 (below), compared to 1961–1990. Projections are based on the ENSEMBLES project. They have been obtained from different regional climate models (RCMs) performing at 25 km spatial resolution with boundary conditions from five global climate models (GCMs), all using the IPCC SRES A1B emission scenario.

Source: van der Linden and Mitchell, 2009.

2.2.3 Temperature extremes

Relevance

Global climate change is affecting the frequency and intensity of extreme events. Extremes of both warm and cool temperature are important indicators as they can have strong impacts on natural as well as human systems. Importantly, a temperature that is 'normal' for one region may be extreme for another region that has not regularly experienced this temperature in the past. For example, mortality has been estimated to increase by between 1 and 4 % for every 1 °C increase above a location-specific temperature threshold, with the elderly, disabled and socio-economically deprived at most risk (Baccini et al., 2008; EEA, 2011a) (see also Section 4.4).

Past trends

Extreme high temperatures, for example number of warm days and nights and heat waves, have become more frequent in the past while extreme low temperatures, for example cool days and nights, cold spells and frost days, have become less frequent (Klein Tank and Wijngaard, 2002; IPCC, 2007b). The average length of summer heat waves over western Europe has doubled since 1880, and the frequency of hot days has almost tripled (Della-Marta et al., 2007). All these observations are consistent with the general warming trend observed across Europe.

Since 1960, significant increases in the number of warm days and nights, and decreases in the number of cool days and nights have been noted throughout Europe (Map 2.3). Between 1960 and 2011, the number of warm days increased by between 4 and 10 days per decade across Europe, and the number of warm nights increased by between 5 and 11 per decade (not shown). The number of cool nights decreased by between 1 and 6 per decade in the same period. Western and central Europe have shown the largest increases in warm days/nights, and the Iberian peninsula, north-western Europe and Scandinavia have shown the largest warming in cool days/nights. Despite a clear long-term warming trend across Europe, it is normal to observe considerable variability between and within years. Further information on recent heat extremes is provided in Box 2.3.

Projections

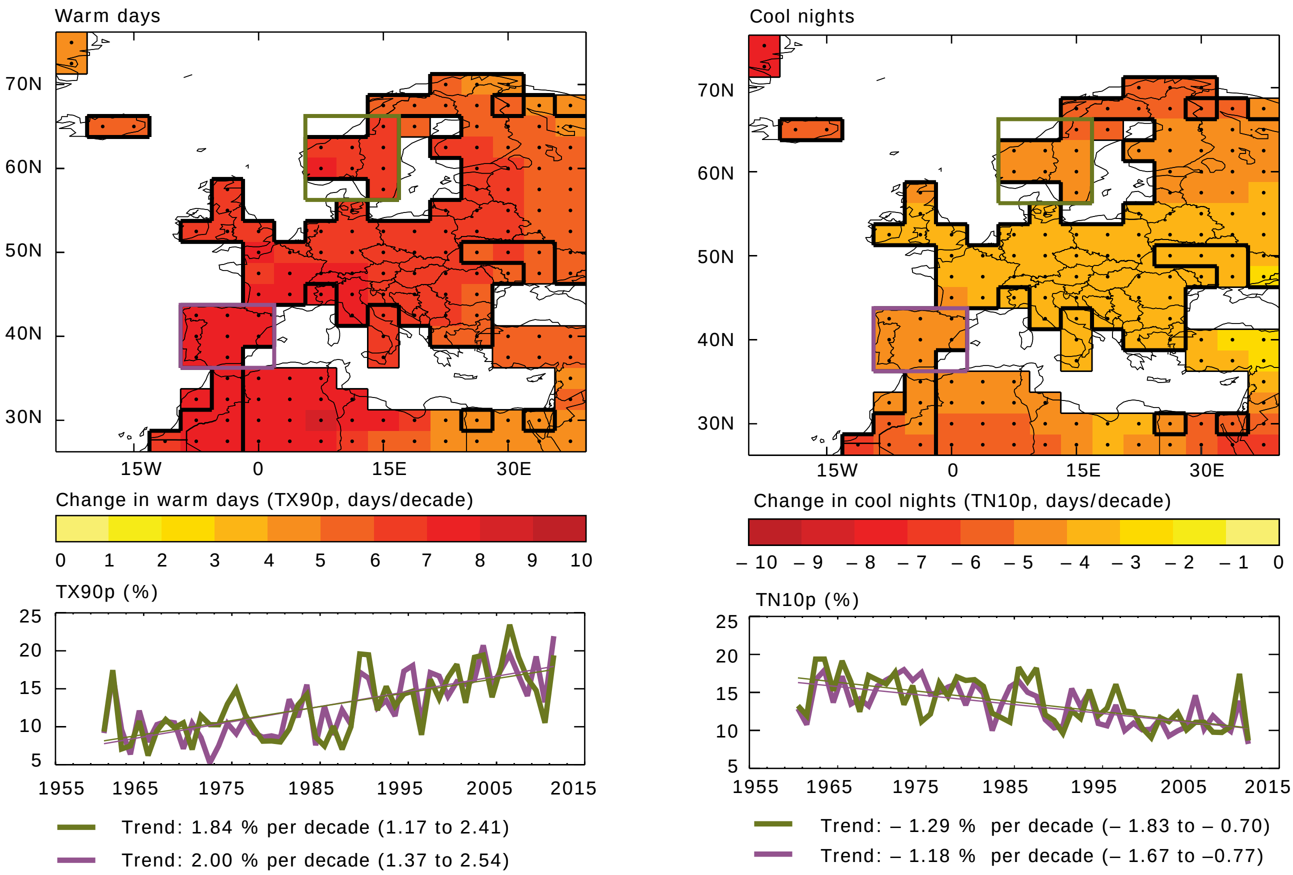
Extreme high temperatures across Europe are projected to become more frequent and last longer during this century (IPCC, 2007a; b; Haylock et al., 2008; Sillman and Roeckner, 2008; Seneviratne et al., 2012). These changes are consistent with projections of future average warming as well as observed trends over recent decades.

The number of days that combine a hot summer day (defined as having a temperature exceeding 35 °C) and a tropical night (defined as having a minimum temperature higher than 20 °C) is a basic indicator of human comfort due to heat stress. Model projections project the number of such combined heat stress days to double across most parts of southern Europe by 2071 to 2100 (Map 2.4). The most severe increases, of about 25 days per year, are projected in low-altitude river basins and along the Mediterranean coasts where many densely populated urban centres are located (Fischer and Schär, 2010).

Key messages: 2.2.3 Temperature extremes

- Extremes of cold have become less frequent in Europe while warm extremes have become more frequent. Since 1880, the average length of summer heat waves over western Europe has doubled and the frequency of hot days has almost tripled.
- Recent cold winters in northern and western Europe do not contradict the general warming trend on decadal time scales. Historic records show a clear long-term warming trend across Europe but it is normal to observe considerable variability between and within years due to natural variability.
- Extreme high temperatures are projected to become more frequent and last longer across Europe over the 21st century.

Map 2.3 Trends in warm days and cool nights across Europe (1960–2012)



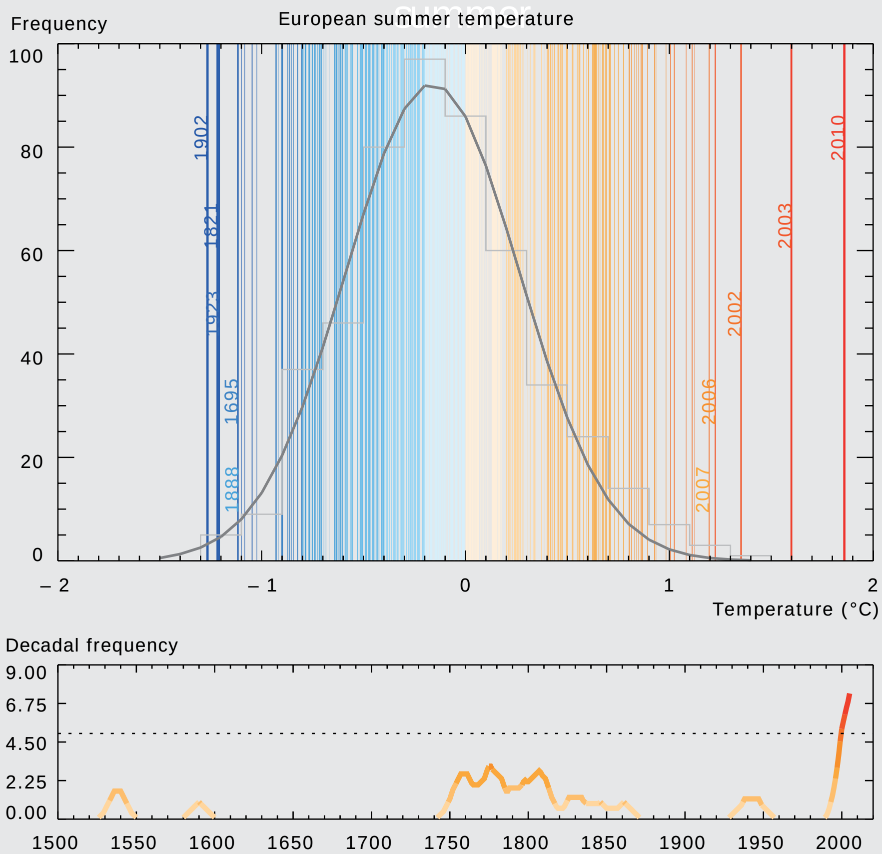
Note: Warm days/nights are defined as being above the 90th percentile of the daily maximum/minimum temperature and cool days/nights are similarly below the 10th percentile (Alexander et al., 2006). Grid boxes outlined in solid black contain at least three stations and so are likely to be more representative of the grid-box. High confidence in the long-term trend is shown by a black dot. (In the maps above, this is the case for all grid boxes.) Area averaged annual time series of percentage changes and trend lines are shown below each map for one area in northern Europe (green line, 5.6 ° to 16.9 °E and 56.2 ° to 66.2 °N) and one in south-western Europe (purple line, 350.6 ° to 1.9 °E and 36.2 ° to 43.7 °N).

Source: ECA&D dataset (Klein Tank and Wijngaard, 2002).

Box 2.3 A decade of European temperature extremes

Recent years have seen an exceptionally large number of record-breaking and destructive heat waves in many parts of the world (Coumou and Rahmstorf, 2012). Several recent studies indicate that many, possibly most, of these heat waves would not have occurred without anthropogenic climate change. The five warmest summers in Europe in the last 500 years all occurred in the recent decade (2002–2011) (see Figure 2.9). In 2003, Western Europe suffered its hottest summer by far for at least 500 years (Luterbacher et al., 2001; Dobrovolny et al., 2010; Coumou and Rahmstorf, 2012), with temperatures in Switzerland topping the previous record by a full 2.4 °C, equivalent to 5.4 standard deviations (Robine et al., 2008). Greece experienced its hottest summer in 2007, with summer temperatures in Athens exceeding the 1961–1990 mean by 3.3 °C, corresponding to 3.7 standard deviations (Founda and Giannakopoulos, 2009). In 2010, central Russia suffered its worst heat wave since records began, with the July temperature in Moscow beating the previous record by 2.5 °C.

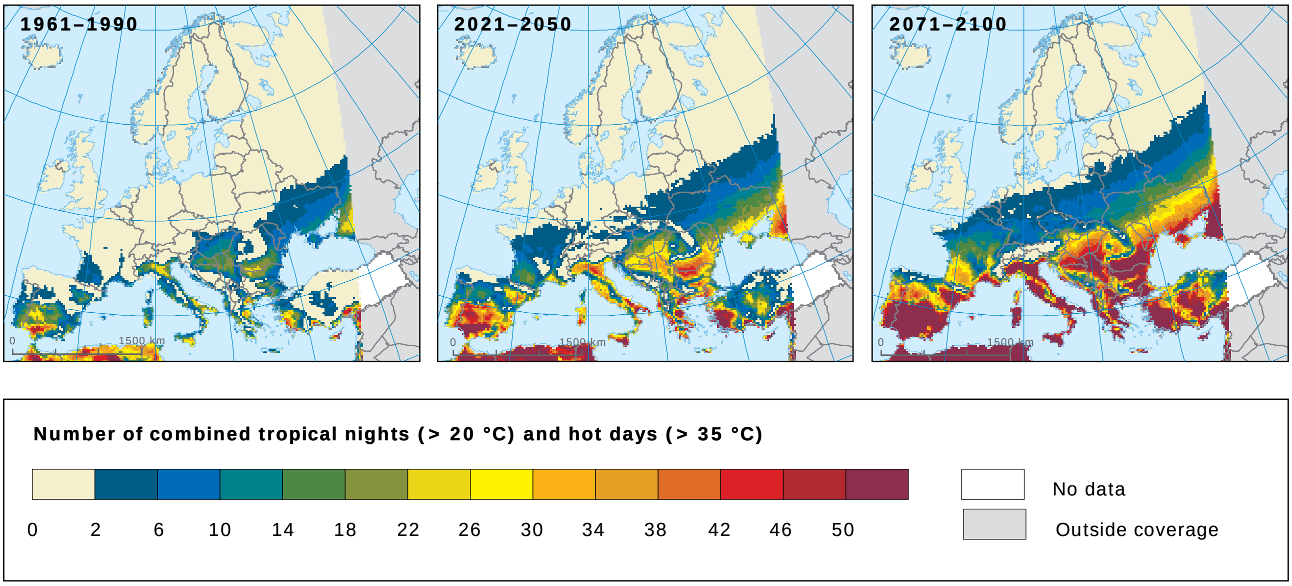
Figure 2.9 European summer temperatures for 1500–2010



Note: The upper panel shows the statistical frequency distribution of European (35 °N, 70 °N, 25 °W, 40 °E) summer land-temperature anomalies (relative to the 1970–1999 period) for the 1500–2010 period (vertical lines). The five warmest and coldest summers are highlighted. Grey bars represent the distribution for the 1500–2002 period with a Gaussian fit shown in black. The lower panel shows the running decadal frequency of extreme summers, defined as those with a temperature above the 95th percentile of the 1500–2002 distribution. A 10-year smoothing is applied.

Source: Barriopedro et al., 2011. Reprinted with permission from AAAS.

Map 2.4 Projections of extreme high temperatures



Note: Extreme high temperatures are represented by the combined number of hot summer (June–August) days (TMAX > 35 °C) and tropical nights (TMIN > 20 °C). All projections are the average of six regional climate model (RCM) simulations of the EU ENSEMBLES project using the IPCC SRES A1B emission scenario for the periods 1961–1990, 2021–2050 and 2071–2100.

Source: Fischer and Schär, 2010. © Nature Publishing Group. Reprinted with permission.

2.2.4 Mean precipitation

Relevance

Precipitation plays a vital role in all human-environment systems and sectors, including agriculture, water supply, energy production, tourism and natural ecosystems. Daily precipitation totals are standard meteorological measures that have been recorded systematically since the 1860s. However, despite longevity of the precipitation record in certain areas, the high spatial and temporal variability of precipitation means that the climate change signal cannot be detected with certainty in all European regions. Difficulties for detecting a significant trend can arise from the small sampling area of rain gauges, calibration errors in instrumentation, erroneous measurements during weather conditions such as snow or gales, and from limited sampling of the spatial variability of precipitation, such as in mountainous areas. Therefore, observed and projected precipitation changes should always be considered in the context of interannual variability and the measurement or modelling uncertainty.

Key messages: 2.2.4 Mean precipitation

- Annual precipitation trends since 1950 show an increase by up to 70 mm per decade in north-eastern and north-western Europe and a decrease by up to 70 mm in some parts of southern Europe.
- Seasonal precipitation trends show an increase in winter precipitation in northern Europe and a decrease in southern Europe, albeit with large interannual variations.
- There is a robust signal from regional simulations across many parts of central and western Europe across all seasons. However, many parts of Europe, such as eastern and southern Europe, lack model consensus on the direction of change.

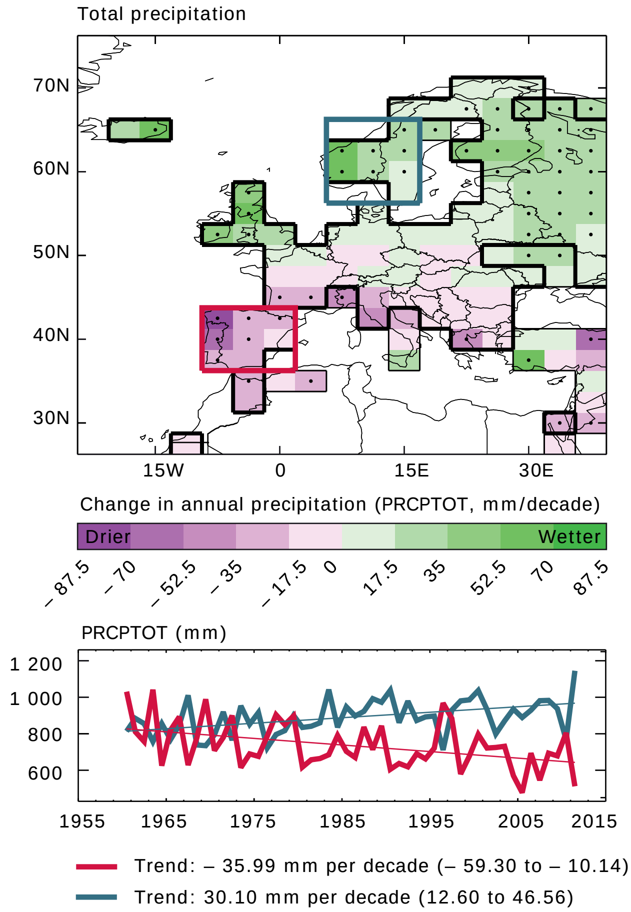
Past trends

Annual precipitation records averaged across Europe show no significant changes since 1950 according to the E-OBS dataset (Haylock et al., 2008), based on the European Climate Assessment dataset (Klok and Klein Tank, 2009). At the sub-continental scale, the trend in precipitation is most significant in north-eastern and south-western Europe. The majority of Scandinavia and the Baltic States have observed an increase in annual precipitation of greater than 14 mm per decade, with an increase of up to 70 mm per decade in western Norway. In contrast, annual precipitation has decreased in the Iberian Peninsula, in particular in north-western Spain and in northern Portugal (Map 2.5). While there is some evidence linking land use, in particular forest cover, to local and regional precipitation patterns (Millán, 2008), it is not clear if the relatively minor land-use changes since 1950 have influenced the observed precipitation trends.

Projections

Seasonal mean precipitation values and inter-annual variability is better reproduced by an ensemble of RCMs than by any single RCM (Beniston et al., 2007; Tapiador, 2010). Recent work, building on the two EU-funded research projects PRUDENCE (Christensen et al., 2002) and ENSEMBLES (van der Linden and Mitchell, 2009) has shown that RCMs have a reasonably strong consensus across Europe in predicting changes in seasonal average rainfall (Tapiador, 2010). These projections indicate a general increase in annual precipitation in northern Europe and a decrease in southern Europe. The change in annual mean between 1961–1990 and 2071–2100 according to the ENSEMBLES project (van der Linden and Mitchell, 2009) varies between 10% and 20 % in northern Europe and between – 5 to – 20 % in southern Europe and the Mediterranean (Map 2.6 left). Projections for summer precipitation show a decrease over southern, central and northwest Europe, which can reach of up to 60 % in parts of southern Europe. Precipitation is projected to remain constant or to increase slightly in northeast Europe (van der Linden and Mitchell, 2009; Tapiador, 2010) (Map 2.6 right).

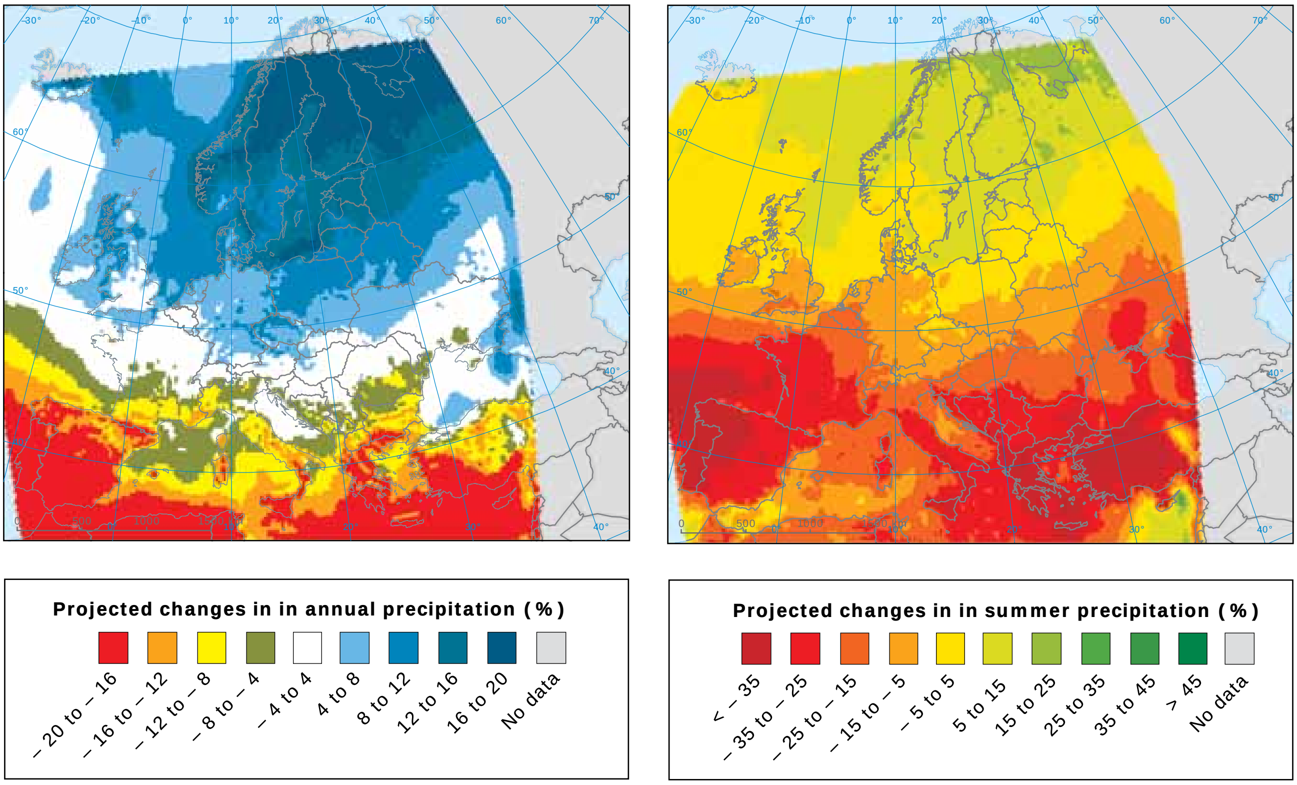
Map 2.5 Trends in annual precipitation across Europe (1960–2012)



Note: The trends are calculated using a median of pairwise slopes algorithm. Black dots represent high confidence in the sign of the long-term trend in the box (if the 5th to 95th percentile slopes are of the same sign). Boxes which have a thick outline contain at least three stations. Area averaged annual time series of percentage changes and trend lines are shown below each map for one area in northern Europe (blue line, 5.6 to 16.9 °E and 56.2 to 66.2 °N) and one in south-western Europe (red line, 350.6 to 1.9 °E and 36.2 to 43.7 °N).

Source: HadEX dataset, updated with data from the ECA&D dataset.

Map 2.6 **Projected changes in annual (left) and summer (right) precipitation (%) between 1961–1990 and 2071–2100**



Note: Projections are based on the ENSEMBLES project. They have been obtained from different regional climate models (RCMs) performing at 25 km spatial resolution with boundary conditions from five global climate models (GCMs), all using the IPCC SRES A1B emission scenario.

Source: van der Linden and Mitchell, 2009.

2.2.5 Precipitation extremes

Relevance

Changes in the frequency and intensity of extreme precipitation (see Box 2.4 for definitions) can have considerable impacts on society, including the built environment, agriculture, industry and ecosystem services. An assessment of past trends and future projections of extreme precipitation is therefore essential for advising policy decisions on mitigation and adaptation to climate change (Kendon et al., 2008). The risks posed by precipitation-related hazards, such as flooding events (including flash floods) and landslides, are also influenced by non-climatic factors, such as population density, floodplain development and land-use change. Hence, estimates of future changes in such risks need to consider changes in both climatic and non-climatic factors. Estimates of trends in heavy or extreme precipitation are more uncertain than trends in mean precipitation because, by their very nature, extreme precipitation events have a low frequency of occurrence. This leads to greater uncertainties when assessing the statistical significance of observed changes.

Past trends

Observational records do not indicate widespread significant trends in either the number of consecutive wet days (indicating flood risks) or dry days (indicating drought risks) across Europe (Map 2.7). Some changes in these variables have been observed across Europe but most of them are not statistically significant due to large natural variability. Interestingly, parts of north-western and north-eastern Europe show significant increasing trends in both the number of wet days and dry days. The proportion of Europe that has experienced extreme or moderate meteorological drought conditions did not change significantly during the 20th century (Lloyd-Hughes and Saunders, 2002). Summer droughts have also shown no statistically significant trend during the period 1901–2002 (Robock et al., 2005) ([41]).

Box 2.4 Definition of precipitation extremes

The term 'precipitation extreme' can refer to both high and low extremes of precipitation. High extremes of precipitation are defined either by the amount of precipitation in a given time period (e.g. daily or hourly) or by the period above a location-specific threshold. Indicators for extreme precipitation may be defined in terms of return periods (such as 1 in 20 years, termed absolute extremes). Alternatively, they may be defined relative to the normal precipitation distribution in an area (e.g. the heaviest 5 % of daily precipitation averaged over a 30-year time period, relative extremes). The former captures infrequent but possibly high impact events, whereas the latter has a more frequent sampling rate, capturing on average 18 days per year (over 30 years). The approach that is chosen depends largely on the application of the end user.

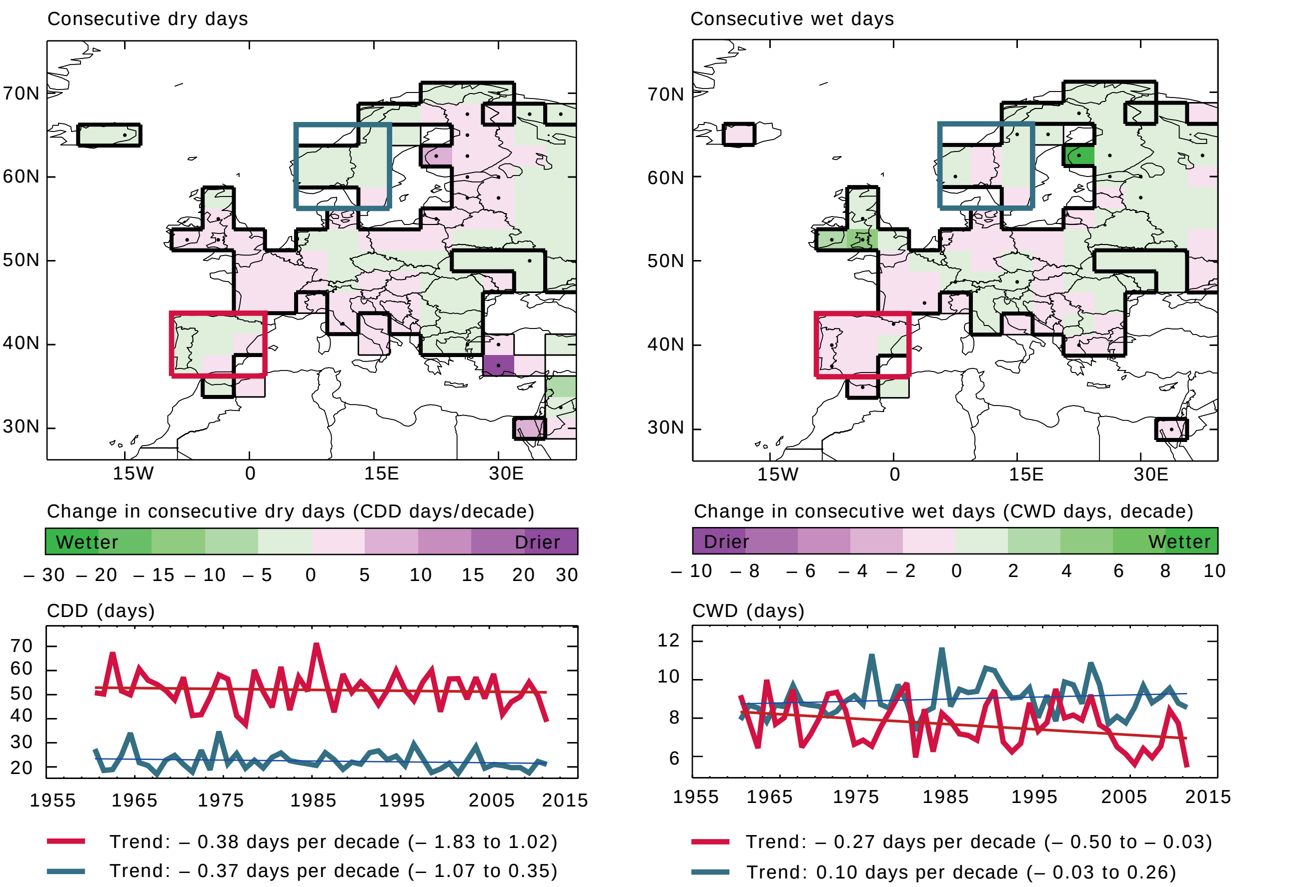
Low extremes of precipitation can be quantified in terms of consecutive dry days. Note, however, that an assessment of changes in drought conditions should also consider other factors, such as soil moisture and vegetation responses to changing atmospheric CO_2 concentration.

Key messages: 2.2.5 Precipitation extremes

- There are no widespread significant trends in either the number of consecutive dry or wet days across Europe.
- Heavy precipitation events are likely to become more frequent in most parts of Europe. The changes are strongest in Scandinavia in winter and in northern and eastern central Europe in summer.

([41]) More about droughts can be found in Section 3.3.4.

Map 2.7 Trends in consecutive wet days and consecutive dry days (1960–2012)



Note: High confidence in a long-term trend is shown by a black dot (if the 5th to 95th percentile slopes are of the same sign). Boxes which have a thick outline contain at least three stations. Area averaged annual time series of percentage changes and trend lines are shown below each map for one area in northern Europe (blue line, 5.6 to 16.9 °E and 56.2 to 66.2 °N) and one in south-western Europe (red line, 350.6 to 1.9 °E and 36.2 to 43.7 °N).

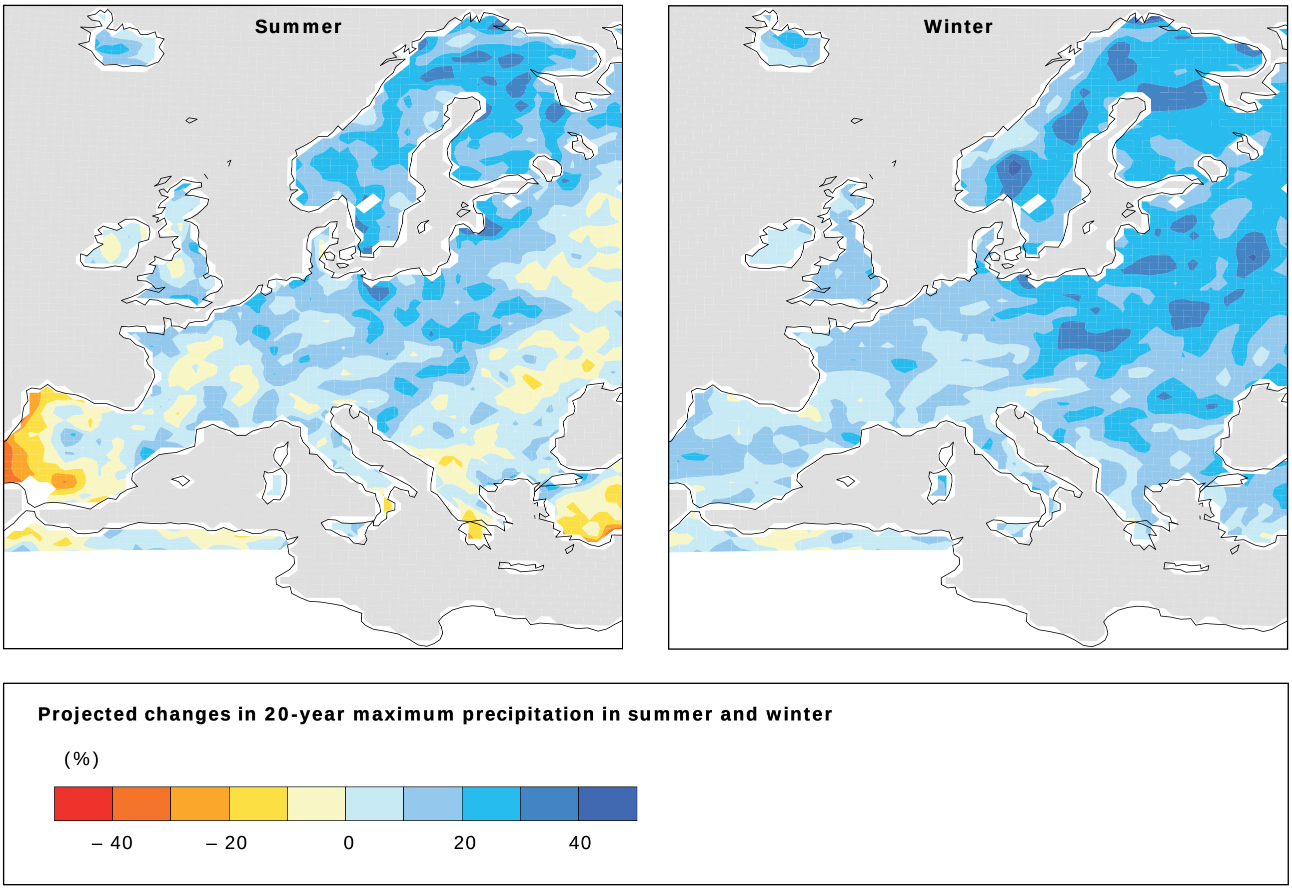
Source: HadEX dataset, updated with data from the ECA&D dataset.

Projections

Model-based projections for the 21st century show a reduction in the contribution of low rainfall days to total annual precipitation, and an increase in the contribution of high rainfall days in most parts of Europe, with the exception of the Iberian Peninsula and Mediterranean regions (Boberg et al., 2009). The recurrence time of intense precipitation is reduced from 20 years in the 1961–1990 periods to 6–10 years in the 2071–2100 period over northern and eastern central Europe in summer (Map 2.8 left) and to 2–4 years in Scandinavia in winter (Map 2.8 right) (Haugen and Iversen, 2008; Nikulin et al., 2011; Seneviratne et al., 2012).

Extreme precipitation events are likely to become more frequent in Europe (Solomon et al., 2007). Changes in extreme precipitation depend on the region, with a *high confidence* of increased extreme precipitation in northern, Atlantic (all seasons) and central Europe (except in summer) (Seneviratne et al., 2012). Future projections are inconsistent in southern Europe (all seasons) (Sillman and Roeckner, 2008; Boberg et al., 2009; Seneviratne et al., 2012). The number of consecutive dry days is projected to increase significantly in southern and central Europe, in particular in summer, and to decrease in northern Europe, in particular in winter (IPCC, 2012, figure 3.10).

Map 2.8 Projected changes in 20-year maximum precipitation in summer and winter



Note: Projected changes in 20-year maximum daily precipitation in summer (left) and winter (right) from 1961–1990 to 2071–2100 based on the ensemble mean using a regional climate model (RCM) nested in 6 general circulation model (GCMs). Changes that approximately lie outside of ± 10 % for the ensemble average are significant at the 10 % significance level.

Source: Nikulin et al., 2011.

2.2.6 Storms

Relevance

Storms are atmospheric disturbances that are defined by strong sustained wind. In many cases, they are accompanied by heavy precipitation (rain, hail or snow) and lightning. In Europe, storms can range from relatively small and localised events to large features covering a substantial part of the continent. They typically develop from extra-tropical cyclones which are low-pressure weather systems that occur between 30 and 80 °N and capture their energy from the temperature contrast between the sub-tropical and polar air masses that meet in the Atlantic Ocean. These extra-tropical cyclones are

Key messages: 2.2.6 Storms

- Storm location, frequency and intensity have shown considerable variability across Europe over the past century, making it difficult to identify clear trends. A recent reanalysis suggests that storminess has increased over the past century in northern and north-western Europe but this finding is not yet robust.
- Climate change projections for storms in the North Atlantic and Europe region show no clear consensus in either the direction of movement or the intensity of storm activity. However, a recent study involving 20 climate models projects enhanced extreme wind speeds over northern parts of central and western Europe, and a decrease in extreme wind speeds in southern Europe.

closely associated with atmospheric fronts which delineate changes in temperature, moisture, wind speed and direction, and atmospheric pressure. In northern and north-western Europe severe cyclones can occur all year. In central Europe severe cyclones occur mainly between November and February whereas weaker cyclones can also occur in other seasons.

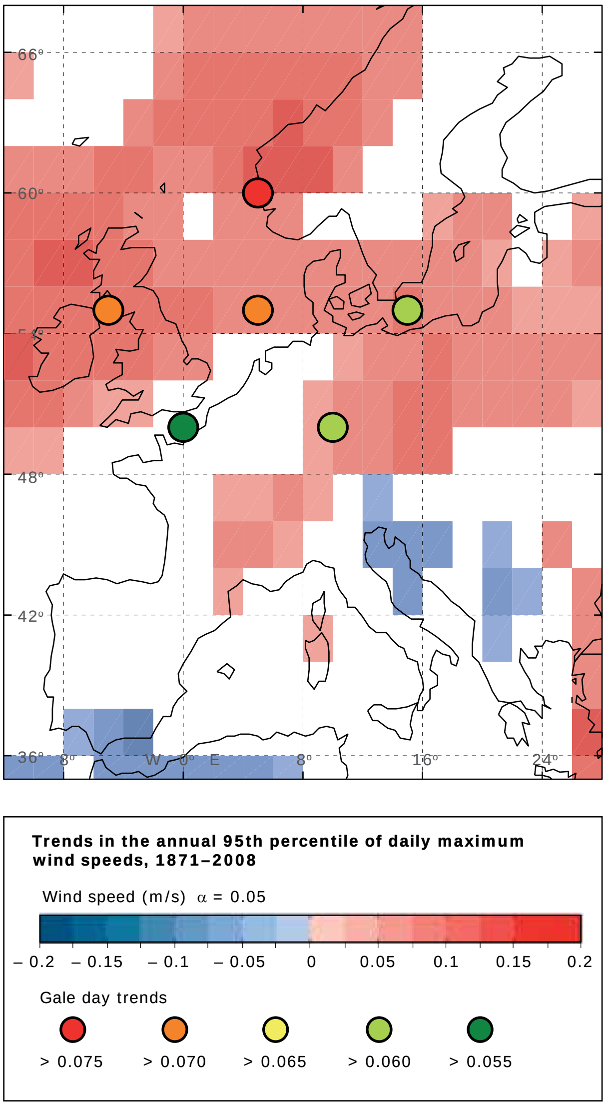
Studies of storm activity have increased in recent years as a result of improved observational datasets and the development of algorithms for the identification and quantification of these phenomena (Ulbrich et al., 2009). In addition, high-resolution GCM simulations for both present-day climate and climate change scenarios are increasingly becoming available (van der Linden and Mitchell, 2009). Nevertheless, there are still considerable uncertainties in our understanding of the processes influencing current storm activity and how these may be affected by climate change (Bengtsson et al., 2006; Pinto et al., 2007; Ulbrich et al., 2009).

Storm events are associated with intense winds and precipitation, which may lead to structural damage, flooding and storm surges (see Section 3.2.3 and Chapter 5). These events can have large impacts on human health and on vulnerable systems, such as forests, and transport and energy infrastructures. According to the Munich Re NatCatSERVICE and the EM-DAT database, storms were the costliest natural hazard (in terms of insured losses) in Europe between 1998 and 2009; they ranked fourth in terms of the number of human casualties (EEA, 2011b).

Past trends

Studies of past changes in extra-tropical storms have used a variety of methods for analysing their activity in the storm track regions, making it difficult to compare the results of different studies or to assess if there is any underlying climate change signal (Meehl et al., 2007; Ulbrich et al., 2009; Wang et al., 2011). Storm location and intensity in Europe has shown considerable variation over the past century. Locally, increases in maximum gust wind speeds have been observed over recent decades (Usbeck et al., 2010) but there is evidence for decreases in storm frequency since the 1990s (Ulbrich et al., 2009). Wind data at the local or regional levels can show a series of decreases and increases continuing over several decades. Long records of wind speed for various regions across Europe indicate that storminess has not significantly changed over the past 200 years (Matulla et al., 2007). They also indicate relatively high levels of storminess in north-western European during the 1880s, followed by below average conditions between the 1930s and 1960s, a pronounced increase in storminess until the mid-1990s, and average or below activity afterwards. Somewhat similar patterns were observed in other parts of Europe.

Map 2.9 Trends in the extreme wind speeds in the period 1871–2008 based on reanalysis



Note: Trends in the annual 95th percentile of daily maximum wind speeds in the 20th century reanalysis data set (ensemble mean) during the period 1871–2008. The trend is given in the units of the interannual standard deviation and plotted only when significant. The coloured circles indicate trends in the number of 'gale days' (an index that represents the number of extremely windy days) over the period at the specific locations.

Source: Donat, Renggli, et al., 2011.

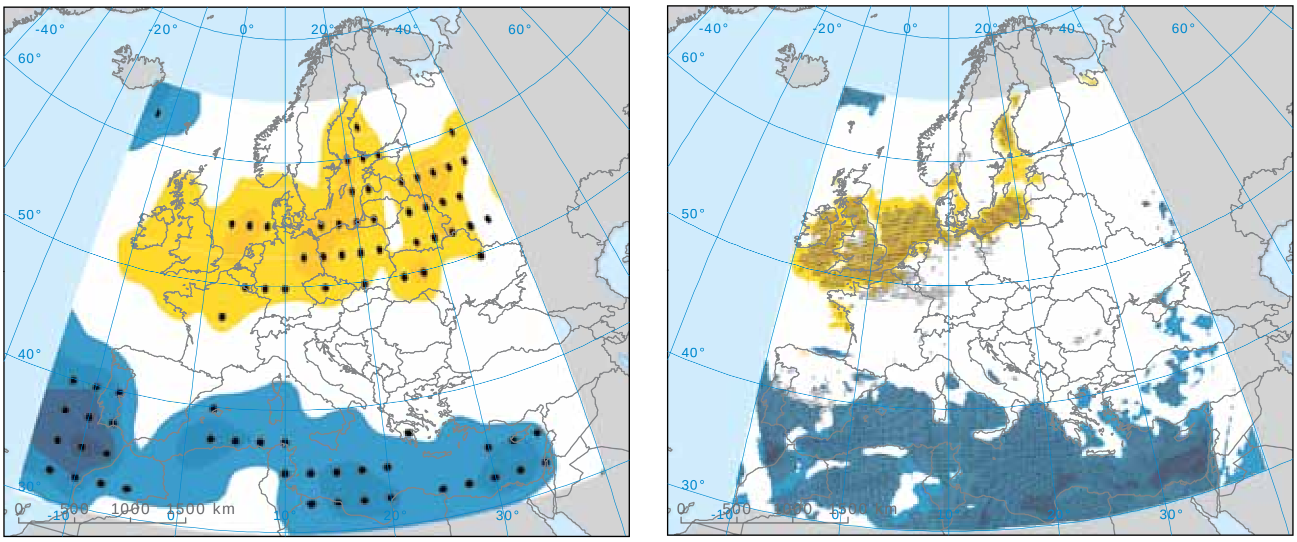
Reanalyses for the time span 1871 to 2008 suggest an increasing long-term trend in storminess across north-western Europe. Storminess towards the end of the 20th century reached unprecedented values in the north-eastern North Atlantic, the North Sea and the Baltic Sea region (Map 2.9) (Donat, Renggli, et al., 2011). However, somewhat different results were found in another reanalysis (Wang et al., 2011).

Projections

The simulation of extra-tropical cyclones in climate models remains a scientific challenge in spite of significant recent progress. Climate change projections show no clear consensus in either the direction of movement (poleward or equator-ward) or the intensity of extra-tropical cyclone activity in the North Atlantic region of western Europe (Meehl et al., 2007; Ulbrich et al., 2009; McDonald, 2011). Earlier models showed some agreement on a future poleward shift in storm tracks, which would increase the frequency of the most intense wind events in higher latitudes (Gastineau and Soden, 2009). However, more recent projections with climate models that include a higher resolution stratosphere show an equator-ward shift in the Atlantic storm track which could double the predicted increase in winter rainfall over western and central Europe compared to other climate projections (McDonald, 2011; Scaife, 2011). It should be noted that the measure used to identify 'storm tracks' is different to that for 'cyclone tracks', so caution should be exercised when comparing these two measures.

Several studies suggest decreases in the number of storms in Europe but increases in the strongest, most damaging storms, in particular in northern and western Europe (Pinto et al., 2007, 2009; Debernard and Røed, 2008; Della-Marta and Pinto, 2009; Donat et al., 2010). A recent study involving ensemble simulations with 9 GCM and 11 RCM projects enhanced extreme wind speeds over northern parts of central and western Europe in most simulations and in the ensemble mean, and a decrease in extreme wind speeds in southern Europe (Donat, Leckebusch, et al., 2011) (see Map 2.10).

Map 2.10 Projected changes in extreme wind speed based on GCM and RCM ensembles



Projected changes in extreme wind speed based on GCM (left) and RCM (right) ensembles

Magnitude of change (ms[-1])

– 1.0 – 0.75 – 0.5 – 0.25 0.25 0.5 0.75 1.0

● Statistical significance above 0.95

Note: Ensemble mean of changes in extreme wind speed (defined as the 98th percentile of daily maximum wind speed) for A1B (2071–2100) relative to 1961–2000. Left: based on 9 GCMs. Right: based on 11 RCMs. Coloured areas indicate the magnitude of change (unit: m s–1), statistical significance above 0.95 is shown by black dots.

Source: Donat, Leckebusch, et al., 2011.

2.3 Cryosphere

2.3.1 Overview

Relevance

The cryosphere includes all permanent or seasonal snow and ice on land, in the seas, rivers and lakes, and in the ground (permafrost). It is the second largest component of the climate system after the oceans with regard to mass and heat capacity. Because of its importance several recent publications have compiled relevant research on the cryosphere (Voigt et al., 2010; AMAP, 2011; Olsen et al., 2012).

Snow and ice are important for the global climate system (see Section 2.1). Much of the sunlight that hits these surfaces is reflected back into space instead of warming the Earth. As melting of snow and ice expands to darker surfaces such as water or ground, more heat is absorbed. These positive ice-temperature feedbacks are already accelerating the loss of sea ice in summer and autumn, which has resulted in higher winter near-surface air temperatures in the Arctic (Screen and Simmonds, 2010).

Ice and snow are important for many ecosystems. Some species spend their entire life-cycle in areas dominated by the cryosphere whereas others are adapted to temporary snow and ice. Observed changes in the cryosphere are already affecting species interactions and entire ecosystems (Post et al., 2009). Model studies also suggest positive vegetation-climate feedbacks, which accelerate climate change. For example, the expansion of deciduous vegetation in the Arctic can contribute to temperature change by creating more dark surfaces (Swann et al., 2010).

Mountain permafrost areas in the Alpine region affect both the landscape and ecosystems. The permafrost soils in boreal and Arctic ecosystems store almost twice as much carbon as is currently present in the global atmosphere (Zimov et al., 2006). Permafrost thaw at high latitudes could thus cause carbon emissions, which would further accelerate climate change (Schuur et al., 2009; Shakhova et al., 2010; Avis et al., 2011).

The cryosphere plays an important role in water management. Two thirds of the world's freshwater resources are frozen. Seasonal melting releases water during the warm season, thereby supporting water supplies and hydropower. Changes in the cryosphere have further social and economic consequences by affecting sea ice, the distribution of permafrost on land, and by contributing to global sea-level rise. Such changes affect transport routes, building technology, tourism and recreation, and opportunities to exploit natural resources.

Selection of indicators

The cryosphere provides easily observable signs of climate change over a wide range of time scales, from millennia to seasonal variations within a year. This section presents the following indicators, which cover the main components of the cryosphere:

- *Snow cover:* Snow covers a large area, but has relatively small volume. It's reflection of light is important for climatic conditions, it insulates the soil in winter and it is an important temporary water storage.
- *Greenland ice sheet:* The continental ice sheet of Greenland influences the global climate in many

Key messages: 2.3 Cryosphere

- Almost all components in the cryosphere are decreasing, which is consistent with a warming climate. The fast reduction in Arctic Sea ice is particularly prominent.
- Further reductions in the cryosphere are projected for the future. The projected changes vary across regions and indicators, and there are large uncertainties in some of the projections.
- The melting of ice and snow and thawing of permafrost may cause positive feedbacks that can accelerate climate change further.
- Changes in the cryosphere affect global sea level, many ecosystems and their services, freshwater supply, river navigation, irrigation and power generation. The projected changes can increase natural hazards and the risk of damage to infrastructure. At the same time they can create new opportunities for navigation and the exploitation of natural resources.

ways. First of all, it has important effects on global sea level. Furthermore, it modifies ocean temperatures and circulation, vegetation and land-surface albedo.

- *Glaciers:* Glaciers and ice caps influence sea level, river flow and freshwater supply, ecosystems and many human activities.
- *Permafrost:* Permafrost is ecologically important in high mountains and in Arctic areas. It influences the water content of soils, vegetation, ecosystems and landscapes. The thawing of permafrost causes structural change of landscapes and potentially increases natural hazards. In the Arctic, thawing permafrost contributes to the release of GHGs, including CH_4, from frozen organic material.
- *Arctic and Baltic Sea ice:* Sea ice covers large areas. It reflects light more than open sea and impacts on ocean circulation, which transports heat from the equator to the poles. The sea ice and its variation affects navigation and the exploitation of natural resources.
- *Lake and river ice*: Seasonal lake ice is important for aquatic ecosystems and in some areas for winter tourism. This indicator is presented in Section 3.3.6.

Data quality and data needs

Data on the cryosphere vary significantly with regard to availability and quality. Snow and ice cover have been monitored globally since satellite measurements started in the 1970s. Improvements in technology allow for more detailed observations and higher resolution. High quality long-term data is also available on glaciers throughout Europe. Direct historical area-wide data on the Greenland ice sheet tracks about 20 years, but reconstructions give a 200 000 year perspective. Data on permafrost are generally restricted to the last 15–25 years.

Continuous efforts are being made to improve on knowledge of the cryosphere. Intensive development work is under way to develop projections, which are essential for scenarios of climate change impacts and adaptation. Due to their economic importance special effort is also devoted to improving real-time monitoring of, for example, snow cover and sea ice. In general, glacier and sea ice extent are easily observable but ice mass information, for example, is difficult to obtain.

2.3.2 Snow cover

Relevance

Snow influences the climate and climate-related systems because of its high reflectivity, insulating properties, effects on water resources and ecosystems, and cooling of the atmosphere.
A decrease in snow cover contributes to accelerated climate change (Flanner et al., 2011).

In Europe about half of the 800 million people live on areas that have snow cover in January in an average winter. Changes in snow cover affect human well-being through effects on water availability, hydropower, navigation, infrastructure, the livelihoods of indigenous Arctic people, environmental hazards, winter recreation and outdoor light conditions. Variation in snow cover affects winter road and rail maintenance, and the exploitation of natural resources in cold regions (ACIA, 2005; UNEP, 2007). Snow cover is most sensitive to climate change at low elevations in temperate regions.

Key messages: 2.3.2 Snow cover

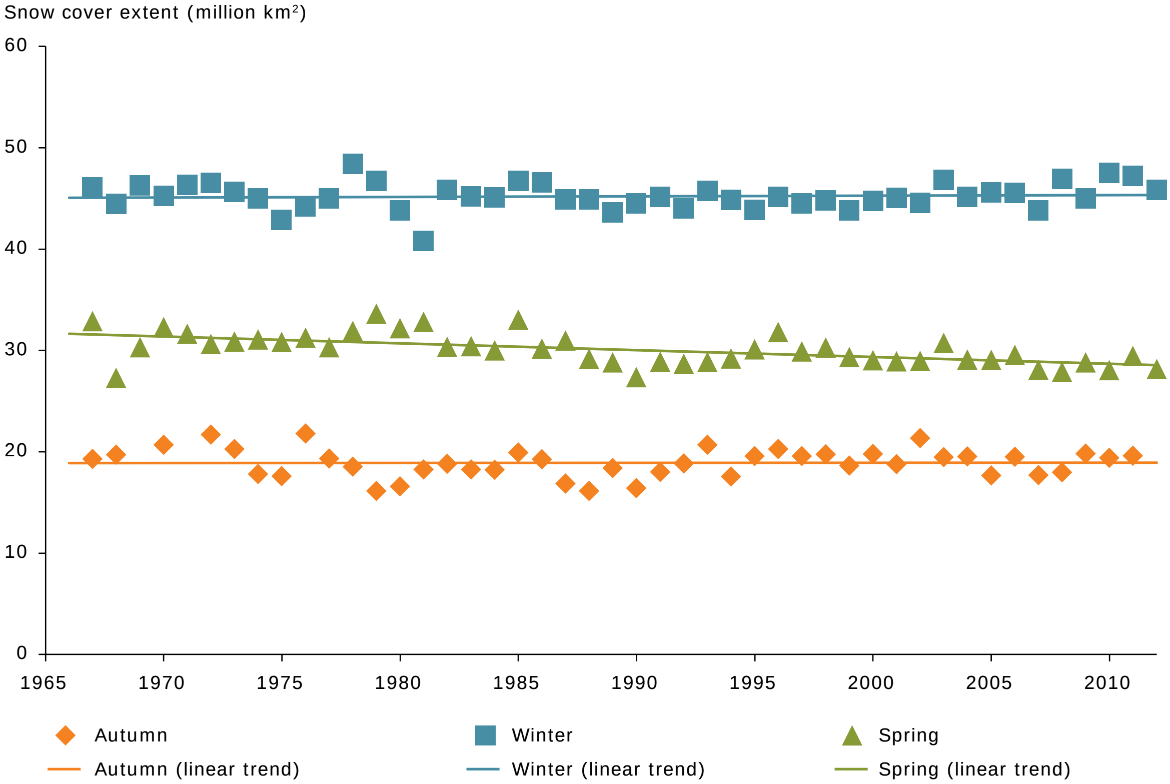
- Snow cover extent in the Northern Hemisphere has fallen by 7 % in March and 11 % in April during the past 4 decades. In winter and autumn no significant changes have occurred.
- Snow mass in Europe has decreased by 7 % in March from 1982 to 2009.
- Model simulations project widespread reductions in the extent and duration of snow cover in Europe over the 21st century. However, there are large uncertainties in the projections.
- Changes in snow cover affect the Earth's surface reflectivity, water resources, the flora and fauna and their ecology, agriculture, forestry, tourism, snow sports, transport and power generation.

Past trends

Satellite observations on the monthly snow cover extent in the Northern Hemisphere are available since November 1966 (RUGSL, 2011). Figure 2.10 shows that snow covered on average 45 % of the land area of the Northern Hemisphere in winter (December to February), varying from less than 41 % in 1980–1981 to over 48 % in 1977–1978 (RUGSL, 2011). This satellite data shows that there are no trends from 1967 to 2010 in snow cover in fall (September-November) and winter (December–February), but snow cover in spring has decreased significantly. According to a detailed statistical analysis of the snow cover in the Northern hemisphere the rate of decrease in March and April in the period 1970–2010 was around 0.8 million km² per decade, corresponding to a 7 % decrease in March and an 11 % decrease in April from the pre-1970 values (Brown and Robinson, 2011).

Trends in snow cover vary in different parts of Europe. In some mountain regions, such as the Alps and the Norwegian mountains, snow depth has decreased at low elevations where the temperature increased over the freezing point whereas it has increased at high elevations where both precipitation and temperature have increased but the temperature has remained below the freezing point for extended periods (Bocchiola and Diolaiuti, 2009; Stewart, 2009; Dyrral, 2010). In other mountain regions such as the Carpathians, Tatra, Pyrenees, and Caucasus, there have been either decreasing or variable trends (Diaz et al., 2003; Lapin et al., 2007).

Figure 2.10 Trend in autumn, winter and spring snow cover extent over the Northern Hemisphere (1967–2011)



Note: Mean autumn (September, October, November), winter (December, January, February) and spring (March, April, May) snow cover extent over the Northern Hemisphere in 1967–2011 with linear trends.

Source: RUGSL, 2011.

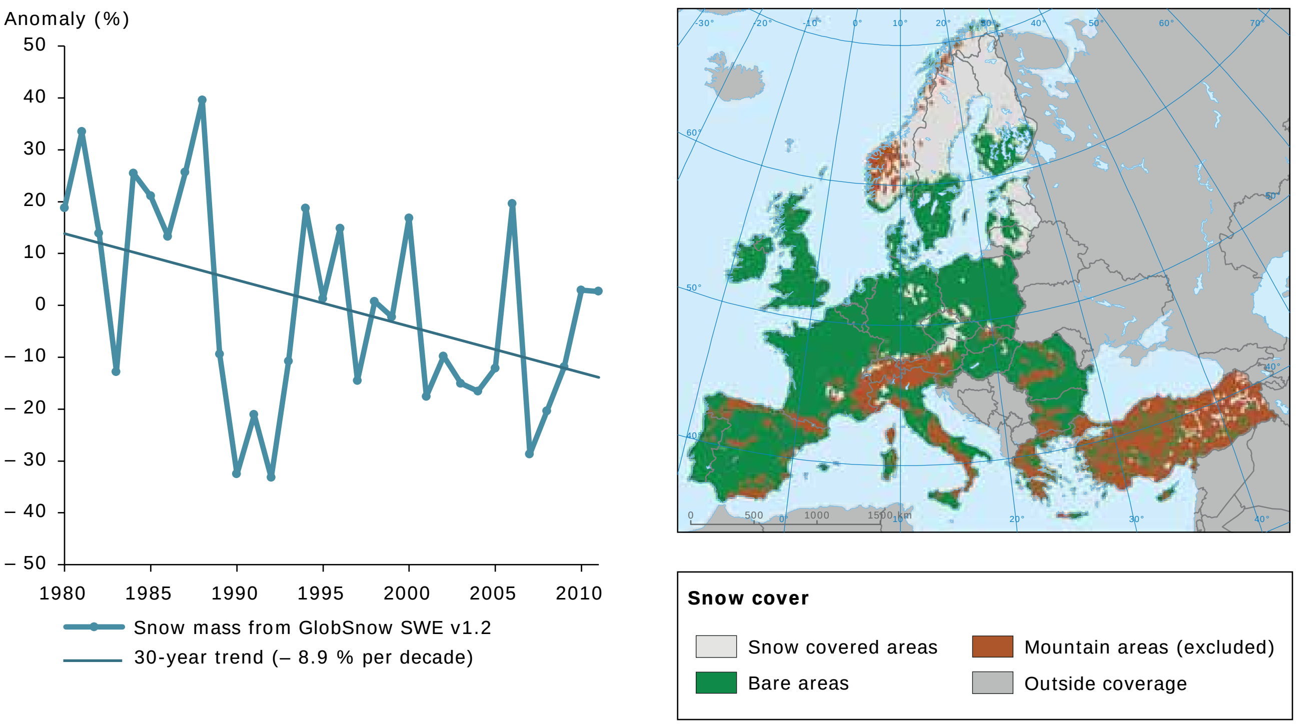
In the lowlands of western Europe, snow is not a permanent winter phenomenon — it may come and go several times during the cold months. Decreasing snow cover trends have been observed in, for example, Britain (Perry, 2006), Germany (Schwarz et al., 2007), Poland (Bednorz, 2011) and Nordic countries (Wilson et al., 2010). In general, snow conditions in these areas correlate strongly with large-scale circulation patterns as indicated by the NAO (Bednorz, 2011; Brown and Robinson, 2011).

The snow mass (i.e. the amount of water that the snow contains) is another important variable describing seasonal snow. In the Northern Hemisphere, a 7 % decrease has been observed between 1982 and 2009 for March (Takala et al., 2011). An extension of this data focusing on EEA member countries, excluding mountain areas, also demonstrates this decline (Figure 2.11).

Projections

The seasonal snow cover is likely to continue shrinking (Stewart, 2009). Map 2.11 shows projections of changes in annual snow fall days based on a multi-model ensemble. The multi-model mean shows decreases in days with snow fall exceeding 1 cm across Europe. Days with snow fall above 10 cm show increases in large parts of northern Europe and decreases in most other regions. There is, however, considerable uncertainty in these projections due to large differences between the upper and lower limits of the model projections (not shown here). Because snow cover is sensitive to snowfall as well as temperature, increased snowfall will not necessarily translate into more snow on the ground (Räisänen and Eklund, 2011). A study has projected a reduced number of snow cover days in northern Europe (defined as 55–70 °N, 4.5–30 °E)

Figure 2.11 Trend in March snow mass in Europe (excluding mountain areas) (1980–2011)



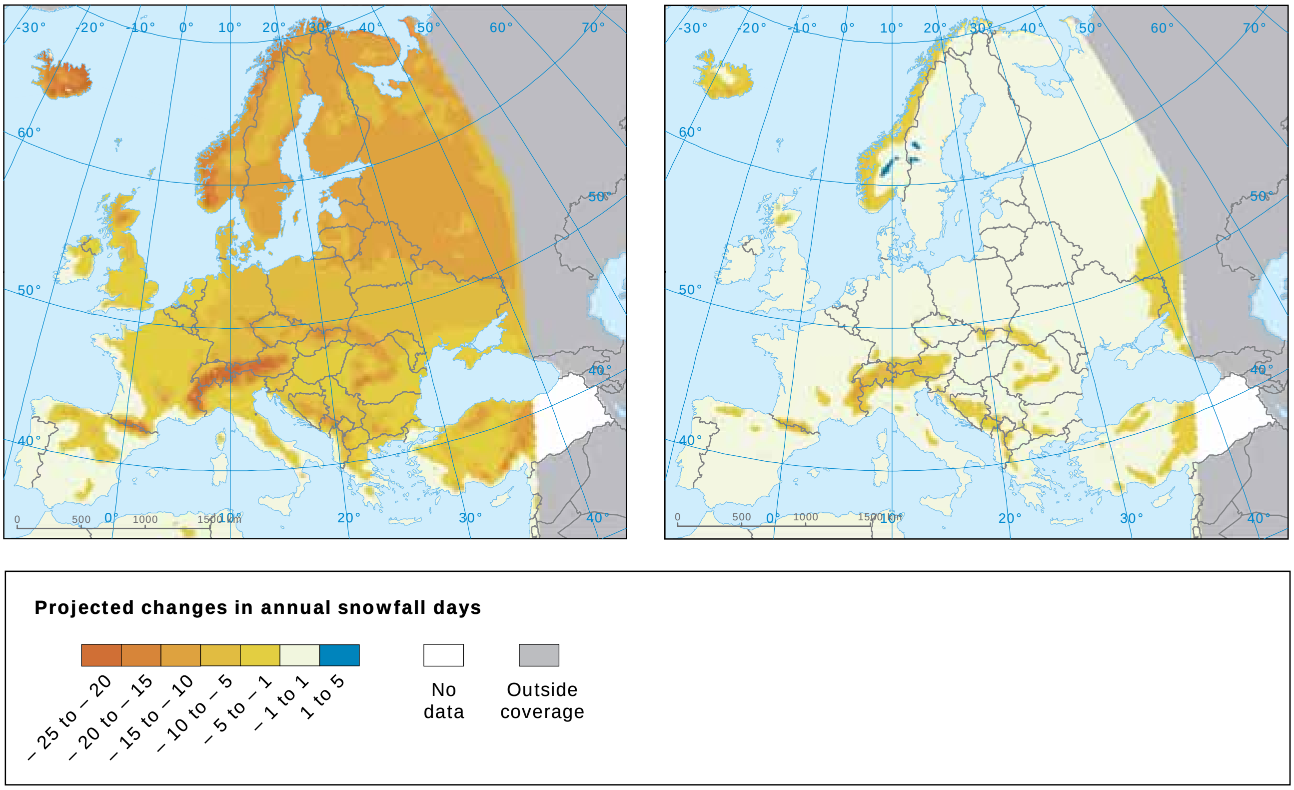
Note: Left: Anomalies for March snow mass and the 30-year linear trend in the EEA region (excluding mountain areas). Right: Snapshot of snow cover on 15 February 2009.

Source: GlobSnow (http://www.globsnow.info) (Luojus et al., 2011).

of up to 40–70 days in 2071–2100 compared to the baseline period 1961–1990. The study used a RCM driven by an ensemble of 7 GCMS for 4 SRES emission scenarios (Kjellström et al., 2011). The projections depend on the emission scenario and the underlying GCM simulation.

Model projections of 21st century change in snow water equivalent (SWE) in the Northern Hemisphere under the SRES A1B emissions scenario suggest that SWE increases in the coldest parts of the Northern Hemisphere continents, but decreases elsewhere (Räisänen, 2007). The multi-model mean from the CMIP5 modelling exercise projects changes in March/April snow cover in the Northern Hemisphere during the 21st century of about 7 % and 27 % in a low emission scenario (RCP 2.6) and a high emission scenario (RCP 8.5), respectively (Brutel-Vuilmet et al., 2012). Despite the projected decrease in long-term mean SWE in the Northern Hemisphere, model simulations indicate occasional winters of heavy snowfall, but these become increasingly uncommon towards the end of the 21st century. Significant reductions in snow mass in Europe are likely to occur in Switzerland (BAFU, 2012), the alpine range of Italy (Soncini and Bocchiola, 2011), the Pyrenees (López-Moreno et al., 2009), the Turkish mountains (Özdoğan, 2011) and Balkan mountains (FAO, 2010). In these areas the change can have dramatic effects as melt water contributes up to 60–70 % of annual river flows.

Map 2.11 Projected changes in annual snowfall days



Note: Multi-model mean of changes in annual snowfall days from 1971–2000 to 2041–2070 exceeding (A) 1 cm and (B) 10 cm based on 6 RCM simulations for the emission scenario A1B.

Source: Vajda et al., 2011.

2.3.3 Greenland ice sheet

Relevance

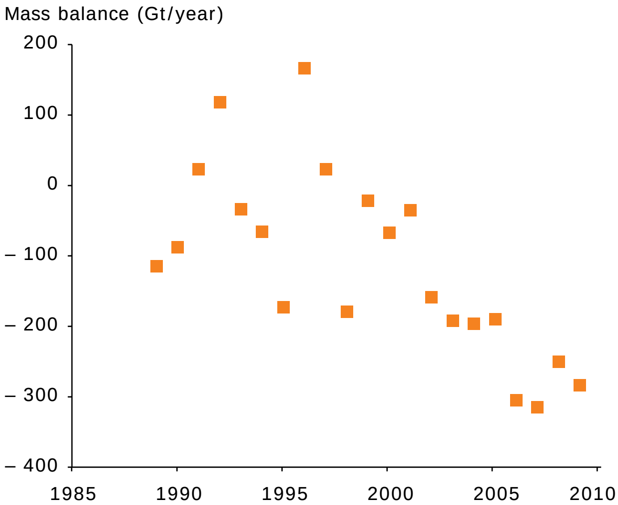
The fate of the Greenland ice sheet highlights potentially major consequences of climate change as it is directly linked to global sea-level rise. The speed of ice loss, known as the ice sheet 'mass balance', is the most important indicator of ice sheet change. An increased rate of mass loss results in a faster rise in sea level. In addition, melt water from Greenland reduces the salinity of the surrounding ocean. An upper layer of fresher water may reduce the formation of dense deep water, one of the mechanisms driving global ocean circulation.

Past trends

The mass balance of the Greenland ice sheet is determined by snow fall, summer melting of snow, and the icebergs breaking off the glaciers. Several different methods are used to monitor the changes of the Greenland ice sheet (Krabill et al., 2002; Shepherd and Wingham, 2007; Chen et al., 2011; Rignot et al., 2011; Zwally et al., 2011). The overall conclusion is that Greenland is losing mass at an accelerating rate (Figure 2.12). The yearly cumulated area where melting occurs has also increased significantly (Figure 2.13). Since 2006, high summer melt rates have led to a Greenland ice sheet mass loss of 273 billion tonnes a year (Rignot et al., 2011). This ice loss corresponds to a sea-level rise of approximately 0.7 mm per year (about a quarter of the total sea-level rise of 3.1 mm a year) (see Section 3.2.2 for further information on global and European sea-level rise).

Exceptional melting was recorded on the Greenland ice sheet in the summer of 2012. On 12 July 2012 nearly the entire ice cover experienced some degree of surface melting (NASA, 2012). The extreme melt event coincided with an unusually strong ridge of warm air over Greenland. The ridge was one of a series that dominated Greenland's weather in the summer of 2012. Ice core data suggest that large-scale melting events of this type have occurred about once every 150 years on average, the most recent one in 1889. It is not currently possible to tell whether the frequency of these rare extensive melt events has changed.

Figure 2.12 Mass balance of the Greenland ice sheet from mass budget calculations (1989–2009)

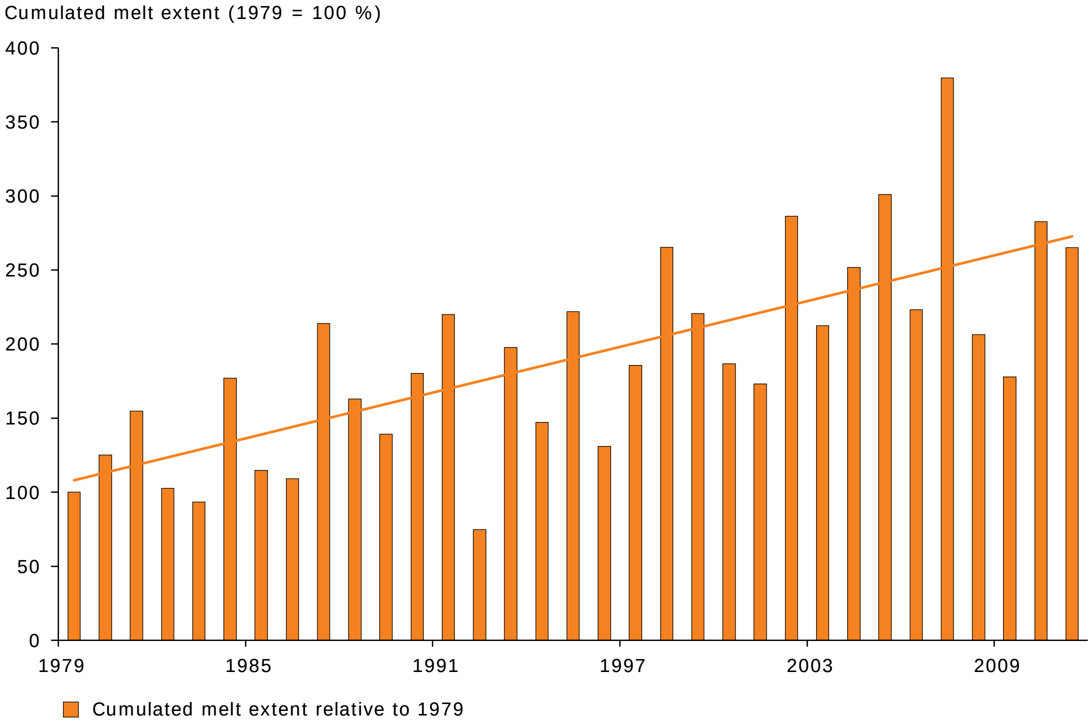


Source: van den Broeke, 2011.

Key messages: 2.3.3 Greenland ice sheet

- The Greenland ice sheet is the largest body of ice in the northern hemisphere and plays an important role in the cryosphere. It changed in the 1990s from being in near mass balance to losing about 100 billion tonnes of ice per year. Ice losses have since then more than doubled to 250 billion tonnes a year averaged over 2005 to 2009.
- The contribution of ice loss from the Greenland ice sheet to global sea-level rise is estimated at 0.14–0.28 mm/year for the period 1993–2003 and has since increased. The recent melting of the Greenland ice sheet is estimated to have contributed up to 0.7 mm a year to sea-level rise, which is approximately one quarter of the total sea-level rise of about 3.1 mm/year.
- Model projections suggest further declines of the Greenland ice sheet in the future but the processes determining the rate of change are still poorly understood.

Figure 2.13 Trend in yearly cumulated melting area of the Greenland ice sheet (1979–2011)



Note: Yearly cumulated area of the Greenland ice sheet showing melt during the period 1979 to 2011 relative to area in 1979. The linear trend 1979–2011 is included.

Source: Fettweis et al., 2011.

Ice is lost from Greenland, in roughly equal amounts, through surface melting and ice motion (van den Broeke et al., 2009). Surface melting occurs when warm air and sunlight first melt all the previous year's snow and then the ice itself. At higher elevations snow accumulates and the local mass balance remains positive. With global warming the height at which melting occurs moves upwards and eventually a tipping point may be reached after which the whole ice sheet starts to melt (Gregory and Huybrechts, 2006).

Projections

Projections of the surface mass balance of the Greenland ice sheet with many global climate models indicate that the 'tipping point' above which the Greenland ice decline will completely melt is a global temperature rise of about 3 °C (Gregory and Huybrechts, 2006). However, this estimate is subject to considerable uncertainty (Bougamont et al., 2007).

Climate models with an embedded dynamic ice sheet model have suggested that a melt of 10–20 % of the current ice sheet volume, inducing ice loss in southern Greenland, would lead to an irreversible sea-level rise of about 1.3 m over several centuries. The addition of contributions by outlet glaciers (Ridley et al., 2005; Pfeffer et al., 2008) and the expected surface mass balance-driven losses give an upper bound of about 19 cm sea-level rise from the Greenland ice sheet by 2100.

2.3.4 Glaciers

Relevance

Glaciers are particularly sensitive to changes in the global climate because their surface temperature is close to the freezing/melting point (Zemp et al., 2006). When the loss of ice, mainly from melting and calving in summer, is larger than the accumulation from snowfall in winter, the mass balance of the glacier turns negative and the glacier shrinks.

Glaciers are an important freshwater resource and act as 'water towers' for lower-lying regions. The water from melting glaciers contributes to water flow in rivers during summer months and thus helps maintain water levels for irrigation, hydropower production, cooling water and navigation. The effects of a reduction in glaciers are, however, complex and vary from location to location (SGHL and CHy, 2011). Glacier melting also contributes to global sea-level rise (Radić and Hock, 2011; Rignot et al., 2011).

Past trends

A general loss of glacier mass has occurred in nearly all European glacier regions (Figure 2.14). The Alps have lost about two thirds of their ice mass since 1850 (Zemp et al., 2005, 2006, 2008) and individual glaciers have faced even greater losses.

Glaciers in different regions have been affected somewhat differently by recent climate change. In particular, Norwegian coastal glaciers were expanding and gaining mass up to the end of the 1990s due to increased winter snowfall on the north Atlantic coast. Now these glaciers are also retreating (Andreassen et al., 2005; Nesje et al., 2008). Some ice caps at higher elevations in north-eastern Svalbard seem to be increasing in thickness (Bamber, 2004; Bevan et al., 2007), but estimates for Svalbard as a whole show a declining mass balance (Hagen et al., 2003; Kohler et al., 2007).

The centennial retreat of European glaciers is attributed primarily to increased summer temperatures. However, changes in winter precipitation, reduced glacier albedo due to the lack of summer snow fall and various other feedback processes, such as the increasing debris cover on the glacier, can influence the behaviour of glaciers, in particular on a regional and decadal scale.

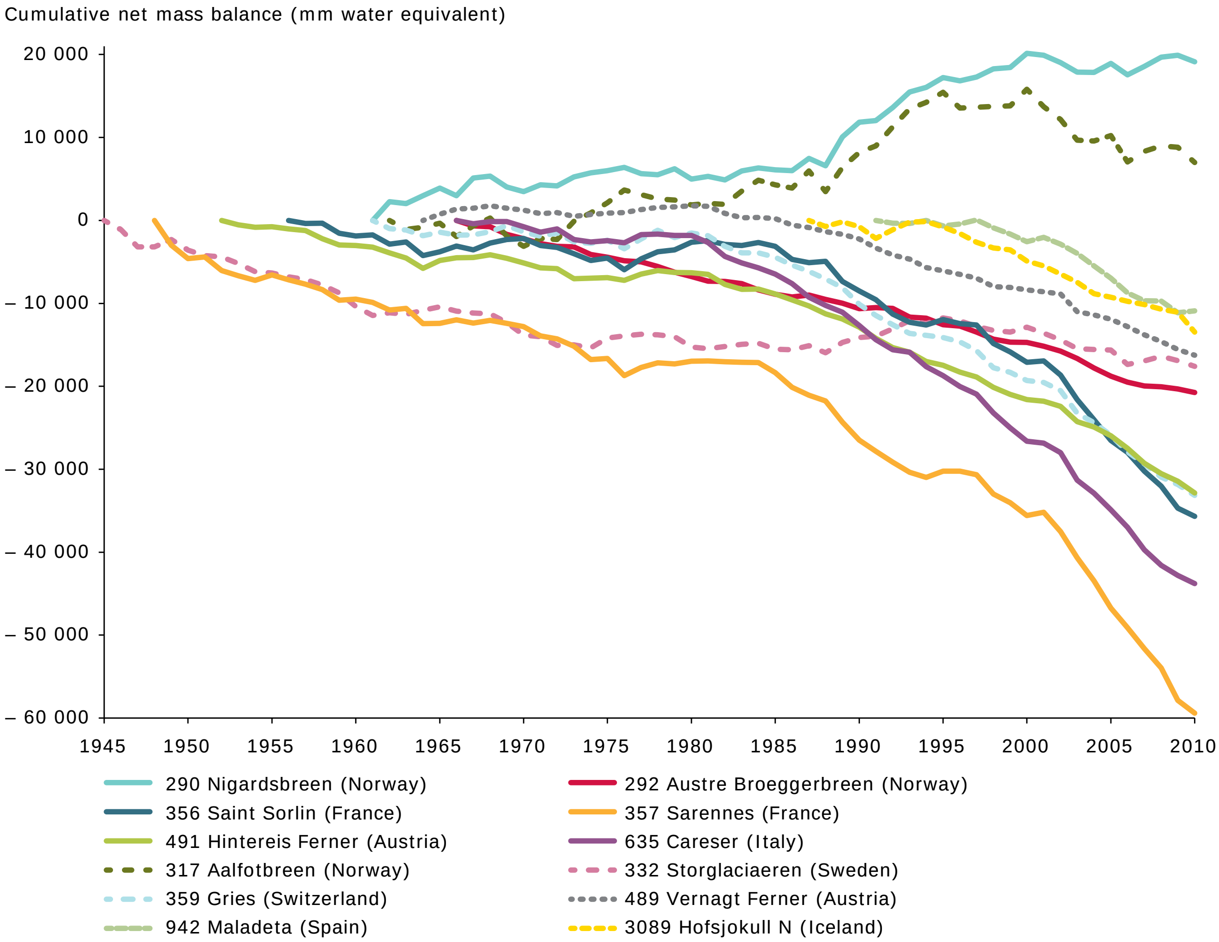
Projections

The retreat of European glaciers is projected to continue throughout the 21st century. One study estimates that the volume of European glaciers will decline between 22 and 66 % compared to the current situation (all European regions combined; Figure 2.15) (Radić and Hock, 2011). The relative volume loss is largest in the European Alps (76 ± 15 % standard deviation of 10 climate scenarios). In Norway nearly all smaller glaciers are projected to disappear and overall glacier area as well as volume may be reduced by about one third by 2100 even under the low SRES B2 emissions scenario (Nesje et al., 2008). If summer air temperatures were to rise by 3 °C and precipitation remained constant, the European Alps could lose about 80 % of their average ice cover compared to the period 1971–1990 (Zemp et al., 2006).

Key messages: 2.3.4 Glaciers

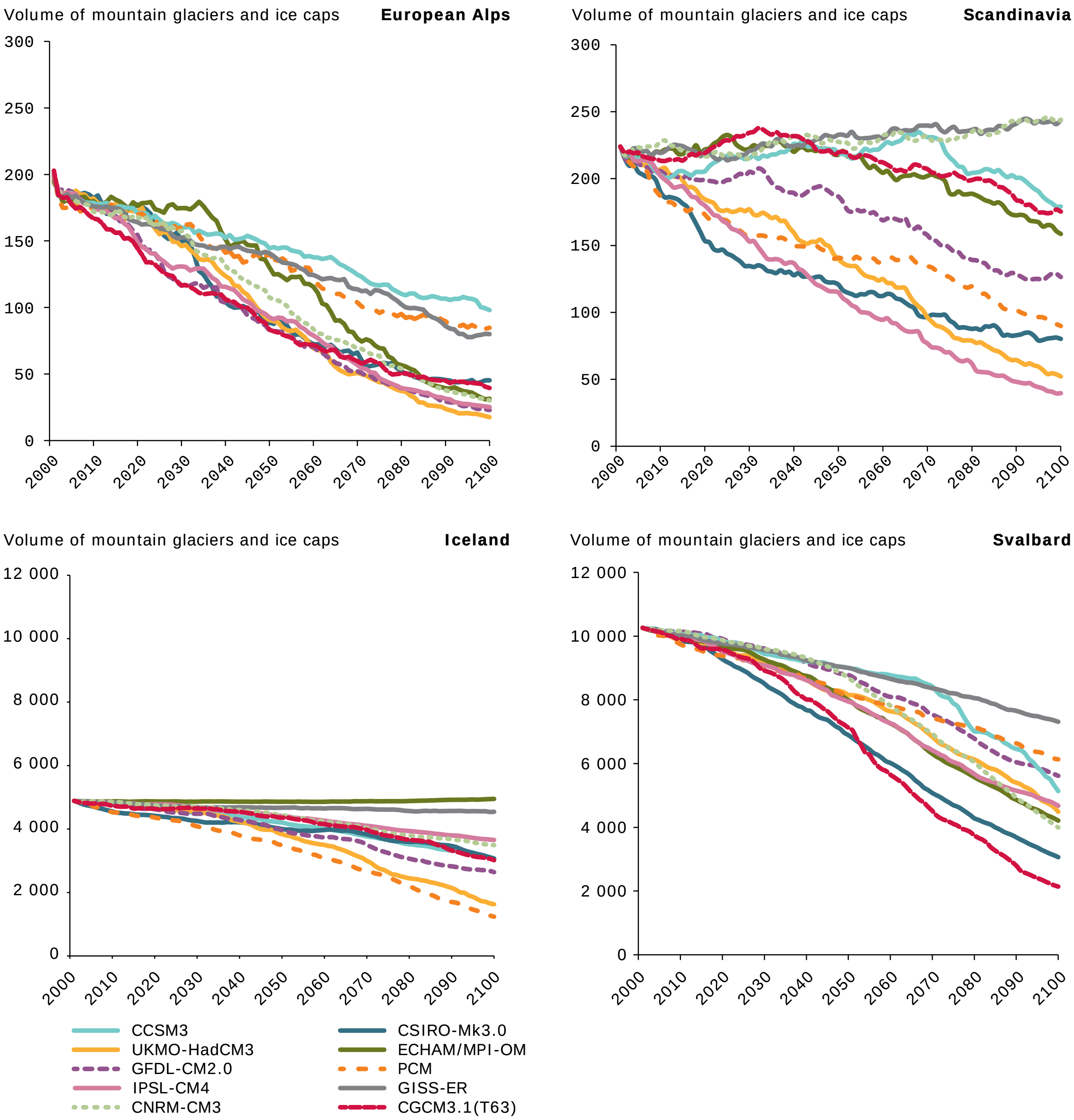
- The vast majority of glaciers in the European glacial regions are in retreat. Glaciers in the European Alps have lost approximately two thirds of their volume since 1850, with clear acceleration since the 1980s.
- Glacier retreat is expected to continue in the future. The volume of European glaciers has been estimated to decline between 22 and 66 % compared to the current situation by 2100 under a business-as-usual emission scenario.
- Glacier retreat contributes to sea-level rise and it affects freshwater supply and run off regimes, river navigation, irrigation and power generation. It may also cause natural hazards and damage to infrastructure.

Figure 2.14 Cumulative specific net mass balance of European glaciers (1946–2010)



Source: Fluctuation of Glaciers Database (FoG), World Glacier Monitoring Service (http://www.wgms.ch), 2011; data for 2010 are preliminary.

Figure 2.15 Projected changes in the volume of all mountain glaciers and ice caps in the European glaciated regions



Note: Projected volume for 2001–2100 of all mountain glaciers and ice caps in the European glaciated regions derived using a mass balance model driven with temperature and precipitation scenarios from 10 GCMs. European Alps (top left), Scandinavia (top right), Iceland (bottom left), Svalbard (bottom right).

Source: Radić and Hock, 2011.

2.3.5 Permafrost

Relevance

Permafrost is permanently frozen ground and consists of rock or soil that has remained at or below 0 °C continuously for more than 2 years. It is a widespread phenomenon in the Arctic as well as in the alpine high mountain environments (Harris et al., 2009; Boeckli et al., 2012; Gruber, 2012). Climate change leads to changes in spatial extent, thickness and temperature of permafrost. The changes are not uniform across all permafrost areas, but depend on the geographical location and specific characteristics of the permafrost.

Permafrost influences the evolution of landscapes and ecosystems and affects human infrastructure and safety. Permafrost warming or thaw increases risks of natural hazards, such as rock falls, debris flows and ground subsidence (Huggel et al., 2012). Arctic permafrost thaw can also accelerate climate change through the increased release of CO_2 and CH_4 which is a powerful GHG (Zimov et al., 2006; Schuur et al., 2009; Isaksen et al., 2011).

Past trends

Permafrost data is collected through national networks as well as globally. This information shows the regional and seasonal variation as well as trends in permafrost temperatures. Changes in below-ground temperatures can be influenced as much by temporal variations of snow cover as by changes in the near-surface air temperature. It has also become evident that landform characteristics such as elevation, topography, surface cover and soil type also influence the effects of climate change on permafrost.

Data from three boreholes, to a depth of 100 m or more, extending from Svalbard to the Alps indicate a long-term regional warming of permafrost of 0.5–1.0 °C during the recent decade (Harris et al., 2009). Continuous monitoring over 5–7 years shows warming down to 60 m depth and current warming rates at the permafrost surface of 0.04–0.07 °C/year, with greatest warming in Svalbard and northern Sweden (Isaksen et al., 2007). In Switzerland, some warming and increasing active-layer depths (top layer of the soil that thaws during the summer) have been observed (Noetzli and Vonder Muehll, 2010), but results vary between borehole locations and site characteristics such as different snow cover, surface cover, subsurface material, ice content in the underground and temperature conditions (Figure 2.16).

In Europe data series with a length of more than 15 years are available from Greenland, Svalbard, northern Sweden and Switzerland. Active layer thickness has generally increased during the period of observation, but there is also significant variation due to site characteristics (Figure 2.17).

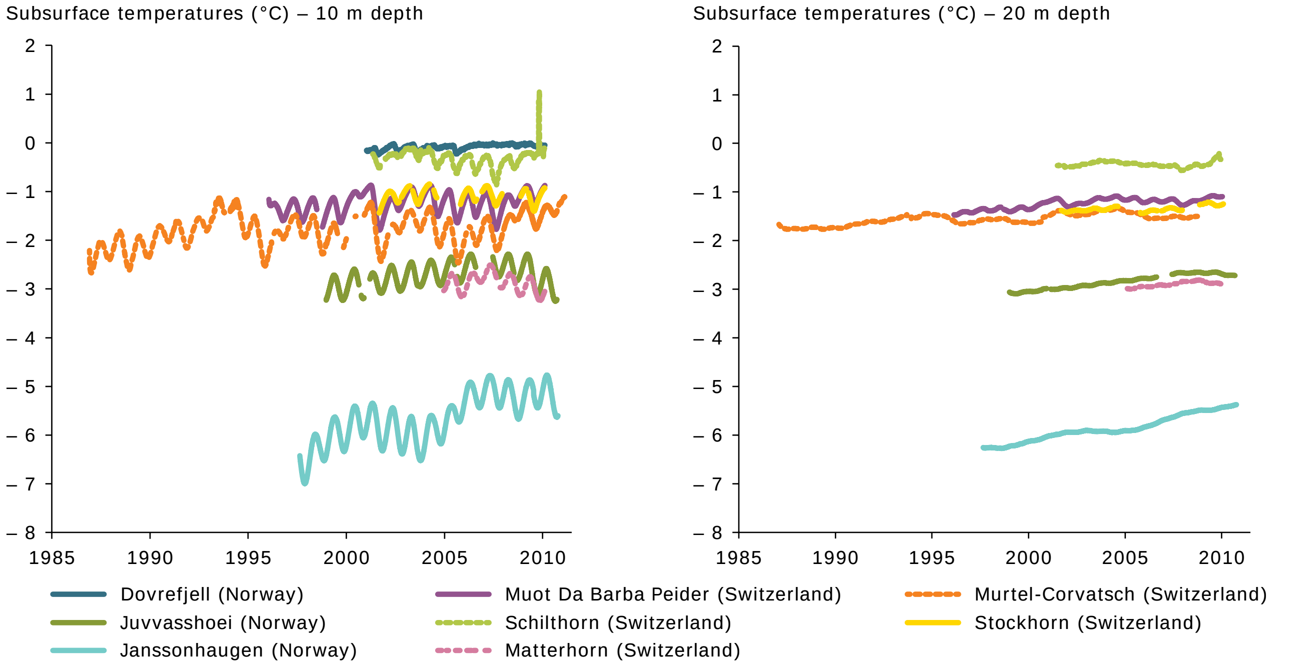
Projections

Permafrost areas are affected by the rate of warming and will very likely continue to thaw across Europe, with the possible exception of Svalbard, where permafrost thaw can mainly be expected at low elevations close to the coast (Voigt et al., 2010; Etzelmüller et al., 2011). Projections have also shown that the palsa mires in Fennoscandia represent a special case of arctic permafrost where rapid responses can be expected. The probability of a complete loss of palsas in northern Fennoscandia during the 21st century is sensitive to the emissions scenarios (see Box 2.5).

Key messages: 2.3.5 Permafrost

- In the past 10–20 years European permafrost has shown a general warming trend, with greatest warming in Svalbard and Scandinavia. The active layer thickness has increased at some European permafrost sites. Several sites show great interannual variability which reflects the complex interaction between the atmospheric conditions and local snow and ground characteristics.
- Present and projected atmospheric warming is projected to lead to widespread warming and thawing of permafrost.
- Warming and thawing of permafrost is expected to increase the risk of landslides, ground subsidence and flash floods from bursting glacial lakes. Thawing of permafrost also affects biodiversity and may accelerate climate change through release of CO_2 and CH_4 from arctic permafrost areas.

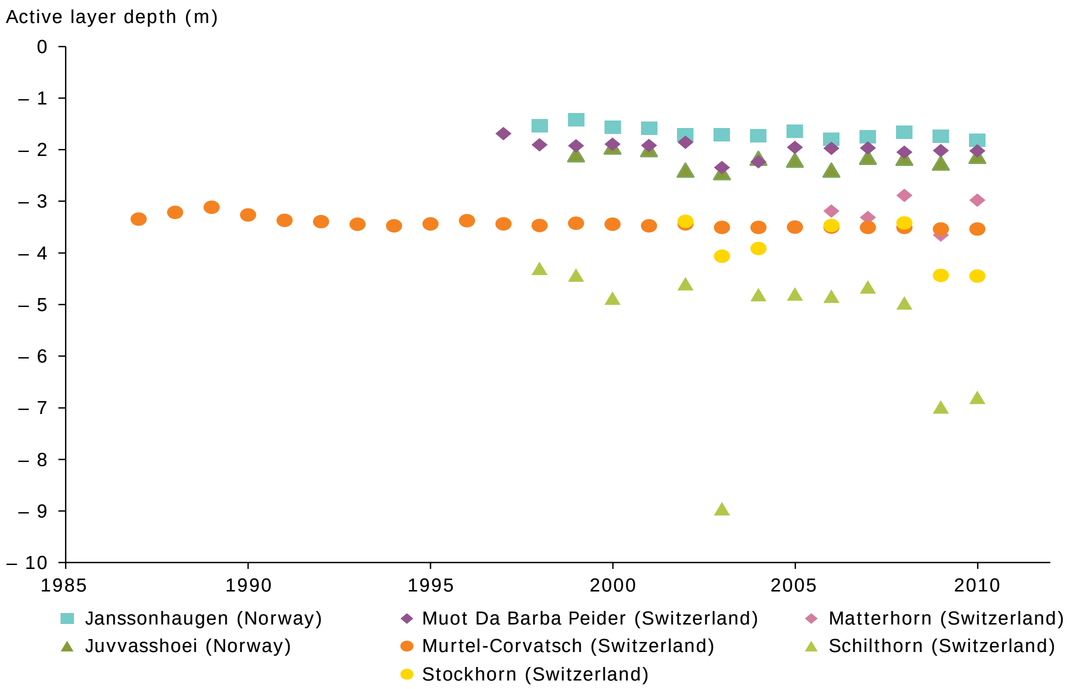
Figure 2.16 Observed permafrost temperatures from selected boreholes in European mountains



Note: Observed permafrost temperatures from a) 10 m and b) 20 m depth and their evolution for selected boreholes in European mountains: the sites of the PACE transect and two additional sites in Switzerland (Matterhorn and M.d. Barba Peider) and one in Norway (Dovrefjell).

Source: Data for Swiss sites are provided by PERMOS and for Norwegian sites by the Norwegian Meteorological Institute. Figure produced by J. Noetzli and K. Isaksen.

Figure 2.17 Comparison of active layer thickness from boreholes in the Alps, Norway and Svalbard



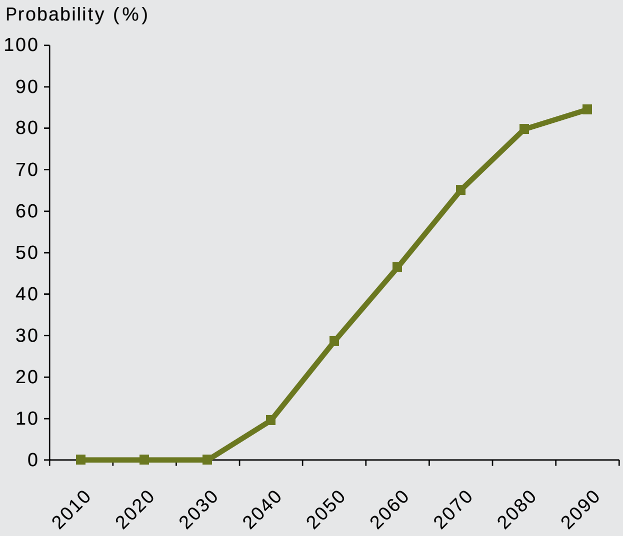
Source: Data for Swiss sites are provided by PERMOS and for Norwegian sites by the Norwegian Meteorological Institute. Courtesy of J. Noetzli and K. Isaksen.

Box 2.5 Lowland permafrost in sub-arctic palsa mires

Lowland permafrost in Europe mainly exists in the northern parts of Norway, Sweden, Finland and Iceland in palsa mires. Palsas are peat mounds with an ice core that is frozen throughout the year. Palsa mires are diverse environments with unique geomorphological processes and a rich diversity of, for example, bird species. The extent and abundance of palsa mires have declined since the 1960s in Sweden, Finland and Norway (Zuidhoff and Kolstrup, 2000; Luoto and Seppälä, 2003; Direktoratet for Naturforvaltning, 2012). The depth of the active layer has increased in northern Sweden during the period 1978–2006 (Åkerman and Johansson, 2008).

The spatial distribution of palsa mires is strongly correlated with climate. Projections of the locations of palsa mires in northern Fennoscandia for the 21st century suggest it to be likely (> 66 %) that palsa mires will disappear completely by the end of the 21st century under medium (A1B; see Figure 2.18) and moderately high (A2) emissions scenarios (Fronzek et al., 2010). For a low emissions (B1) scenario, it was more likely than not (> 50 %) that conditions would remain suitable over a small fraction of the current palsa distribution until the end of the 21st century. A decline in extent and abundance of palsa mires is expected to have a significant influence on the biodiversity of sub-arctic mires and on regional carbon budgets.

Figure 2.18 Probability of complete loss of northern Fennoscandian areas suitable for palsas in the 21st century



Note: Probability of complete loss of northern Fennoscandian areas suitable for palsas during the 21st century estimated using a probabilistic projection of climate change for the SRES A1B scenario.

Source: Adapted from Fronzek et al., 2010.

2.3.6 Arctic and Baltic Sea ice

Relevance

Observed changes in the extent of Arctic Sea ice provide early evidence of global climate warming. Sea ice is a habitat for endemic species in a unique ecosystem, and it also plays an important role for the pelagic ecosystem in the open ocean. Species specialised to live in conditions dominated by sea ice are affected and this can also affect use of living natural resources. Reduced polar sea ice will speed up global warming and is expected to affect ocean circulation and weather patterns across northern Europe (Petoukhov and Semenov, 2010).

The projected loss of sea ice may offer new economic opportunities for oil and gas exploration, shipping, tourism and some types of fishery. Most of these activities would increase pressure on, and risks to, the Arctic environment.

Past trends

In the period 1979–2012 the sea ice extent in the Arctic decreased by 45 000 km^2 per year in winter (measured in March) and by 98 000 km^2 per year in summer (measured in September) (see Figure 2.19). Winter sea ice loss has occurred in the peripheral seas, influenced by warmer oceans, while summer sea ice loss has developed in the Arctic Ocean driven by a warmer atmosphere (caused in part by warmer oceans south of Svalbard). This is evidenced by an earlier onset of summer surface melt (Stroeve et al., 2006). In contrast Antarctic sea ice reached record high levels, with a monthly average Southern Hemisphere winter maximum extent in September 2012 of 19.39 million square kilometres. Scientists largely attribute the increase in Antarctic sea ice extent to stronger circumpolar winds, which blow the sea ice outward, increasing extent (NSIDC, 2012).

Changes in Arctic Sea ice may trigger complex feedback processes. A longer melt season results in a lower sea ice extent in autumn and increased solar heat uptake by the ocean which delays the refreeze (Stammerjohn et al., 2012). However, a warmer atmosphere means more clouds and in summer these reflect sunlight, thus representing a negative feedback. Even so, some evidence suggests that winter regrowth of ice is inhibited by the warmer ocean surface (Jackson et al., 2012). Thinner winter ice leads to more heat loss from the ocean and a warmer atmosphere, and hence a thicker cloud cover which inhibits the escape of heat to space (Palm et al., 2010), which is a positive feedback mechanism.

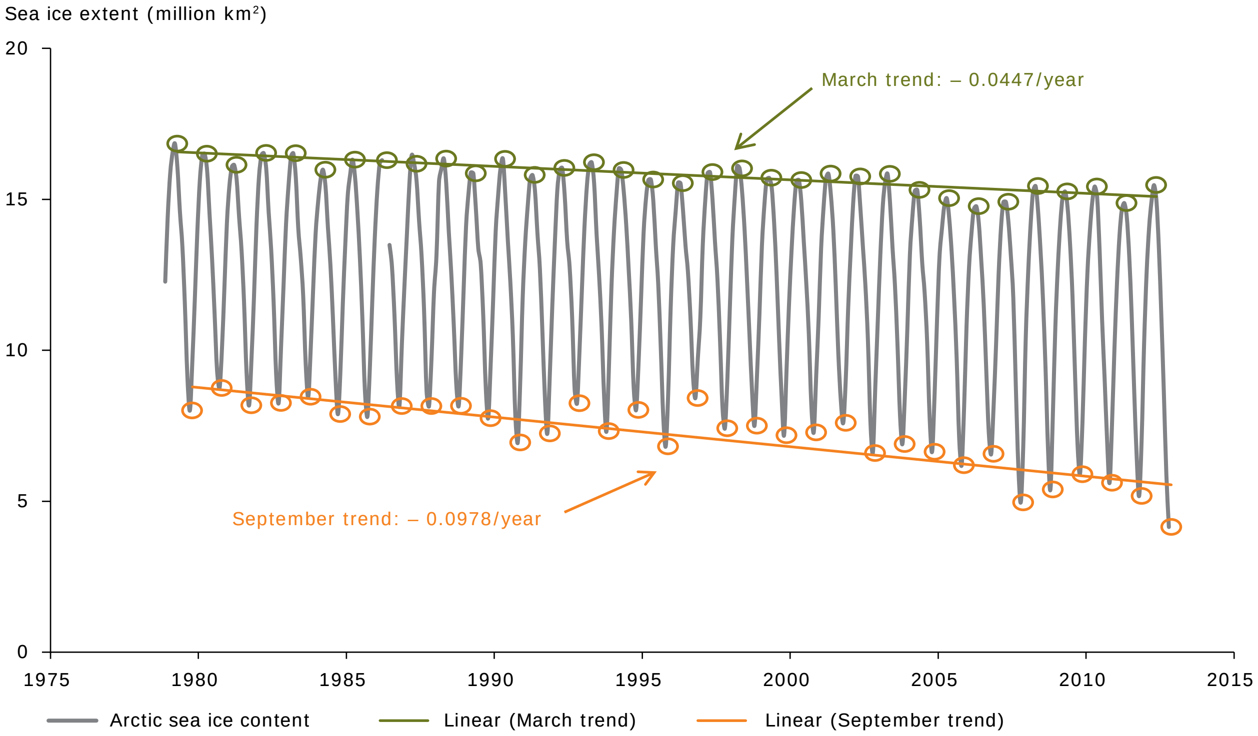
The extent of the minimum sea ice cover at the end of the melt season in September 2007 broke all previously observed records. Comparison of recent sea ice coverage with older ship and aircraft observations suggests that sea ice coverage may have halved since the 1950s (Meier et al., 2007). Since the more reliable satellite observations started in 1979, summer ice has shrunk by 10.2 % per decade (Comiso et al., 2008; Killie and Lavergne, 2011). The reduction in maximum winter extent is smaller, with a decrease of 2.9 % per decade (Stroeve et al., 2007; Comiso et al., 2008; Killie and Lavergne, 2011, personal communication). There is some evidence that the decline in summer ice has accelerated since 1999 (Stroeve et al., 2011).

The Arctic Sea ice is also getting thinner and younger since less sea ice survives the summer to grow into thicker multi-year floes. Currently there is less multi-year ice than seasonal sea ice in the Arctic Ocean (Kwok et al., 2009). It is hard to calculate trends for the whole sea ice cover, but submarine data collected in the central Arctic Ocean considered to be the most representative suggest a decrease of 40 % in sea ice thickness from an average of 3.1 m in 1956–1978 to 1.8 m in the 1990s (UNEP, 2007). British submarine data from 2007 also show continued thinning (Wadhams et al., 2011).

Key messages: 2.3.6 Arctic and Baltic Sea ice

- The extent and volume of the Arctic Sea ice has declined rapidly since global data became available in 1980, especially in summer. Record low sea ice cover in September 2007, 2011 and 2012 was roughly half the size of the normal minimum extent in the 1980s.
- In the period 1979–2012, the Arctic has lost on average 45 000 km^2 of sea ice per year in winter and 98 000 km^2 per year at the end of summer. The decline in summer sea ice appears to have accelerated since 1999.
- Arctic Sea ice is projected to continue to shrink in extent and thickness and may even disappear at the end of the summer melt season in the coming decades. There will still be substantial ice in winter.
- Baltic Sea ice, in particular the extent of the maximal cover, is projected to shrink.

Figure 2.19 Trend in Arctic Sea ice extent in March and September (1979–2012)



Note: Time series of Arctic Sea ice extent from 1979 to 2012. Trend lines and observation points for March (the month of sea ice extent maximum) and September (the month of sea ice extent minimum) have been indicated.

Source: Data produced by the EUMETSAT OSI SAF (http://osisaf.met.no) and the CryoClim (http://www.cryoclim.net) project, delivered through MyOcean (http://www.myocean.eu).

Calculations of sea ice volume from satellite suggest that the Arctic autumn (winter) sea ice volume decreased by 1 237 km³ (862 km³) from 2004 to 2008 (Kwok et al., 2009). This estimate is consistent with the estimate by the Pan Arctic Ice-Ocean Modelling and Assimilation System (PIOMAS), which suggests that the mean monthly sea ice volume decreased by 2 800 km³/decade over the period 1979–2010. PIOMAS further suggests that sea ice volume has decreased by 70 % (September) and almost 40 % (March) relative to the period 1958–1978 (Schweiger et al., 2011).

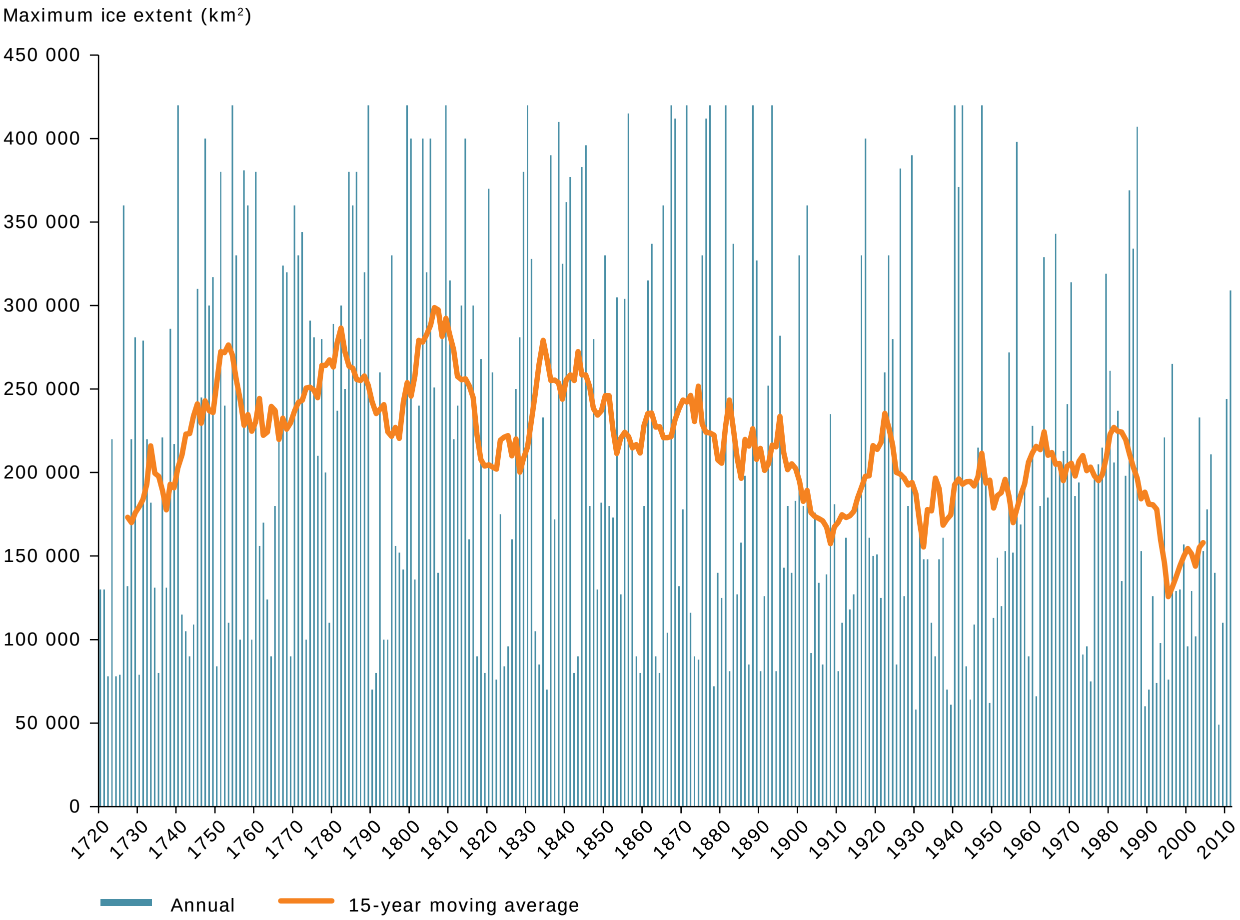
Information on sea ice extent in the Baltic Sea goes back to 1720. The maximum sea ice extent has been decreasing most of the time since about 1800. The decrease in sea ice extent appears to have increased since the 1980s but the large interannual variability prohibits a clear assessment as to whether this increase is statistically significant. The frequency of mild ice winters, defined as having a maximum ice cover of less than 130 000 km², has increased substantially. The frequency of severe ice winters, defined as having a maximum ice cover of at least 270 000 km², has decreased (Figure 2.20).

Projections

Arctic summer sea ice is projected to continue to shrink. It may even disappear at the end of the summer melt season in the coming decades, although there will still be substantial ice in winter (Meehl and Stocker, 2007; Allison et al., 2009). So far summer-time melting of Arctic Sea ice has occurred much faster than projected by most climate models, which decreases confidence in projections of the future rate of Arctic Sea ice decline (Wang and Overland, 2009). It has been suggested that the wide spread in future sea ice projections is due to the inability of many current climate models to properly represent the thickness distribution of Arctic Sea ice (Kwok, 2011).

Projections of Baltic Sea ice extent under different emissions scenarios suggest that the maximal ice cover will continue to shrink significantly in the 21st century (Jylhä et al., 2008).

Figure 2.20 Maximum ice cover extent in the Baltic Sea (1719 / 1720–2010 / 2011)



Note: Maximum extent of ice cover in the Baltic Sea in the winters 1719/1720–2010/2011 (blue bars) and 15-year moving average (orange line).

Source: Jouni Vainio, Finnish Meteorological Institute (updated from Seinä and Palosuo, 1996; Seinä et al., 2001).

3 Climate impacts on environmental systems

3.1 Oceans and marine environment

3.1.1 Overview

Relevance

The oceans play a key role in the regulation of climate by transporting heat northward and by distributing energy from the atmosphere into the deep parts of the ocean. On the one hand, the Gulf Stream and its extensions, the north Atlantic current and drift, influence European weather patterns and storm tracks. The heat transported northward by the oceanic circulation impacts precipitation and wind regimes over Europe. On the other hand, oceans are also affected by the climatic conditions of the atmosphere (see Section 2.2) and the cryosphere (see Section 2.3). The induced changes in physical ocean conditions, in turn, affect the marine ecosystems.

Selection of indicators

This section reviews changes in the following physical and biological indicators of oceans and marine ecosystems in Europe's seas:

- Ocean acidification;
- Ocean heat content;
- Sea surface temperature;
- Phenology of marine species;
- Distribution of marine species.

Key messages: 3.1 Oceans and marine environment

- Impacts of climate change are observed in all European seas, although the extent to which impacts have been documented in time and space varies among the seas.
- The primary physical impact of climate change in European regional seas is increased sea surface temperature. Climate change is expected to impact the physical conditions differently in European regional seas, and consequently biological impacts also vary depending on the region.
- **North-east Atlantic:** Sea surface temperature and ocean heat content are increasing in all regions, although at different rates. Warming is projected to extend throughout the water column during the 21st century. Sea surface temperature changes have already resulted in an increased duration of the marine growing season and in northward movement of marine zooplankton. Some fish species are shifting their distributions northward in response to increased temperatures.
- **Baltic Sea:** Future climate change is projected to warm the Baltic Sea, to decrease its salinity, and to decrease sea ice extent by 50–80 % during the 21st century. These changes in physical variables will affect the ecosystems of the Baltic Sea in many ways. For example, changes in salinity and deep water oxygen levels are likely to impact cod fisheries by affecting the reproductive success of cod.
- **Mediterranean Sea:** Temperature is projected to increase, and run-off to the Mediterranean Sea to decrease, thereby increasing salinity. Stratification is projected to remain largely constant because of the compensating effects of increasing temperature and increasing salinity on the density of sea water. Projected changes in storminess appear to be changing the mixing conditions for nutrients into the surface layer in the central Mediterranean, leading to nutrient poor conditions. The observed invasion and survival of alien species has been correlated to the warming trend in sea surface temperature. Such invasions not only impact local ecosystems, they can also impact the activities of the international fishing fleet.

Uncertainties and data gaps

In general, however, changes related to the physical and chemical marine environment are better documented than biological changes because links between cause and effect are better understood and often time series of observations are longer. For example, systematic observations of both sea-level and sea surface temperature were started around 1880 and are today complemented by observations from space that have high resolution in time and geographical coverage and by Argo floats that also automatically measure temperature and salinity below the ocean surface. Ocean acidification occurs as a consequence of well-defined chemical reactions, but its rate and biological consequences on a global scale is subject to research. The longest available records of plankton are from the Continuous Plankton Recorder (CPR) are some 60 years long. It is a sampler that is towed behind many different merchant vessels, along fixed shipping routes. Sampling was started in the North Sea in the 1950s and today a network covering the entire north Atlantic has been established. No other plankton time series of equivalent length and geographical coverage exist for the European regional seas, although many new initiatives investigating species distributions and their changes in Europe's seas are now emerging.

3.1.2 Ocean acidification

Relevance

Across the ocean, the pH of surface waters has been relatively stable for millions of years. Over the last million years, average surface-water pH oscillated between 8.3 during cold periods (e.g. during the last glacial maximum, 20 000 years ago) and 8.2 during warm periods (e.g. just prior to the industrial revolution). Human activities are threatening this stability by adding large quantities of CO_2 to the atmosphere, which is subsequently partially absorbed in the ocean. This process is referred to as ocean acidification because sea water pH is declining, even though ocean surface waters will remain alkaline.

When CO_2 is absorbed by the ocean, it reacts with water, producing carbonic acid. The role of the carbonate ion is special because it acts as a buffer, helping to limit the decline in ocean pH; however, it is being used up as we add more and more anthropogenic CO_2 to the ocean. As carbonate ion concentrations decline, so does the ocean's capacity to take up anthropogenic CO_2. Currently, the ocean takes up about one fourth of the global CO_2 emissions from combustion of fossil fuels, cement production and deforestation (Canadell et al., 2007; Brewer, 2009; GCP, 2011). Hence, the ocean serves mankind by moderating atmospheric CO_2 and thus climate change, but at a cost, namely changes in its fundamental chemistry.

It has been shown that corals, mussels, oysters and other marine calcifiers have a more difficult time constructing their calcareous shell or skeletal

Key messages: 3.1.2 Ocean acidification

- Surface-ocean pH has declined from 8.2 to 8.1 over the industrial era due to the growth of atmospheric CO_2 concentrations. This decline corresponds to a 30 % change in oceanic acidity.
- Observed reductions in surface-water pH are nearly identical across the global ocean and throughout Europe's seas.
- Ocean acidification in recent decades is occurring a hundred times faster than during past natural events over the last 55 million years.
- Ocean acidification already reaches into the deep ocean, particularly in the high latitudes.
- Average surface-water pH is projected to decline further to 7.7 or 7.8 by the year 2100, depending on future CO_2 emissions. This decline represents a 100 to 150 % increase in acidity.
- Ocean acidification may affect many marine organisms within the next 20 years and could alter marine ecosystems and fisheries.

material as the concentration of carbonate ions decreases. Most, but not all, marine calcifying organisms exhibit the same difficulty (Fabry et al., 2008). Furthermore, pH is a measure which affects not only inorganic chemistry but also many biological molecules and processes, including enzyme activities, calcification and photosynthesis. Thus, anthropogenic reductions in sea water pH could affect entire marine ecosystems. A comprehensive recent study suggests that all coral reefs will cease to grow and start to dissolve at an atmospheric CO_2 level of 560 ppm due to the combined effects of acidification and warming (Silverman et al., 2009). This CO_2 concentration would be attained by 2050 under high business-as-usual emissions scenarios. Other organisms and ecosystems are likely to have different thresholds.

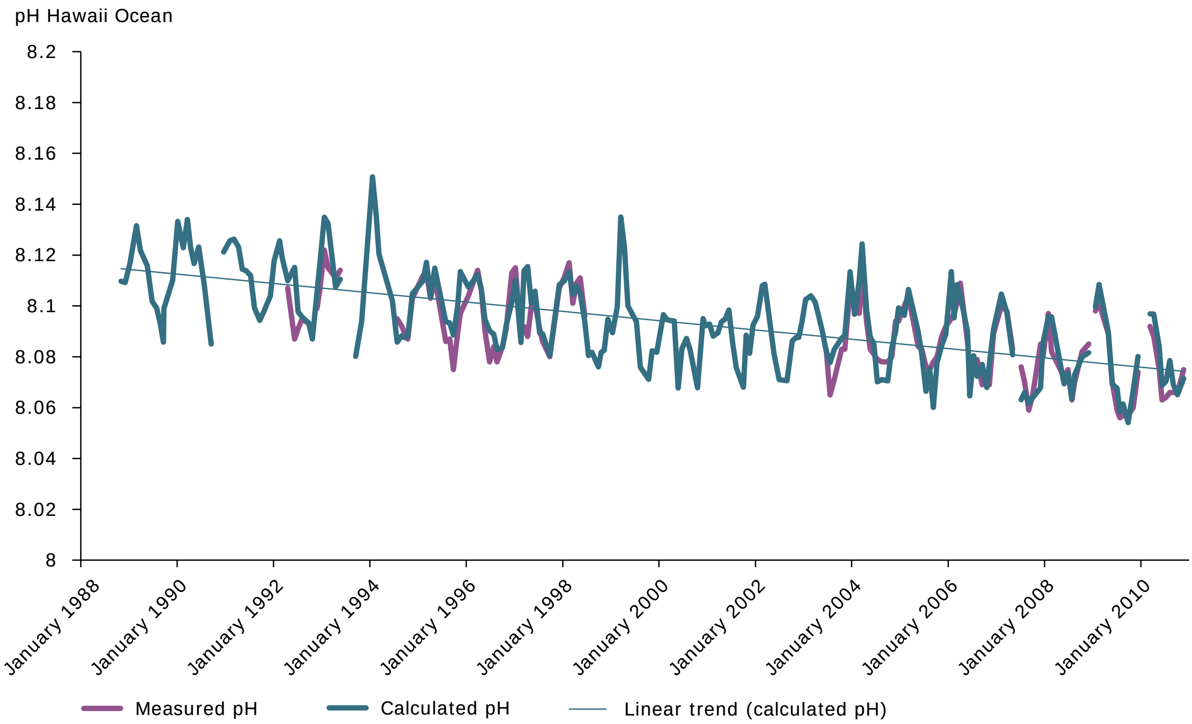
Past trends

In December 2011, the atmospheric CO_2 level reached 392 ppm, which is 40 % more than the pre-industrial concentration (280 ppm); half of that increase has occurred in the last 30 years. Ocean pH has been reduced from 8.2 to 8.1 over the industrial era, which corresponds to a 30 % increase in ocean acidity (defined here as the hydrogen ion concentration). This change has occurred at a rate that is about a hundred times faster than any change in acidity experienced during the last 55 million years. The current decline in pH is already measurable at the three ocean time series stations that are suitable to evaluate long-term trends, located offshore of Hawaii, Bermuda and the Canary Islands. Figure 3.1 shows the time series from Hawaii, which is the longest and best known one, and the changes here are similar to those that are observed at a much shorter time scale in Europe. The measured reductions in surface pH at those stations match exactly the values calculated on the basis of increasing atmospheric CO_2 concentrations, assuming thermodynamic equilibrium between the surface ocean and the atmosphere (Bates, 2005; Santana-Casiano et al., 2007; Dore et al., 2009).

Projections

Average surface-water pH is projected to decline further to 7.7 or 7.8 by the year 2100, depending on future CO_2 emissions. This decline represents a 100 to 150 % increase in acidity. When atmospheric CO_2 reaches 450 ppm, parts of the Southern Ocean will start becoming corrosive to calcium carbonate

Figure 3.1 Decline in pH measured at the Aloha station as part of the Hawaii Ocean time series



Source: Dore, 2012.

during winter (McNeil and Matear, 2008). Ten per cent of the Arctic Ocean may become corrosive to calcium carbonate already by 2020 (Steinacher et al., 2009), and surface waters of the Baltic Sea will still become corrosive well before the end of the century. In the Black Sea and Mediterranean Sea there is no danger of surface waters becoming corrosive to calcium carbonate before 2100, but they will suffer sharp reductions in carbonate ion concentrations (Med Sea – 37 %; Black Sea – 45 %). These rapid chemical changes are an added pressure on marine calcifiers and ecosystems of the European seas that are already heavily suffering from other anthropogenic influences.

Without dramatic actions to curb CO_2 emissions, recovery from human-induced acidification will require thousands of years for the Earth system to re-establish roughly similar ocean chemical conditions (Archer, 2005; Tyrrell et al., 2007; Archer and Brovkin, 2008) and millions of years for coral reefs to return, based on palaeo-records of natural coral reef extinction events (Veron, 2008).

3.1.3 Ocean heat content

Relevance

The World Ocean is the dominant component of the Earth's heat balance. Oceans cover roughly 72 % of the planet's surface, and water has a heat uptake capacity that is around 20 times greater than that of the atmosphere (Levitus et al., 2009, 2012). About 90 % of the total warming caused by climate change is manifested in increased global heat content. Hence, a precise estimate of Ocean Heat Content (OHC) is essential for understanding the role of oceans in past climate change, and for assessing future climate change (Hansen, 2005; Church et al., 2011; Hansen et al., 2011). OHC is defined as the integrated temperature change times the density of sea water, times specific heat capacity from the surface down to the deep ocean. Estimates of it are made based on temperature measurements or on reanalyses made using a combination of models and observations (see Section 2.1).

Changes in heat content also cause the ocean to expand or contract, thereby changing sea level regionally and globally (Cazenave and Llovel, 2010). This thermosteric effect has contributed about one quarter to global sea-level rise since 1993 (see Section 3.2.2).

Past trends

The warming of the World Ocean accounts for approximately 90 % of the warming of the Earth during the last 6 decades (Church et al., 2011; Hansen et al., 2011; Levitus et al., 2012).

Figure 3.2 shows that the heat content of the World Ocean has increased since around 1970. The linear trend over the whole time series 1955–2010 of the uppermost 700 m and 2 000 m layer was 0.27 Wm^{-2} and 0.39 Wm^{-2} (per unit area of the World Ocean), respectively. Two thirds of the observed increase of global heat content has occurred in the upper 700 m of the ocean, with increases in the layers below 700 m depth accounting for the remaining one third (Dore et al., 2009; Levitus et al., 2009, 2012; Purkey and Johnson, 2010). Heat content has increased in all major sea basins of the World Ocean, in particular in the Atlantic Ocean (Levitus et al., 2012).

Several global ocean data assimilation products are available to compare observation-based estimates with independent reanalysis data. Global and basin-scale heat content warming trends in the upper 700 m of the ocean computed from a set of

Key messages: 3.1.3 Ocean heat content

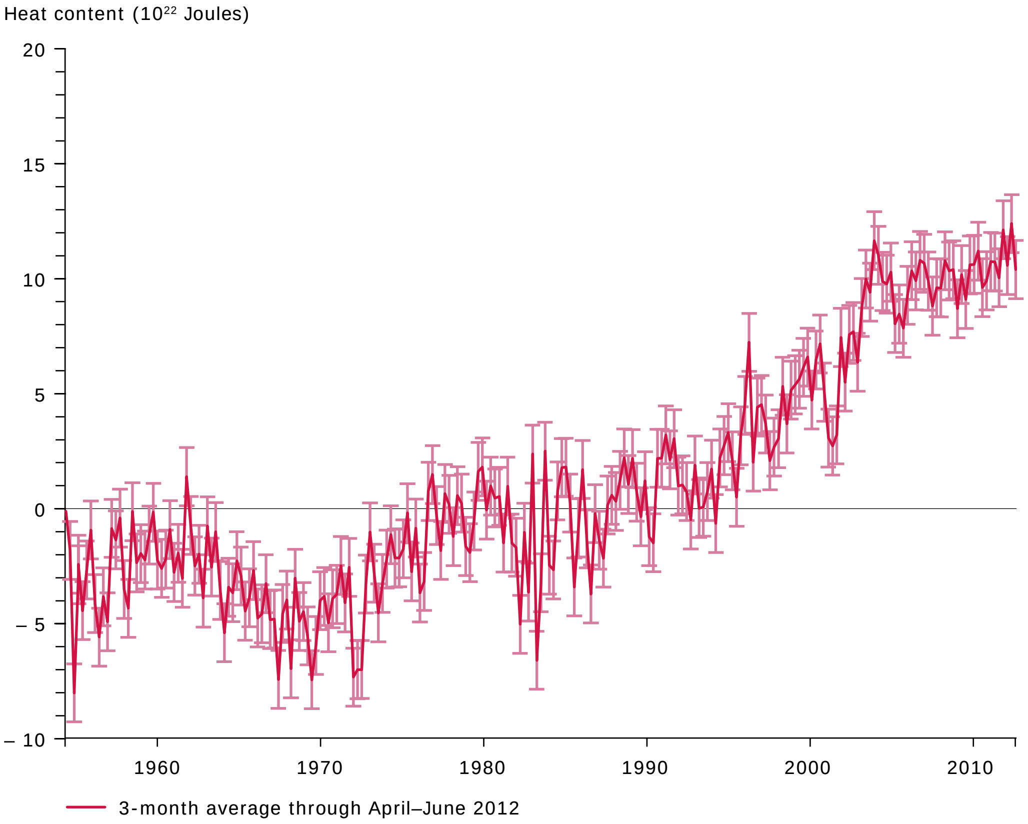
- The warming of the World Ocean accounts for approximately 93 % of the warming of the Earth system during the last 6 decades.
- An increasing trend in the heat content in the uppermost 700 m depth of the World Ocean is evident over the last 6 decades. Recent observations show substantial warming also of the deeper ocean (between 700 m and 2 000 m depth).
- Further warming of the oceans is expected with projected climate change, but quantitative projections of ocean heat content are not available.

global ocean reanalyses fall within the range of the most recent observation-based estimates derived using different methods (Lyman et al., 2010; Masina et al., 2011) (see also Box 3.1).

Projections

Projections of OHC are very uncertain and are hence not included here.

Figure 3.2 Ocean heat content calculated based on observations made in the upper 700 m of the water column (1955–2011)



Source: Updated from Levitus et al., 2009.

Box 3.1 Making the right observations

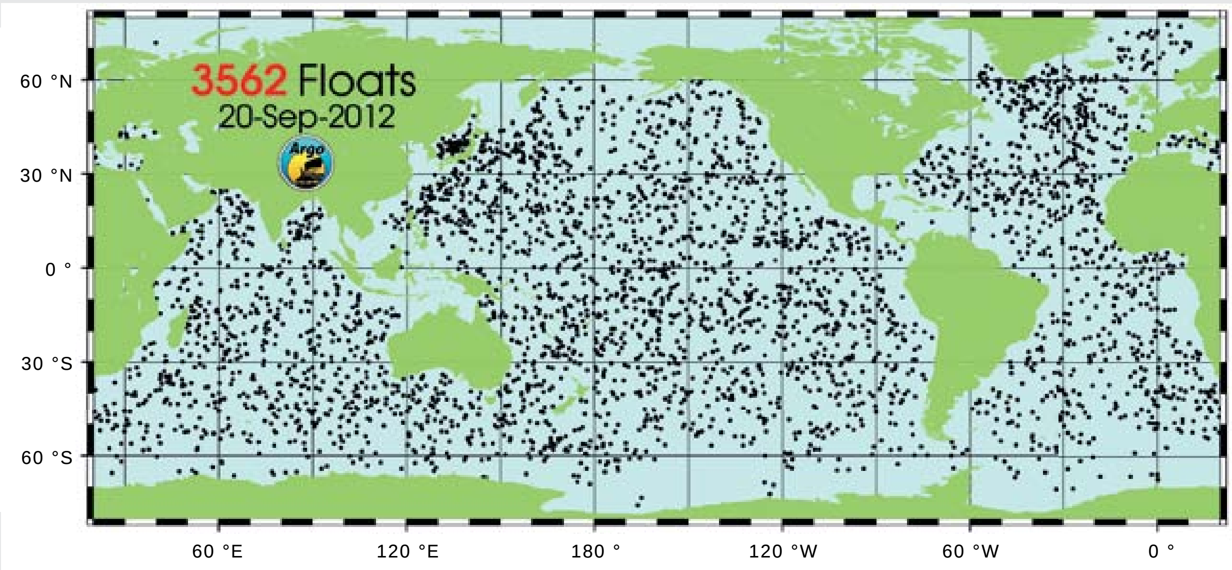
The very large heat capacity of the oceans means that temperature changes must be measured with great precision and with high resolution, both of which have been difficult to achieve. The majority of the historical global temperature changes come from Expendable Bathythermographs (XBTs) and Conductivity/Temperature/Depth (CTD) shipboard measurements. However, spatial and temporal sparseness of data, regional and temporal biases in observations, and changing proportions of data from different instrument types, established the need for a homogeneous global observing system. This need led to the implementation of the international array of Argo profiling floats. Argo is a global array of 3 000 free-drifting profiling floats that measure the temperature and salinity of the upper 2 000 m of the ocean (see Map 3.1). Temperature, salinity and velocity of the upper ocean are continuously monitored, and all data is made publicly available within hours after collection. One of Argo's most important contributions is a major improvement in estimates of OHC (von Schuckmann and Le Traon, 2011; Levitus et al., 2012).

The main challenge for Argo is to maintain the global array for the next decades, which requires international commitments to provide and deploy about 800 to 900 floats per year.

Additional floats would be needed for more uniform sampling and for expanded coverage of polar regions, marginal seas and the deep ocean below 2 000 m depth.

In 2008, the project Euro-Argo started developing a European infrastructure for Argo to the level where European partners have the capacity to support approximately one quarter of the global array, and to provide an additional 50 floats per year for enhanced coverage in the European and marginal seas. The Euro-Argo project includes among others Germany, France and the United Kingdom, which are the major European contributors to Argo. In 2012, the collaboration around Euro-Argo was formalised in a Research Infrastructure Consortium which enables Europe to build and sustain its contribution to the global array while providing enhanced coverage in the North-east Atlantic, Mediterranean and Black Seas.

Map 3.1 Location of Argo floats in 2012



Source: See http://www.argo.ucsd.edu and http://www.euro-argo.eu/About-us/The-Research-Infrastructure.

3.1.4 Sea surface temperature

Relevance

Sea surface temperature (SST) is relevant for monitoring of climate change because it reflects regional changes in ocean temperature, whereas OHC is estimated globally. SST is closely linked to one of the strongest drivers of climate in western Europe, the ocean circulation that is known as Atlantic Meridional Overturning Circulation (MOC) or alternatively as the great conveyor belt. This circulation carries warm upper waters north in the Gulf Stream and returns cold deep waters south. It is widely accepted that the MOC is an important driver of low-frequency variations in sea surface temperature on the time scale of several decades (Griffies, 1997). It is also widely accepted that the NAO-index (a proxy of atmospheric variability) plays a key role in forcing variations in MOC as well as the northward extent of the Gulf Stream (Frankignoul and Kestenare, 2005; de Coëtlogon et al., 2006).

The MOC sensitivity to greenhouse warming remains a subject of much scientific debate, largely because its large natural variability and the scarcity of observations makes trend detection very difficult (Curry, 2005; Cunningham et al., 2007; Matei et al., 2012).

One of the most visible ramifications of increased temperature in the ocean is the reduced area of sea ice coverage in the Arctic polar region (see Section 2.3.6). There is an accumulating body of evidence suggesting that many marine ecosystems are also sensitive to changes in SST. For example, the spread of oxygen-free areas (so called dead zones) in the Baltic Sea in the past 1 000 years was strongly linked to above-average SST (Kabel et al., 2012).

Past trends

SST is increasing globally and in Europe's seas (Frankignoul and Kestenare, 2005) but the rate of warming varies across European seas (Figure 3.3 and Map 3.2). Observed changes in SST of the global ocean and the regional seas of Europe are consistent with the changes in atmospheric temperature (Levitus, 2000; Rayner et al., 2006).

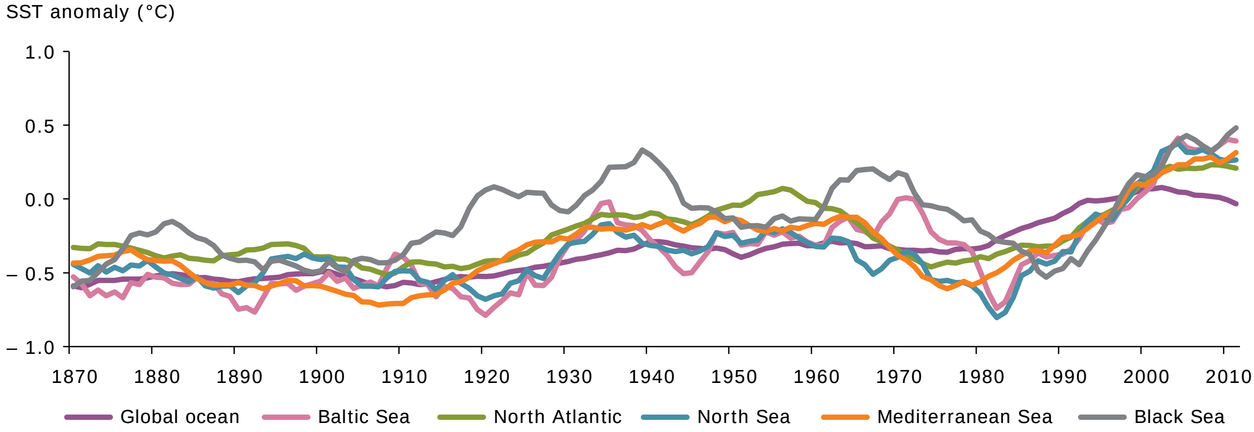
Projections

Global SST is projected to rise more slowly than atmospheric temperature. Initially ocean warming will be largest in the upper 100 m of the ocean, but warming will continue to penetrate in the deep ocean during the 21st century (Watterson, 2003; Stouffer, 2004; IPCC, 2007). It is not possible to project changes in SST or the different geographic regions across Europe because the spatial resolution of the coupled ocean-climate models is not high enough to evaluate trends on the scale of individual European regional seas.

Key messages: 3.1.4 Sea surface temperature

- Sea surface temperature in European seas is increasing more rapidly than in the global oceans.
- The rate of increase in sea surface temperature in all European seas during the past 25 years is the largest ever measured in any previous 25-year period. It has been about 10 times faster than the average rate of increase during the past century and beyond.
- Global sea surface temperature is projected to rise more slowly than atmospheric temperature.

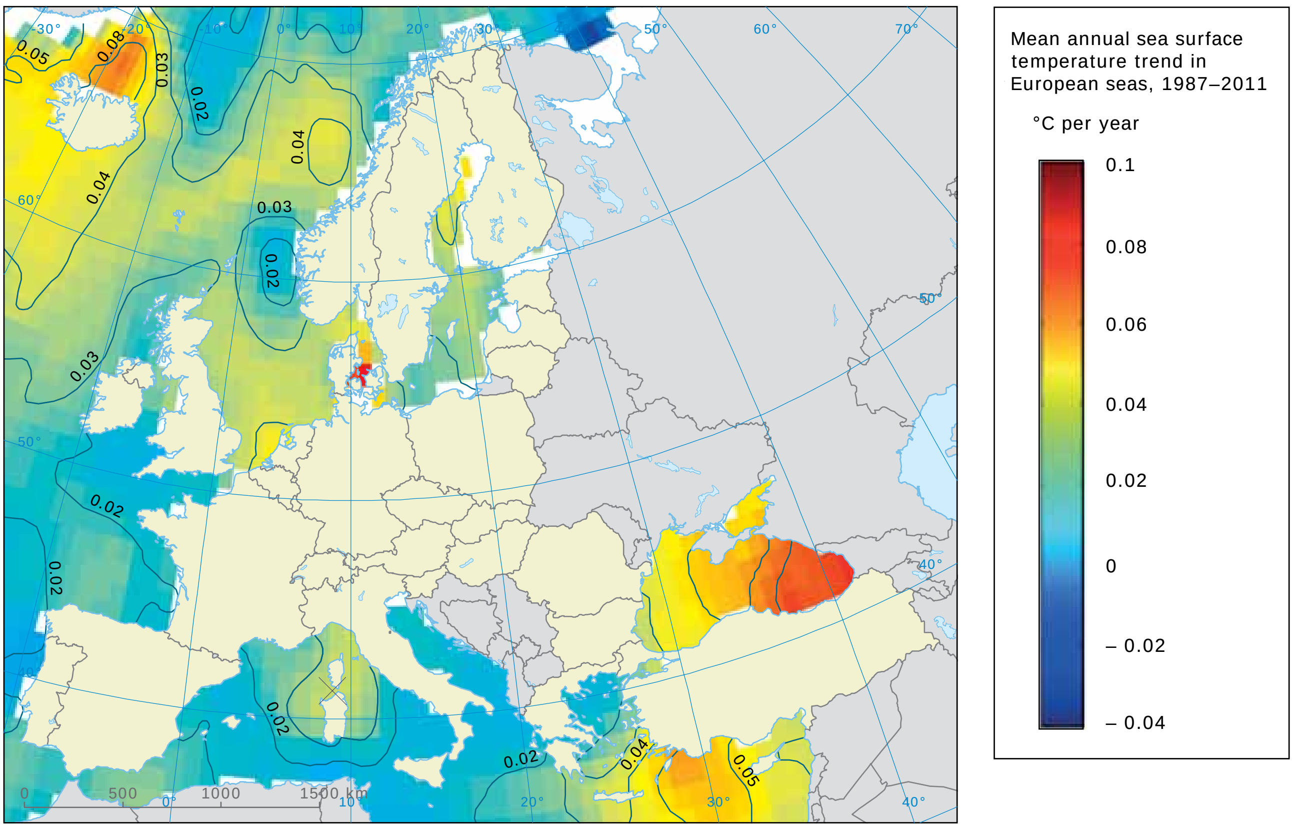
Figure 3.3 Annual average sea surface temperature anomaly in different European seas (1871–2011)



Note: Time series of annual average sea surface temperature (°C), referenced to the average temperature between 1986 and 2010, in each of the European seas.

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

Map 3.2 Mean annual sea surface temperature trend (in °C per year) in European seas (1987–2011)



Source: HADSST1 dataset (http://hadobs.metoffice.com/hadisst/data/download.html), masked where ice coverage constituted more than 20 % of the sea water.

3.1.5 Phenology of marine species

Relevance

Phenology is the study of annually recurring life-cycle events of species, such as the timing of migrations and flowering of plants. In the marine environment, phenology indicators include the timing of the spring phytoplankton bloom and the peak in abundance of other marine organisms. Change in phenology is one of the key indicators of the impacts of climate change on biological populations. Because marine species have different sensitivities to changes in temperature, these changes may lead to large shifts in the marine food web that can ultimately affect the food available to fish, birds or marine mammals. Differing responses have been seen across various levels of the food web (Thackeray et al., 2010).

Changes in the phenology of different plankton species are seen as a factor contributing to the decline in North Sea cod stocks, which was caused initially by over-fishing, and they have probably affected other fish populations (such as sand eels) that are an essential food source for seabirds (Beaugrand et al., 2003; Edwards and Richardson, 2004; Frederiksen et al., 2006).

In the North Sea, work on pelagic phenology has shown that plankton communities, including fish larvae, are very sensitive to regional climate warming. Responses to warming vary between trophic levels and functional groups, which may create a so-called 'trophic mismatch' between one species and their food source (Thackeray et al., 2010) (see also Section 3.4 for terrestrial ecosystems). The sexual maturation of decapoda larvae has been found to be particularly sensitive to water temperature and is therefore regarded as representative of phenological changes in the shelf-sea environments (Lindley, 2009). Other taxa that also have their seasonal development closely triggered by temperature changes are also highly sensitive (e.g. echinoderm larvae, dinoflagellates, copepods).

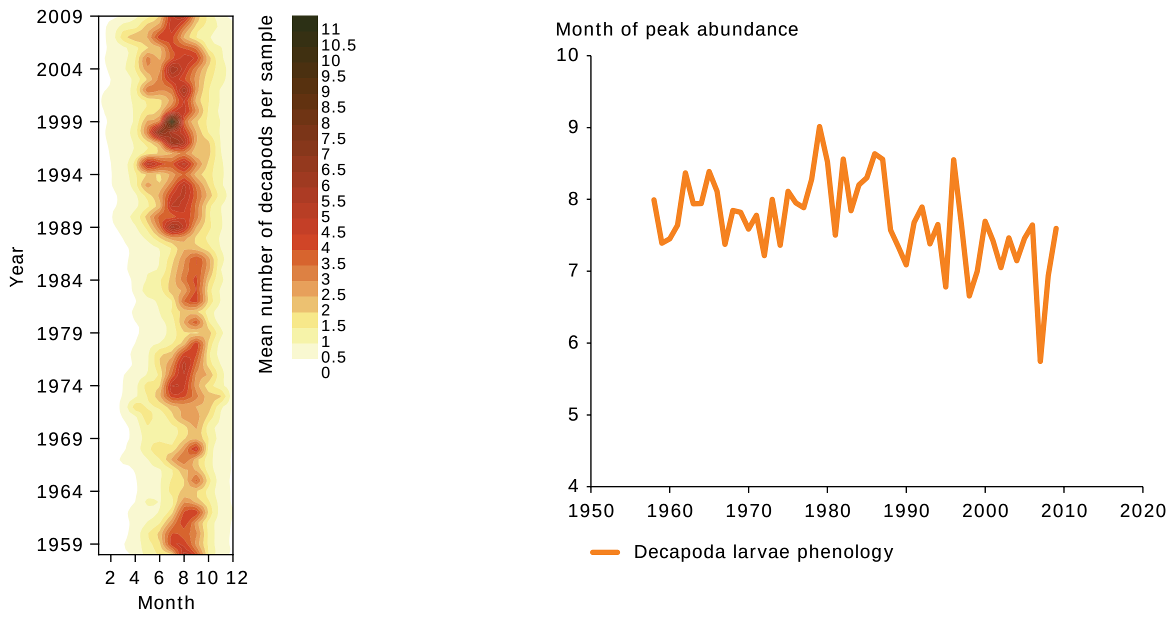
Past trends

The zooplankton growing season indicator shows the annual timing of peak seasonal abundance of decapoda larvae from 1958–2009 in the central North Sea (Figure 3.4 left). A shift towards an earlier seasonal peak is clearly visible, in particular since 1988. Since the 1990s the seasonal development of decapoda larvae has occurred 4–6 weeks earlier than the long-term average (baseline mean 1958–2009). This trend towards an earlier seasonal appearance of decapoda larvae during the 1990s is highly correlated with SSTs (Figure 3.4 right). Even though decapoda larvae are not routinely identified to species level, a recent study has shown that these phenological shifts are a response at the species level, and not simply different seasonal timings by different species (Lindley and Kirby, 2010).

Key messages: 3.1.5 Phenology of marine species

- Temperature increases in the ocean have caused many marine organisms in European seas to appear earlier in their seasonal cycles than in the past. Some plankton species have advanced their seasonal cycle by 4–6 weeks in recent decades.
- Projections of the phenological responses of individual species are not available, but phenological changes are expected to continue with projected further climate change.
- Changes in the plankton phenology have important consequences for other organisms within an ecosystem and ultimately for the structure of marine food -webs at all trophic levels. Potential consequences include increased vulnerability of North Sea cod stocks to over-fishing; and changes in seabird populations.

Figure 3.4 Decapoda larvae abundance and phenology in the central North Sea



Note: Left: Decapoda larvae abundance in the central North Sea 1958–2009.

Right: Phenology shown as average month of peak decapoda abundance (number of individuals) in the central North Sea 1958–2009.

Source: Sir Alister Hardy Foundation for Ocean Science (SAHFOS).

Projections

Projections of the phenological responses of individual species under climate change have not yet been made, but the empirical evidence suggests that phenological changes will continue as climate warming continues. It is currently uncertain as to whether genetic adaptations within species populations can cope with these changes, at least partly, or whether the pace of climate change is too fast for genetic adaptations to take place. This uncertainty is further compounded by the difference in phenological responses between species and functional groups. If current patterns and rates of phenological change are indicative of future trends, future climate warming may exacerbate trophic mismatching. This could further disrupt the functioning, persistence and resilience of many ecosystems, potentially having a major impact on ecosystem services.

3.1.6 Distribution of marine species

Relevance

Changes in the distribution of organisms are one of the key indicators of marine climate change impacts. Distribution maps from the North-east Atlantic are used as one part of this indicator to demonstrate large-scale changes at the decadal scale. The second part of this indicator describes the ratio between a warm-water species (*Calanus helgolandicus*) and a cold-water species (*Calanus finmarchicus*) in the North Sea on an annual basis (see Figure 3.5). In the eastern Mediterranean Sea, the introduction of warm and tropical alien species from the Red Sea has been exacerbated by observed warming, leading to a 150 % increase in the annual mean rate of species entry after 1998 (Raitsos et al., 2010).

Changes in marine plankton can trigger further effects on marine and terrestrial ecosystems. For example, increases in the surface temperature of the North Sea in recent decades have triggered establishment of warm-water swimming crabs, which in turn allowed establishment of colonies of lesser black-backed gulls in Belgium and northern France, with expected follow-on impacts on terrestrial ecosystems through their fertilisation of terrestrial soils (Luczak et al., 2012).

Past trends

Increases in regional sea temperatures have triggered a major northward movement of warmer-water plankton in the North-east Atlantic and a similar retreat of colder-water plankton to the north. This northerly movement is about 10 ° latitude (1 100 km) over the past 40 years (a mean poleward movement of between 200 and 250 km per decade), and there appears to have been an acceleration since 2000 (Beaugrand, 2009). Recently, a Norwegian study showed even faster rates of northward movement between 1997 and 2010. Out of about 1 600 benthic marine species found in coastal waters of southern Norway, 565 species had expanded their distribution northwards along the coast, at rates of 500–800 km per decade (Brattegard, 2011). These rates are much faster than any other documented terrestrial study.

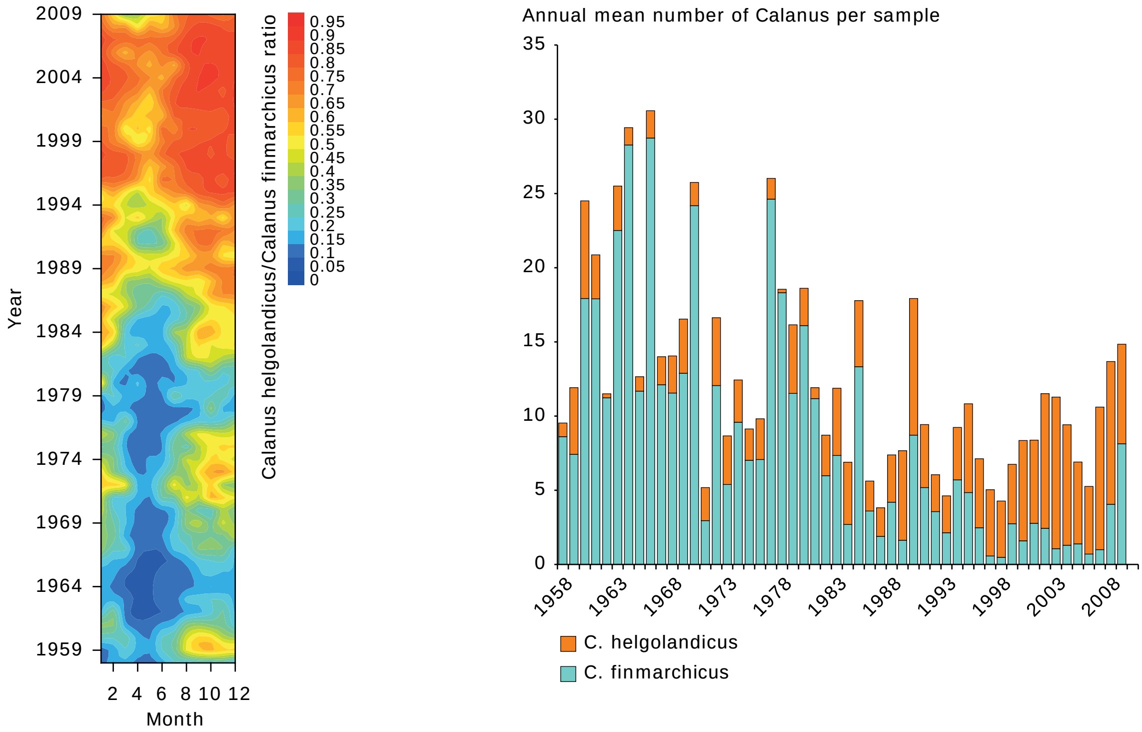
Projections

Further changes in the distribution of marine species are expected, with projected further climate change, but quantitative projections are not available.

Key messages: 3.1.6 Distribution of marine species

- Increases in regional sea temperatures have triggered a major northward expansion of warmer-water plankton in the North-east Atlantic and a northward retreat of colder-water plankton. This northerly movement is about 10 ° latitude (1 100 km) over the past 40 years, and it seems to have accelerated since 2000.
- Sub-tropical species are occurring with increasing frequency in European waters, and sub-Arctic species are receding northwards.
- Further changes in the distribution of marine species are expected, with projected further climate change, but quantitative projections are not available.

Figure 3.5 *Calanus* ratio in the North Sea



Note: Left: Temporal and seasonal distribution of the *Calanus* ratio 1958–2009.

Right: Change in *Calanus* ratio in the North Sea between 1958 and 2009.

Source: Sir Alister Hardy Foundation for Ocean Science (SAHFOS).

3.2 Coastal zones

3.2.1 Overview

Relevance

Coastal zones in Europe are centres of population and economic activity. They are inhabited by diverse ecosystems, in particular wetland ecosystems. Projected climate change, including sea-level rise and associated changes in frequency and/or intensity of storm surges and erosion, threaten human and natural systems at the coasts in various ways. Management of the coastal zones needs to consider the multiple functions of many coastal areas, which is increasingly occurring through integrated coastal zone management. Adaptation policies also need to consider the full range of adaptation options, including measures such as dike building, beach nourishment, rehabilitation of coastal ecosystems, area-related measures, integrated coastal zone management, and elaboration and distribution of flood hazard and flood risk maps for costal zones according to the Flood Risk Management Directive.

Selection of indicators

This section presents the following indicators on threats to the coastal zone that are sensitive to climate change:

- Global and European sea-level rise;
- Storm surges.

The final section presents information on coastal erosion. This information is not presented as an EEA indicator because regular updates of the underlying information base cannot be expected.

Another important risk in low-lying coastal regions is salt-water intrusion into freshwater reservoirs. Salt-water intrusion can be caused by relative sea-level rise and by overexploitation of groundwater resources. It can threaten freshwater supply, agriculture and ecosystems in coastal regions. However, current data availability is insufficient for developing an indicator on salt-water intrusion. Information on ecological impacts of climate change is not presented in this report due to a lack of data at European scale. Further information on the economic and health risks associated with sea-level rise is presented in Section 5.5.2.

Key messages: 3.2 Coastal zones

- Projected sea-level rise, possible changes in the frequency and intensity of storm surges and the resulting coastal erosion are expected to have major impacts on low-lying coastal areas across Europe.
- Future global mean sea-level rise in the 21st century is likely to be greater than during the 20th century. It is more likely to be less than 1 m than to be more than 1 m.
- Projections of changes in storms currently have high uncertainty. Increases in extreme coastal water levels will likely be dominated by increases in local relative mean sea level rather than by changes in storm activity in most locations.
- Coastal erosion in Europe causes significant ecological damage, economic loss and other societal problems. About one quarter of the European coastline for which data is available is currently eroding.

3.2.2 Global and European sea-level rise

Relevance

Sea level is an important indicator of climate change because it is associated with significant potential impacts on settlements, infrastructure, people and natural systems. It acts on time scales much longer than those of indicators that are closely related to near-surface temperature change (see Section 2.2). Even if GHG concentrations were stabilised immediately, sea level would continue to rise for centuries.

Low-lying coastlines with high population densities and small tidal ranges are most vulnerable to sea-level rise, in particular where adaptation is hindered by a lack of economic resources or by other constraints. In Europe, the potential impacts of sea-level rise include flooding, coastal erosion, and the loss of flat coastal regions (EEA, 2010). Rising sea levels can also cause salt-water intrusion into low-lying aquifers and endanger coastal ecosystems and wetlands. Higher flood levels increase the risks to life and property, including sea dikes and other infrastructure, with possible follow-up effects on tourism, recreation and transportation functions. Damage associated with sea-level rise would frequently result from extreme events, such as storm surges, the frequency of which would increase as the mean sea-level rises (see Section 3.2.3).

Changes in global average sea level result from a combination of several physical processes. Thermal expansion of the oceans occurs as a result of warming ocean water. Additional water is added to the ocean from a net melting of glaciers and small ice caps, and from the large Greenland and West Antarctic ice sheets. Further contributions may come from changes in the storage of liquid water on land, either in natural reservoirs such as groundwater or man-made reservoirs.

The locally experienced changes in sea level differ from global average changes for various reasons. Changes in water density are not expected to be spatially uniform, and changes in ocean circulation also have regionally different impacts. At any particular location there may also be a vertical movement of the land in either direction, for example due to the post-glacial rebound (in northern Europe) or to local groundwater extraction.

Past trends

Sea-level changes can be measured using tide gauges and remotely from space using altimeters. Many tide gauge measurements have long multi-decade time series, with some exceeding more than 100 years. However, the results can be distorted by local effects. Satellite altimeters enable sea level to be measured from space and give much better spatial coverage (except at high latitudes). However, the length of the record is limited.

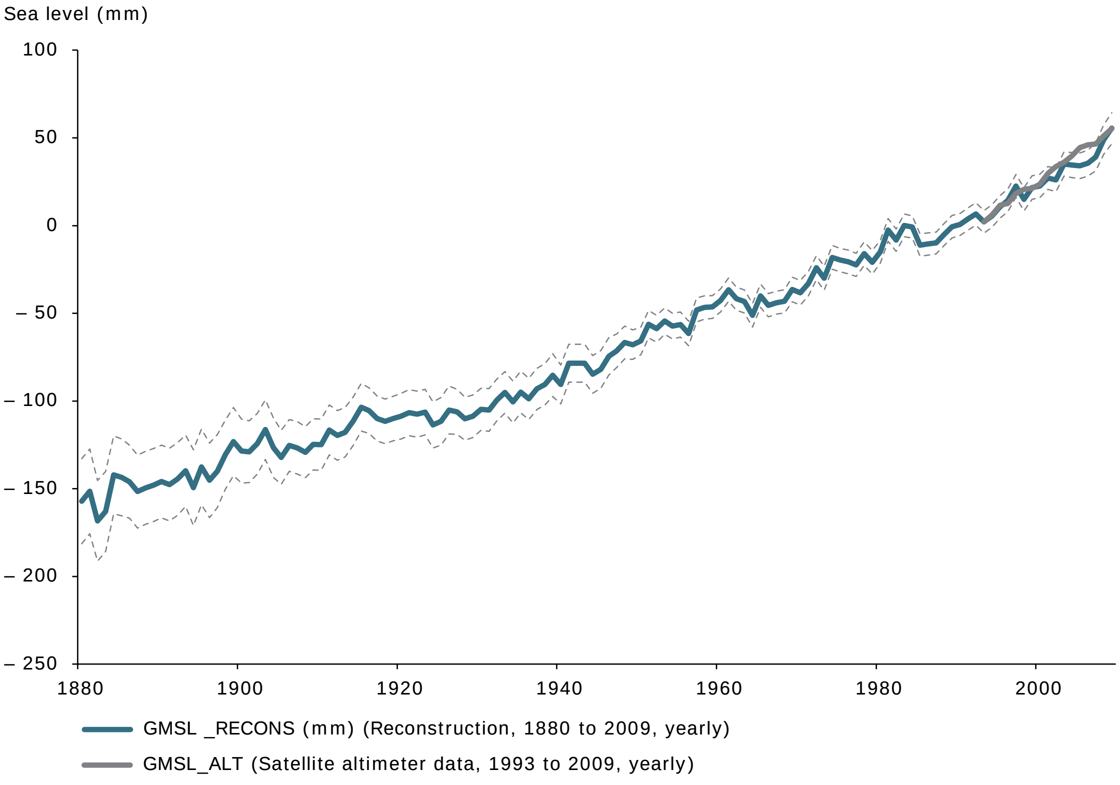
Key messages: 3.2.2 Global and European sea-level rise

- Tide gauges show that global mean sea level rose at a rate of around 1.7 mm/year over the 20th century, but there has been significant decadal variations around this value.
- Satellite measurements show a rate of global mean sea-level rise of around 3 mm/year over the last 2 decades.
- Sea level is not rising uniformly at all locations, with some locations experiencing much greater than average rise.
- Projections of global mean sea-level rise in the 21st century range between 20 cm and about 2 m. Modelling uncertainty contributes at least as much to the overall uncertainty as uncertainty about future GHG emissions scenarios. It is likely that 21st century sea-level rise will be greater than during the 20th century. It is more likely to be less than 1 m than to be more than 1 m.
- Coastal impacts also depend on the vertical movement of the land, which can either add to or subtract from climate-induced sea-level change, depending on the particular location.

Rates of global mean sea-level (GMSL) rise have been estimated at approximately 3 mm/year since around the mid-1990s (Church and White, 2011). This is greater than the longer term rise during the 20th century of around 1.7 mm/year, which is shown in Figure 3.6. There is evidence that the contribution from the melting cryosphere has increased recently (Velicogna, 2009). Both for recent decades and over the longer term historical period, there is some variability evident about the trend. In particular, there are periods during the 20th century before the 1990s where the rate of sea-level rise may have reached the recent rate of 3 mm/year for some years, although the higher rates of sea-level rise were generally sustained for shorter periods than recently. For a very recent time period, the variability in sea level includes a notable dip, starting in 2010. It has been suggested, based on observations from the GRACE satellite, that this observed recent dip in sea level may be related to the switch from El Niño to La Niña conditions in the Pacific and associated changes in precipitation patterns and storage of water on land (NASA, 2012).

It is not yet clear from observations whether the generally increased rate of sea-level rise observed since the mid-1990s will continue into the future. The many observations of surging outlet glaciers and ice streams (which could lead to high future rates of sea-level rise) must be balanced by recent work showing that some outlet glaciers on the Greenland ice sheet have now either stopped accelerating or even slowed down (Joughin et al., 2010). Modelling work of individual ice sheet glaciers also shows the potential for decadal and multi-decadal variability in glacier flow (Nick et al., 2009). There is sufficient evidence, based on recent observations, to be concerned about the possibility for an increase in the rate of sea-level rise to 2100 beyond that projected by the models used in the IPCC AR4 (IPCC, 2007) (see Figure 3.7). However, a greater understanding of the potential for accelerated ice sheet dynamical processes that could give rise to such rapid sea-level rise is needed from improved physically-based models and from appropriate palaeo observations before more precise and reliable estimates of future sea-level rise can be made.

Figure 3.6 Change in global mean sea level from 1860 to 2009



Note: Global mean sea level from 1860 to 2009 as estimated from coastal and island sea-level data (1880–2009, blue, with uncertainty range) and from satellite altimeter data (1993–2009, grey).

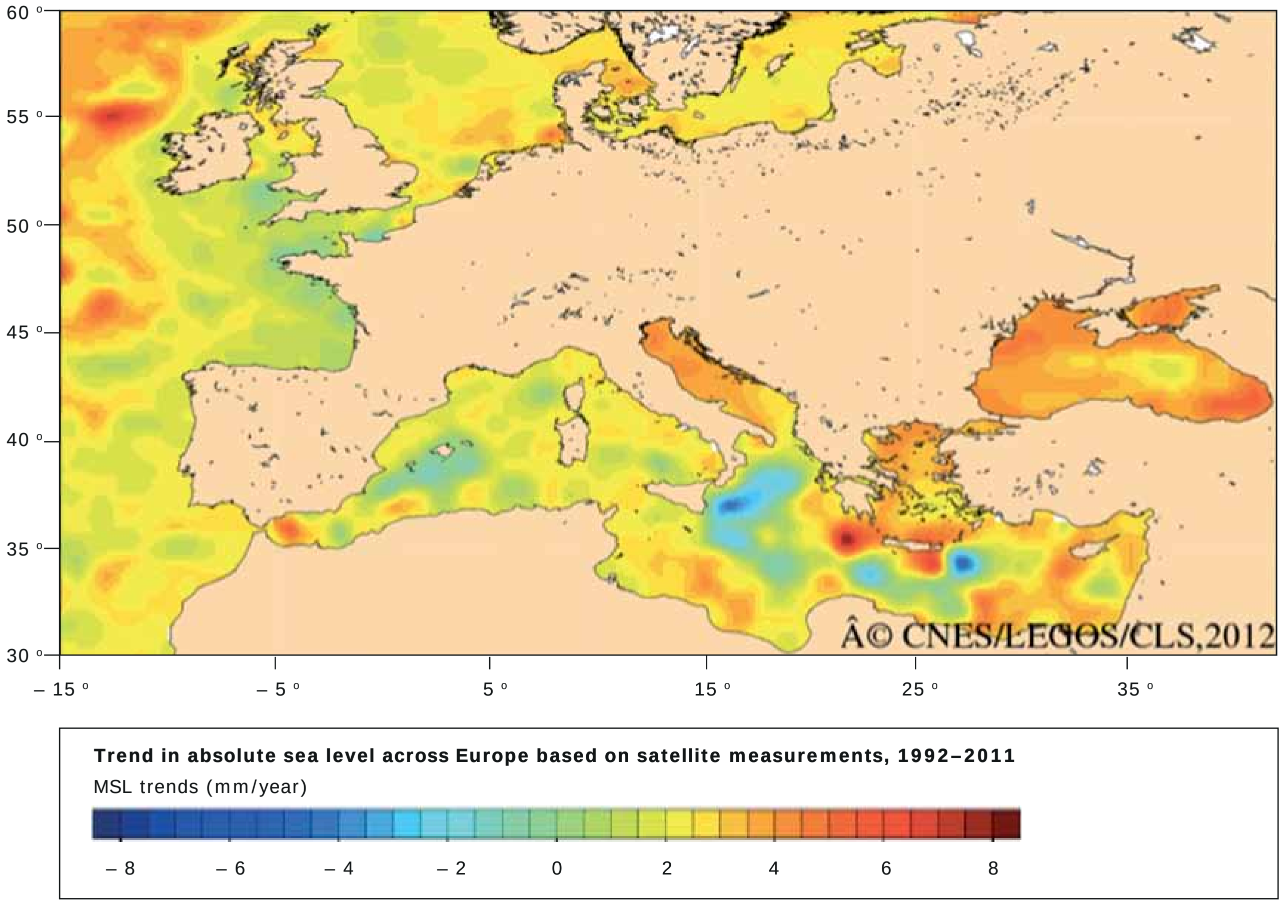
Source: Church and White, 2011.

Deviations in the rate of sea-level rise at individual locations are evident in both tide gauge and satellite studies. Map 3.3 shows the rates of change in sea level since 1992 for the European region based on satellite observations. Trends in the North Sea are typically around 2 mm/year, except for some parts of the southern-most North Sea where they are larger. Parts of the English Channel and the Bay of Biscay show a small decrease in sea level over this period. The Baltic Sea shows an increase of between around 2 mm/year and 5 mm/year. In the Mediterranean Sea there are regions with increases of more than 6 mm/year, and with decreases of more than – 4 mm/year. The Black Sea has seen an increase in sea level of between zero and around 5 mm/year.

The reasons for these big differences, even within a particular sea or basin, are due to different physical processes being the dominant cause of sea-level change at different locations. For instance, the Mediterranean Sea is a semi-closed, very deep basin, exchanging water with the Atlantic Ocean through the narrow Gibraltar Strait only. It is a concentration basin where evaporation greatly exceeds precipitation and river run-off. Therefore, salinity is one of the main physical parameters influencing the thermohaline circulation and sea-level variability in the Mediterranean, which may counteract the thermal expansion due to a rise in temperature. The NAO, interannual wind variability, changes in global ocean circulation patterns, and the location of large scale gyres are further factors that can influence local sea level in the European seas.

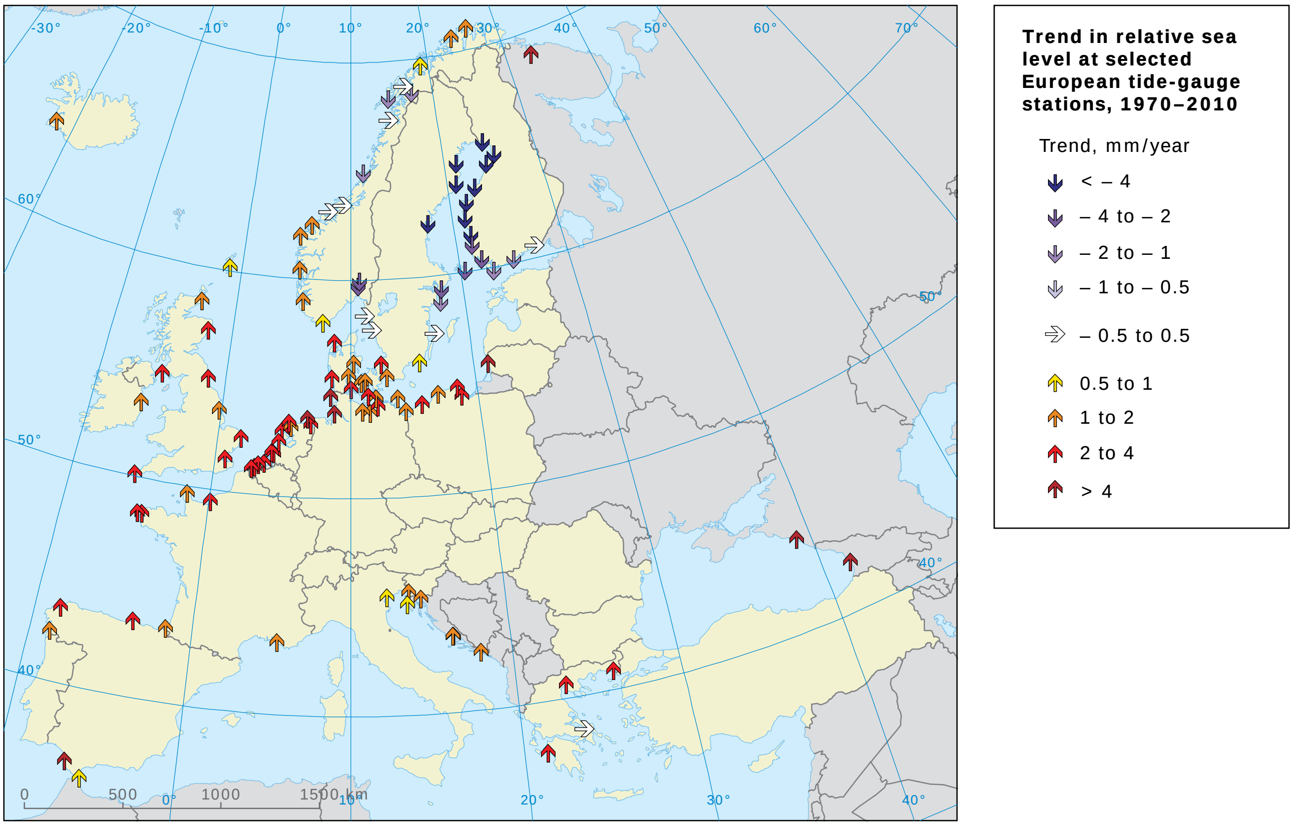
Map 3.4 shows observed trends in sea level from selected tide gauge stations in Europe. These trends can differ from those measured by satellites (see Map 3.3) because of the different time periods covered and because tide gauge measurements are influenced by vertical land movement whereas

Map 3.3 Trend in absolute sea level across Europe based on satellite measurements (1992–2011)



Source: Map supplied by Michaël Ablain (produced at CLS/CNES/LEGOS group, also available through MyOcean).

Map 3.4 Trend in relative sea level at selected European tide gauge stations (1970–2010)



Note: These measured trends are not corrected for local land movement. No attempt has been made to assess the validity of any individual fit, so results should not be treated as suitable for use in planning or policymaking.

Source: Woodworth and Player, 2003; Permanent Service for Mean Sea Level (PSMSL), 2012; 'Tide Gauge Data' (http://www.psmsl.org/products/trends).

satellite measurements are not. In particular, the lands around the northern Baltic Sea are still rising since the last ice age due to the post-glacial rebound (Johansson et al., 2002).

A significant recent step forward in projecting future sea levels is an improved understanding of the contributions to recent sea-level rise. A recent study found good agreement over the four last decades between observed total global sea-level rise and the sum of known contributions (Church and White, 2011). Table 3.1 summarises the main contributions based on that study. According to this table, thermal expansion was likely to have been the most important contributor to sea-level rise throughout the whole period (1972–2008). Sea-level rise has accelerated in the latter part of that period (1993–2008) when the melting of glaciers and ice caps became the most important source of sea-level rise.

Projections

Currently there are two main approaches to projecting future sea level: physically-based models that represent the most important known processes, and statistical models that apply the observed relationship between temperature or radiative forcing on the one hand and sea level on the other hand in the past and extrapolate it to the future. Both approaches produce a spread of results, which results in large uncertainties around future sea-level rise.

The IPCC AR4 contained several statements on future sea level. Most often quoted is the range of sea-level rise projected by physically-based models for thermal expansion, glaciers and small ice caps, the mass balance of the Greenland and West Antarctic ice sheet, and a term to represent the observed dynamic acceleration of the melting of the major ice sheets. The result is a global average

Table 3.1 Contributions to the sea-level budget since 1972

Component	1972 to 2008 (mm/year)	1993 to 2008 (mm/year)
Total from tide gauges	1.83 ± 0.18b	2.61 ± 0.55
Total from tide gauges and altimeter	2.10 ± 0.16	3.22 ± 0.41
1. Thermal expansion	0.80 ± 0.15	0.88 ± 0.33
2. Glaciers and ice caps	0.67 ± 0.03	0.99 ± 0.04
3. Greenland ice sheet	0.12 ± 0.17	0.31 ± 0.17
4. Antarctic ice sheet	0.30 ± 0.20	0.43 ± 0.20
5. Terrestrial storage	– 0.11 ± 0.19	– 0.08 ± 0.19
Sum of components (1. + 2. + 3. + 4. + 5.)	**1.78 ± 0.36**	**2.54 ± 0.46**

Source: Church and White, 2011.

increase of between 0.18 m and 0.59 m from the 1980–1999 mean to the 2090–2099 mean. The range depends on both the spread in future GHG emissions and uncertainty from computer models. The largest sea-level rise contribution was projected to come from the thermal expansion (0.10 to 0.41 m), followed by melting of glaciers and ice caps (0.07 to 0.17 m) and Greenland ice sheet (0.01 to 0.12 m). The IPCC AR4 went further by including a simple sensitivity study, which allowed for future linear increases in the dynamic ice sheet component with temperature. Whilst it is not clear that such a relationship would be linear the calculations suggest an additional 17 cm of rise could occur during the 21st century. The report acknowledged that limitations in understanding and models meant that it was not possible to provide with any degree of confidence either a highest plausible 21st century rise or central estimate of rise for all of the component sea-level terms.

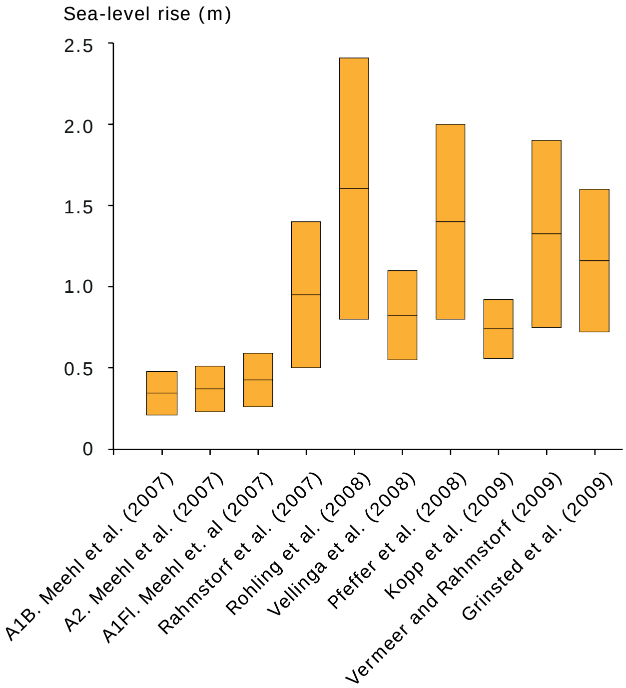
Since publication of the IPCC AR4, further progress has been made in understanding and simulating sea-level changes (Church and White, 2011). However, global physical models are still particularly limited in their representation of ice sheet processes (Nicholls et al., 2010). Since current understanding suggests that the potential for 21st century sea-level rise significantly above the AR4 range would largely result from potential increases in the ice sheet dynamical contributions, the lack of suitable physically-based models is still a significant hindrance to making reliable projections.

Statistical models of sea-level rise are also available. These models use observed relationships between changes in sea level and either surface air temperature or radiative forcing (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009). The statistical models are then combined with 21st century projections of radiative forcing or temperature and used for projection purposes. Typically, they produce larger sea-level rise projections than current physically-based models. Future projections based on this approach have limitations because the balance of contributions to sea-level rise during the future may not be the same as the balance during the tuning period of these statistical relationships (Lowe and Gregory, 2010). However, the differences between the two modelling approaches may also be interpreted as indicating the scale of processes not well represented in physically-based models.

In view of these limitations to future projections purely from models, some studies have combined understanding from current physical models with other strands of evidence to provide information on possible high-end sea-level rise amounts. Evidence stands include maximum rates of sea-level rise at the last interglacial and plausible kinematic constraints on future ice flows. A synthesis of high-end sea-level rise estimates based on all sources of information available is provided in Figure 3.7.

The major conclusion from recent studies is that it is still not possible to rule out GMSL increases during the next century of up to approximately 2 m. However, the balance of evidence suggests increases significantly in excess of 1 m are still considered much less likely than lower rates of sea-level rise. This is consistent with the results of the Thames Estuary 2100 study in the United Kingdom (Lowe et al., 2009) and a recent study in the Netherlands (Katsman et al., 2011). The latter, for example, combined modelling and expert judgement to derive a plausible high-end global scenario of 21st century

Figure 3.7 Range of high-end estimates of global sea-level rise published after the IPCC AR4



Note: Range of high-end global sea-level rise (metre per century) estimates published after the IPCC Fourth Assessment Report (AR4). AR4 results are shown for comparison in the three left-most columns.

Source: Nicholls et al., 2010.

sea-level rise of 0.55 to 1.15 m. However, they again concluded that although the probability of larger increases is small, it was still not possible to rule out increases approaching around 2 m based on palaeo-climatic evidence (Rohling et al., 2008). In summary, the highest projections available in the scientific literature should not be treated as likely increases in 21st century sea level, but they are useful for vulnerability tests against flooding in regions where there is a large risk aversion to flooding, or the consequences of flooding are particularly catastrophic.

Specific projections for regional seas

Future projections of the spatial pattern of sea-level rise also remain highly uncertain. There was little improvement in reducing this uncertainty between the IPCC Third and Fourth Assessment Report. Recent model improvements, however, may reduce this uncertainty in the future. One study produced estimates of sea-level rise around the United Kingdom based on results from the IPCC AR4 (Lowe et al., 2009). This study estimates absolute sea-level rise (which exclude changes in land level) around the United Kingdom for the 21st century in the range of 12 cm (the lower bound of the Low emission scenario) to about 76 cm (the upper bound of the High emission scenario). Larger rises could result from an additional ice sheet term, but this is more uncertain. Another study estimated the plausible high-end scenario for 21st century sea-level rise on the North Sea coast of the Netherlands in the range 40 to 105 cm (Katsman et al., 2011). Making multi-decadal regional projections for relatively small isolated and semi-isolated basins, such as the Mediterranean, is even more difficult than for the global ocean. One study made projections for the Mediterranean Sea based on the output of 12 global climate models for 3 emission scenarios (Marcos and Tsimplis, 2008). The results project an ocean temperature-driven sea-level rise during the 21st century between 3 and 61 cm over the basin, which needs to be combined with a salinity-driven sea-level change between – 22 and + 31 cm.

3.2.3 Storm surges

Relevance

A storm surge is a temporary deviation in sea water level from that of the astronomical tide caused by changes in air pressure and winds. Most concern is centred on positive surge events where the surge adds to the tidal level and increases the risk of coastal flooding by extreme water levels. Changes in the climatology of extreme water levels may result from changes in time mean local sea level (i.e. the local sea level relative to land averaged over a year), changes in storm surge characteristics, or changes in tides. Here the focus will be on changes in the storm surge characteristics, which are closely linked to changes in the characteristics of atmospheric storms, including the frequency, track and intensity of the storms. The height of surges is also strongly affected by regional and local-scale geographical features, such as the shape of the coastline. Typically, the highest water levels are found on the rising limb of the tide (Horsburgh and Wilson, 2007). The biggest surge events typically occur during the winter months in Europe.

The most obvious impact of extreme sea levels is flooding (Horsburgh et al., 2010). The most well known coastal flooding event in Europe in living memory occurred in 1953 due to a combination of a severe storm surge and a high spring tide. The event caused in excess of 2 000 deaths in Belgium, the Netherlands and the United Kingdom, and damaged or destroyed more than 40 000 buildings. Currently around 200 million people live in the coastal zone in Europe, and insurable losses due to coastal flooding are likely to rise during the 21st century, at least for the North Sea region (Gaslikova et al., 2011). In addition to the direct impact of flooding, increases in the frequency of storm surges can also exacerbate other coastal problems, such as erosion, salt water intrusion, migration or river flooding.

Past trends

Producing a clear picture of either past changes or future projections of storm surges for the entire European coast line is a challenging task because of the impact of local topographical features on the surge events. Whilst there are numerous studies for the North Sea coastline, fewer are available for the Mediterranean and Baltic Seas, although this situation is starting to improve. The uncertainty in future projections of storm surges remains high and is ultimately linked to the uncertainty in future mid-latitude storminess changes (see Section 2.2). This is an area where current scientific understanding is advancing quickly, with some of the latest climate models simulating significant differences in mid-latitude storm development, evolution and movement (Scaife et al., 2011) compared to the generation of climate models used in current studies of future storm surges.

The most comprehensive global studies of trends in extreme coastal sea level and storm surges examined trends from hourly tide gauge records at least for the period since 1970, and for earlier periods of the 20th century for some locations (Woodworth and Blackman, 2004; Menéndez and Woodworth, 2010). The results show that changes in extreme water levels tend to be dominated by the change in the time mean local sea level. In the north-west European region there is clear evidence of widespread increase in sea level extremes since

Key messages: 3.2.3 Storm surges

- Several large storm surge events have caused loss of life and damage to property in Europe during the past century. The most notable event occurred in 1953 when more than 2 000 people were killed, and there was massive damage to property around the coastline of the southern North Sea.
- There is strong evidence that extreme coastal water levels have increased at many locations around the European coastline. However, this appears to be predominantly due to increases in time mean local sea level at most locations rather than to changes in storm activity.
- Large natural variability in extreme coastal sea levels makes detecting long-term changes in trends difficult in the absence of good quality long observational records.
- Multi-decadal projections of changes in storms and storm surges for the European region currently have high uncertainty. The most recent studies indicate that increases in extreme coastal water levels will likely be dominated by increases in local relative mean sea level, with changes in the meteorologically-driven surge component being less important at most locations.

1970, but much less evidence of such a trend over the entire 20th century. When the contribution from time mean local sea level changes and variations in tide are removed from the recent trends, the remaining signals due to changes in storminess are much smaller or even no longer detectable.

Additional studies are available for some European coastal locations, but typically focus on more limited spatial scales. A study that examined the trend in water levels at 18 sites around the English Channel found that the rates of change in extreme water levels were similar to the rates observed for mean sea level change (Haigh et al., 2010). However, the study also noted sizeable variations in storm surge heights, with the largest surge intensity occurring in the late 1950s. This large natural variability makes it difficult to detect changes in the rate of change in water level extremes. A similar conclusion, that the change in annual maximum sea levels are increasing at a rate not significantly different from the observed increase in mean sea level, was found in separate analyses for Newlyn in the United Kingdom for the period 1915–2005 (Araújo and Pugh, 2008) and for 73 tide gauges along the Atlantic and Mediterranean coastlines in southern Europe (Marcos et al., 2011). In contrast, significant increases in storm surge height during the 20th century were found along the Estonian coast of the Baltic Sea (Suursaar et al., 2009).

We conclude that whilst there have been detectable changes in extreme water levels around the European coastline, most of these are dominated by changes in time mean local sea level. The contribution from changes in storminess is currently small in most European locations and there is little evidence that any trends can be separated from long-period natural variability.

Projections

Future projections in storm surges can be made using either dynamic or statistical modelling of storm surge behaviour driven by the output of general circulation climate models (Lowe et al., 2010). Several climate modelling studies have projected changes in storm surge height and frequency for the 21st century, mostly using the SRES A1B, A2 or B2 scenarios (see Section 1.5.1). The results critically depend on the simulated changes in mid-latitude storms; this topic remains a highly uncertain and rapidly evolving scientific field. The limited number of studies that separate out any long-term climate change signal from multi-decadal climate variability suggests that changes in atmospheric storminess are likely to be less important than increases in mean local sea level.

Early studies on future changes in surge magnitude in the North Sea region all identified certain areas where increase in surge magnitude were projected, but they did not agree over its magnitude or even which regions will be affected (Lowe et al., 2001; Hulme et al., 2002; Lowe and Gregory, 2005; Woth et al., 2005; Beniston et al., 2007; Debernard and Røed, 2008). Furthermore, most of these studies have not adequately considered that changes in various indices of storminess over the European region exhibit decadal and multi-decadal oscillations (Sterl et al., 2009) (Jenkins et al., 2007).

Two recent studies addressed some of the deficiencies in earlier studies by using ensemble simulations of climate models to drive a surge model of the North Sea for the period 1950–2100. One study found no significant change in the 1 in 10 000 year return values of storm surges along the Dutch coastline during the 21st century (Sterl et al., 2009). The other study projected small changes in storm surge heights for the 21st century around much of the UK coastline. Most of these changes were positive but they were typically much less than the expected increase in time mean local sea level over the same time period (Lowe et al., 2009). However, larger increases in storm surge for this region during the 21st century cannot yet be ruled out.

A study on the Mediterranean region projected a reduction in both the number and frequency of storm surge events during the 21st century (Marcos et al., 2011). A study on the Baltic Sea projected increases in extreme sea levels over the 21st century that were larger than the time mean local sea-level rise for some future scenarios simulated by some of the climate models used (Meier, 2006). The largest changes in storm surge height were in the Gulf of Finland, Gulf of Riga and the north-eastern Bothnian Bay. A study on storm surges around the coast of Ireland projected an increase in surge events on the west and east coasts but not along the southern coast (Wang et al., 2008). However, not all of the changes were found to have a high statistical significance.

At some locations, such as Hamburg, local changes in bathymetry caused by erosion, sedimentation and waterworks can have a much larger impact than climate change (von Storch and Woth, 2008). Finally, recent work has shown that sea-level rise may also change extreme water levels by altering the tidal range (Pickering et al., 2012).

3.2.4 Coastal erosion

Relevance

Coastal erosion is the process of wearing away material from a coastal profile due to imbalance in the supply and export of material from a certain section. It takes place in the form of scouring in the foot of the cliffs or dunes or at the sub-tidal foreshore. Coastal erosion takes place mainly during strong winds, high waves and high tides and storm surge conditions, and results in coastline retreat and loss of land (Mangor, 2001).

More than 5 million people in Europe are living in areas at risk from coastal erosion and marine flooding (defined as being below 5 m elevation, but not further than 1 km distance from the coastline) ([42]). The increasing human use of the coastal zone has turned coastal erosion from a natural phenomenon into a problem of growing importance for societies. Adverse impacts of coastal erosion most frequently encountered in Europe can be grouped in three categories: 1) coastal flooding as a result of complete dune erosion, 2) undermining of sea defences associated with foreshore erosion and coastal squeeze, and 3) retreating cliffs, beaches and dunes causing loss of lands of economic and ecological value (Conscience, 2010).

Coastal erosion in Europe causes significant economic loss, ecological damage and societal problems. Loss of property, residential and commercial buildings, infrastructure, beach width, and valuable coastal habitat causes millions of euros worth of economic damage each year and presents significant management issues. At the same time protection is expensive. For example, in France some EUR 20 million is spent each year on mitigation measures and in the Netherlands the annual budget for sand nourishment amounts to some EUR 41 million (Marchand, 2010).

Past trends

Many European coasts are endangered because they are being affected by coastal erosion. According to the Eurosion Project ([43]) (Eurosion, 2004), about 20 000 km of coasts faced serious impacts in 2004. Most of the impact zones (15 100 km) are actively retreating, some of them in spite of coastal protection works (2 900 km). In addition, another 4 700 km have become artificially stabilised.

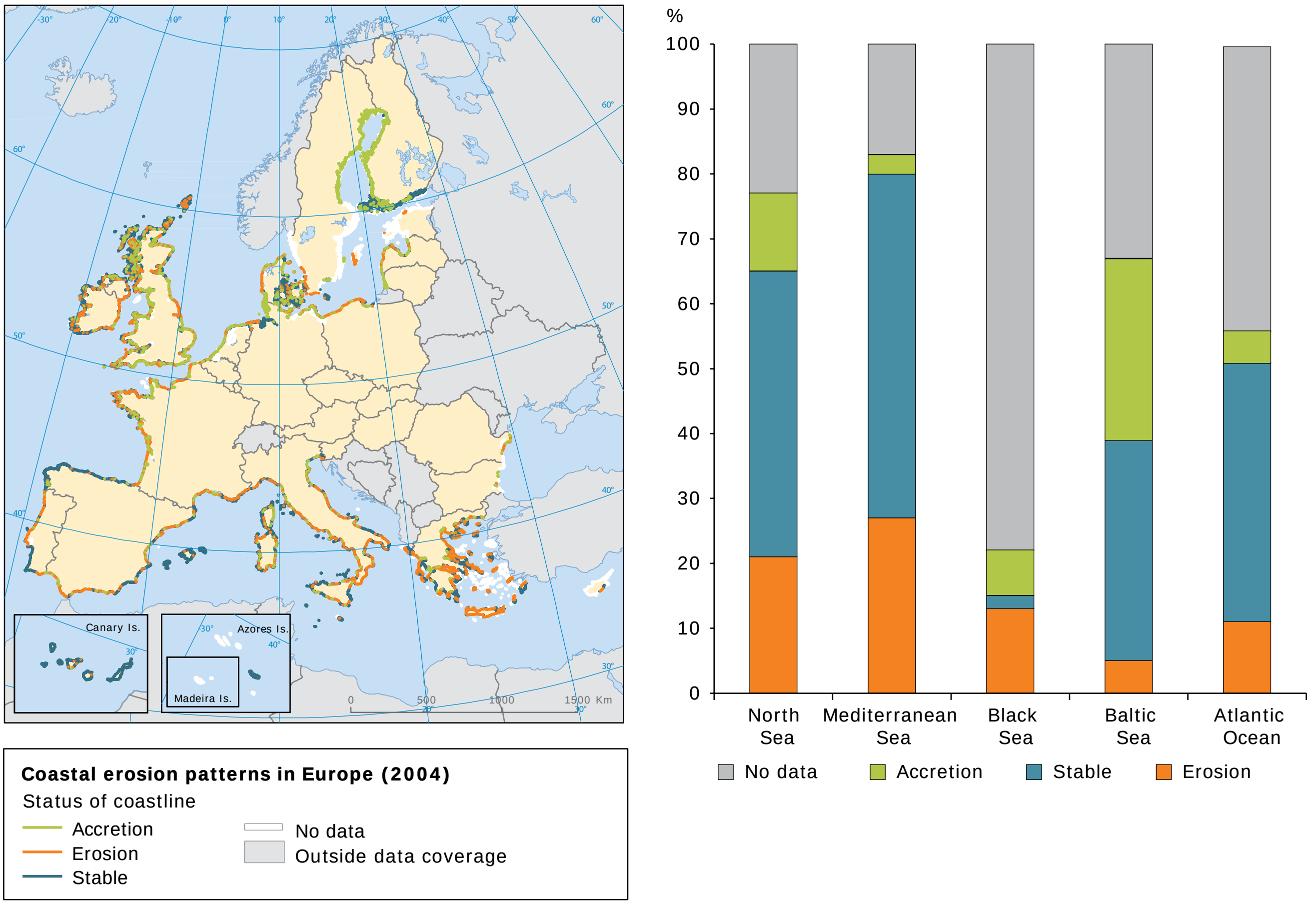
Figure 3.8 shows the pattern of erosion and accretion in Europe, including statistics for all European seas. The largest percentage of eroding coasts is found along the Mediterranean and North Seas. The Baltic Sea is the only sea where the proportion of accumulative coasts is larger than that of eroding coasts, mostly due to the isostatic land uplift in the northern parts of the Baltic. In total, ca. 15 % of the European coastline was eroding, and about the same length was accreting (almost exclusively in northern Europe); 40 % was stable, and data was missing for the remaining 30 %. Other climate change drivers that may exacerbate erosion rates are increased storminess, higher waves and changes in prevalent wind and wave directions.

Key messages: 3.2.4 Coastal erosion

- Coastal erosion in Europe causes significant economic loss, ecological damage and societal problems. About one quarter of the European coastline for which data is available is currently eroding.
- Projections for coastal erosion are not available. Future climate change, in particular rising sea levels, is expected to accelerate coastal erosion.

([42]) Calculation by EEA, based on the 2001 population census.
([43]) See http://www.eurosion.org.

Figure 3.8 Coastline dynamics in Europe



Source: Deduce project ([44]) (http://www.deduce.eu/IFS/IFS26.pdf).

In some regions in Europe, coastal erosion can reach up to 2 m per year. The average annual rate of erosion at the Holderness Coast in north-east England is around 2 m per year (Sistermans and Nieuwenhuis, 2004). Erosion rates of more than 2 m per year during the period 1991–2001 were observed at Forte Novo in the central Algarve in Portugal (Andrade et al., 2001).

Projections

Coastal erosion will be increased by climate change. Sea-level rise is one of the most important drivers for accelerated erosion because it implies an increase in sediment demand, as retreating coastline and higher sea levels will raise extreme water levels, allow waves to break nearer to the coast and transmit more wave energy to the shoreline. Other climate change drivers that may exacerbate erosion rates are increased storminess, higher waves and changes in prevalent wind and waves directions (Marchand, 2010).

([44]) See http://www.deduce.eu.

3.3 Freshwater quantity and quality

3.3.1 Overview

Water is essential to life and is an indispensable resource for ecosystems and for nearly all human activities. It is intricately linked with climate such that any alteration in the climate system will induce changes in the hydrological cycle. Consequently, the spatial and temporal distribution of freshwater resources and those socio-economic activities dependent upon water are affected by climate variability and climate change.

There is growing evidence that climatic changes in recent decades have already affected the global hydrological cycle, such as by changes in seasonal river flow and increasing severity and frequency of both floods and droughts in some regions. However, the detection of significant long-term trends in hydrological variables is generally difficult due to substantial interannual and decadal variability. Furthermore, the attribution of observed changes is complicated because of modifications to natural water flow arising from water abstractions and land-use change.

Indicator selection

This section presents information on the following indicators:

- *River flow:* This indicator monitors changes in annual and seasonal river flow, which is central for water availability to households, industry and agriculture.
- *River floods:* This indicator monitors changes in river floods events, which are among the most costly weather disasters in Europe.
- *River flow droughts:* This indicator monitors changes in low river flow, which can have significant negative impacts on households, industry, navigation, agriculture and ecosystems.
- *Water temperature of rivers and lakes:* Water temperature is one of the central parameters that determine the overall health of aquatic ecosystems because aquatic organisms have a specific range of temperatures that they can tolerate.
- *Lake and river ice:* This indicator is relevant for freshwater ecosystems and for transport.

The concluding subsection presents selected information on the impacts of past and projected changes in these indicators for *freshwater ecosystems and water quality*. This information is not presented in the indicator format because the impacts foreseen for different aquatic species and ecosystems are so diverse that the message cannot be conveyed in one indicator.

Further information on the health and economic risks of floods and droughts is presented in Section 4.4 and in Chapter 5.

Key messages: 3.3 Freshwater quantity and quality

- Climate change has already affected river flow but other factors also have a strong influence.
- In general, river flows have increased in winter and decreased in summer, but with substantial regional and seasonal variation.
- The impact of river flow droughts is currently largest in southern and south-eastern Europe. These impacts are projected to further increase with prolonged and more extreme droughts.
- Climate change has increased water temperatures of rivers and lakes, and has decreased ice cover.
- Changes in stream flow and water temperature have important impacts on water quality and on freshwater ecosystems.

Data quality and data needs

Detailed data on water quantity is often difficult to assess, and homogeneous time series are generally shorter than those for meteorological data. It may, therefore, require substantially more time before statistically significant changes in hydrological variables can be observed than for meteorological variables, especially with respect to extreme events (floods and droughts). Quantitative projections of changes in precipitation and river flows at the basin scale remain highly uncertain due to the limitations of climate models and to scaling issues between climate and hydrological models.

The main data sources for European-wide studies of extreme hydrological events and their changes are global databases for natural disasters. These include general impact-oriented disaster databases such as EM-DAT ([45]) maintained by the Centre for Research on the Epidemiology of Disasters (CRED) and the NatCatService ([46]) maintained by Munich RE, as well as specific mostly event-oriented databases, such as the Dartmouth Flood Observatory ([47]). Some of the limitations of these databases included the use of thresholds for inclusion of an event, which may exclude smaller events with a significant regional impact, changes over time in the comprehensiveness of the coverage (see below), and privacy issues related to detailed data collected by the insurance industry. Improvements of these datasets are planned in coming years. The available data is currently evaluated, for example in the ongoing emBRACE project ([48]). A more detailed and comprehensive event-oriented database that also includes events without any (major) damages would be needed to separate the effect of climate change from socio-economic changes.

The reporting of flood and drought events has generally improved during the past few decades as a result of improvements in data collection and flows of information. As a result, it is often difficult to identify whether an increase in reported flood events (or their impacts) over time is due mostly to improvements in data collection or to actual changes in these events. Furthermore, river flood records are usually sourced from different institutions and often collected using a wide range of different assessment methods and rationales, which may have changed over time. This multitude of sources limits the comparability of key attributes associated with such events (e.g. economic losses, human casualties) across space and time. For a more detailed description of the EM-DAT data, see Section 4.4 on Human Health.

As part of the preliminary flood risk assessment for the European Directive on the assessment and management of flood risks (2007/60/EC) ([49]), EU Member States will give an overview of significant past floods. In addition, a European flood impact database could bring together publicly available inventories of flood events. At the national/regional level, such an inventory would be particularly useful to provide accurate data and assessments which would serve as a basis for disaster prevention. At the European level, these inventories could assist in tracking the trends in flood-disaster losses, and in mitigation programmes monitoring and obtaining a clearer picture of the linkages between climate change and floods and flood losses.

Reliable information on the extent and impacts of water scarcity and droughts (WSD) is indispensable for decision-making at all levels. The European Commission has strengthened its activities through the 2007 Communication on WSD and several studies. The EEA reports 'Water resources across Europe — confronting water scarcity and drought' (EEA, 2009a), 'Regional climate change and adaptation – The Alps facing the challenge of changing water resources' (EEA, 2009b), and 'Towards efficient use of water resources in Europe' (EEA, 2012) include an overview of water availability, water abstraction and water scarcity in Europe or more specific for the Alpine region and discuss management options. The water exploitation index is currently being revised to be calculated on the level of river basins instead of the administrative boundaries of countries. The Joint Research Centre (JRC) of the European Commission has developed a European Drought Observatory (EDO ([50])) for drought forecasting, assessment and monitoring. However, despite several activities, there is no systematic, comprehensive record of WSD events in Europe describing their duration, impact and severity, other than meteorological time series for precipitation.

More detailed information is available for some rivers as a result of targeted research projects (Görgen and Beersma, 2010; ICPR, 2011; Wechsung, 2011).

([45]) See http://www.emdat.be.
([46]) See http://www.munichre.com/geo.
([47]) See http://floodobservatory.colorado.edu.
([48]) See http://embrace-eu.org.
([49]) See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:288:0027:0034:EN:PDF.
([50]) See http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000.

3.3.2 River flow

Relevance

River flow is a measure of overall fresh water availability in a river basin. Variations in river flow are determined mainly by the seasonality of precipitation and temperature, as well as by catchment characteristics such as geology, soil and land cover. Changes in temperature and precipitation patterns due to climate change modify the annual water budget of river basins as well as the timing and seasonality of river flows. The consequent changes in water availability may adversely affect ecosystems and several socio-economic sectors including abstraction for drinking water, agriculture, industry, energy production and navigation. Extreme dry periods with low river flow events can have considerable economic, societal and environmental impacts (see Section 3.3.4).

Past trends

Human interventions in catchments including water abstractions, river regulation and land-use change have considerably altered river flow regimes in large parts of Europe, making it difficult to discern any climate-driven changes in river flow to date. However, a comprehensive recent study has investigated time series of river flows in more than 400 small catchments with near-natural flow regimes to overcome these limitations (Stahl et al., 2010). The study finds indicate that annual river flow has generally decreased over the period 1962–2004 in southern and eastern Europe, and it has increased elsewhere. These findings are broadly consistent with results from earlier studies (e.g. (Milly et al., 2005). Seasonal changes are also apparent, with a decreased flow in summer months and an increase in winter months in most catchments (see Map 3.5). Similar results were found in national and regional studies (Birsan et al., 2005; Wilson et al., 2010).

The magnitude of the observed seasonal changes clearly raises concerns for water resource management both today and in future decades. To date, however, despite the evidence of monthly changes to flow, there is no conclusive evidence that low river flows have generally become more severe or frequent in Europe during recent decades (Stahl et al., 2008).

Projections

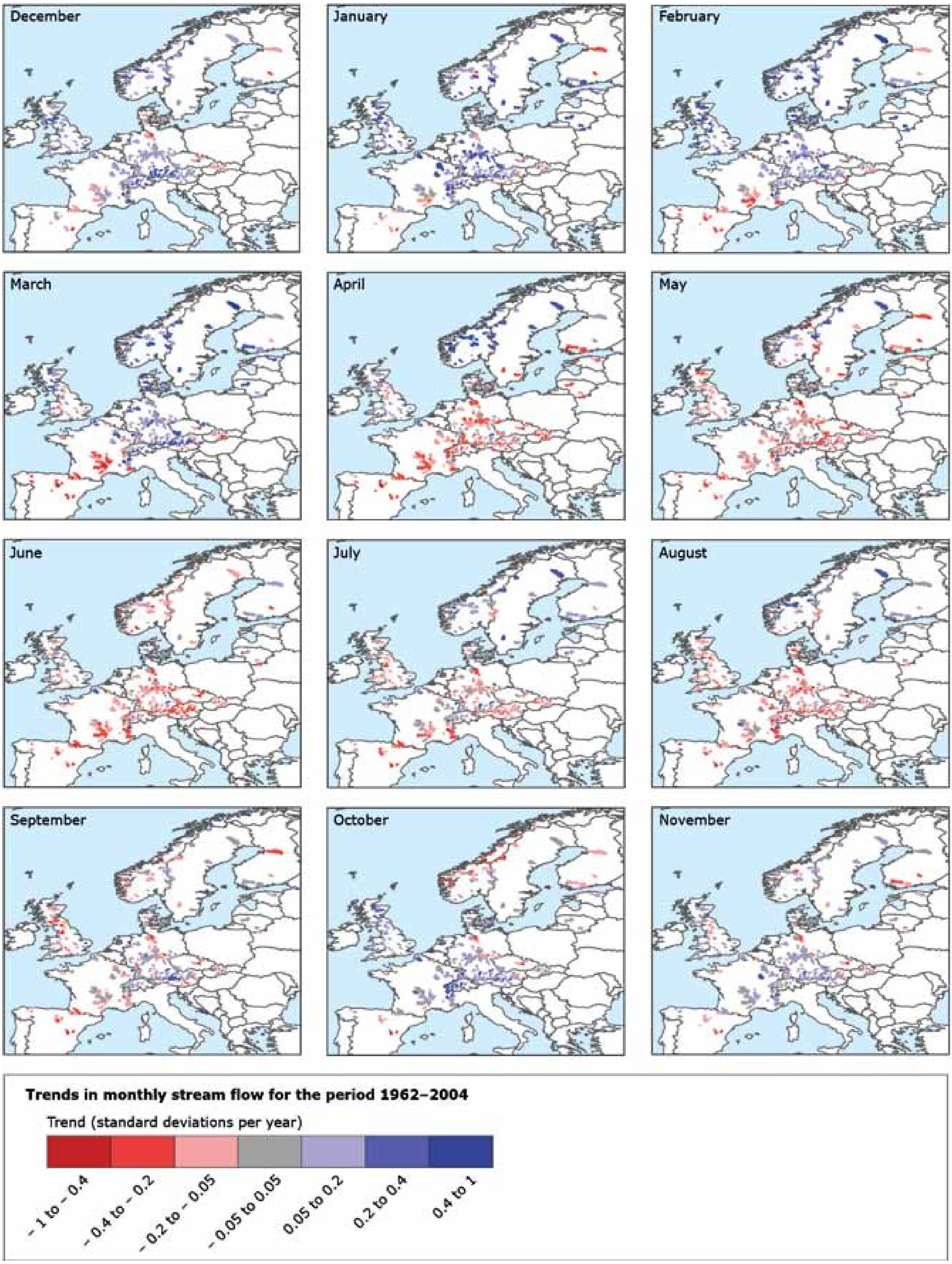
Annual river flow is projected to decrease in southern and south-eastern Europe and increase in northern and north-eastern Europe (Milly et al., 2005; Alcamo et al., 2007; Dankers and Feyen, 2009). Strong changes are projected in the seasonality of river flows, with large differences across Europe. Winter and spring river flows are projected to further increase in most parts of Europe, except for the most southern and south-eastern regions, which would exacerbate the observed trend. In summer and autumn, river flows are projected to decrease in most of Europe, except for northern and north-eastern regions where they are projected to increase (Map 3.6) (Rojas et al., 2012). Such a trend cannot be seen that clear in the observed monthly stream flow for the period 1962–2004 (Map 3.5).

In snow-dominated regions, such as the Alps, Scandinavia and parts of the Baltic, the fall in winter retention as snow, earlier snowmelt and reduced summer precipitation is projected to increase river flows in winter and reduce them in summer, when demand is typically highest (Beniston et al., 2011; BAFU, 2012). For most parts of Europe the peak of the average daily flow for 2071–2100 is projected to occur earlier in the year compared to observations. For northern Europe a slight increase of the peak of average daily flow is projected compared to a decrease in the other stations evaluated (see Figure 3.9).

Key messages: 3.3.2 River flow

- Long-term trends in river flows due to climate change are difficult to detect due to substantial interannual and decadal variability as well as modifications to natural water flows arising from water abstractions, man-made reservoirs and land-use changes. Nevertheless, increased river flows during winter and lower river flows during summer have been recorded since the 1960s in large parts of Europe.
- Climate change is projected to result in strong changes in the seasonality of river flows across Europe. Summer flows are projected to decrease in most of Europe, including in regions where annual flows are projected to increase.

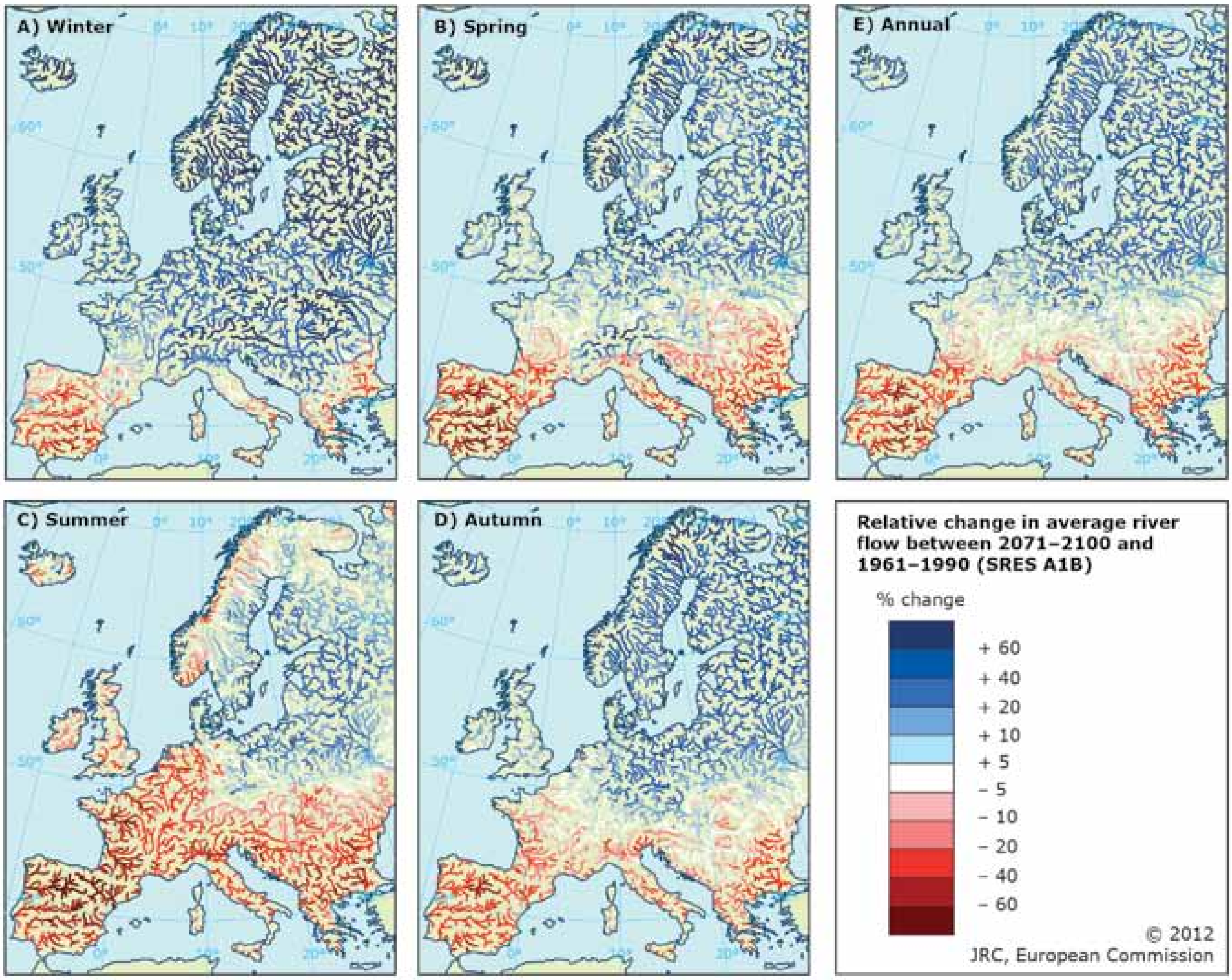
Map 3.5 Trends in monthly stream flow for the period 1962–2004



Note: Red colours mark decreases in stream flow whereas blue colours mark increases in stream flow.

Source: Stahl et al., 2010. Reprinted with permission.

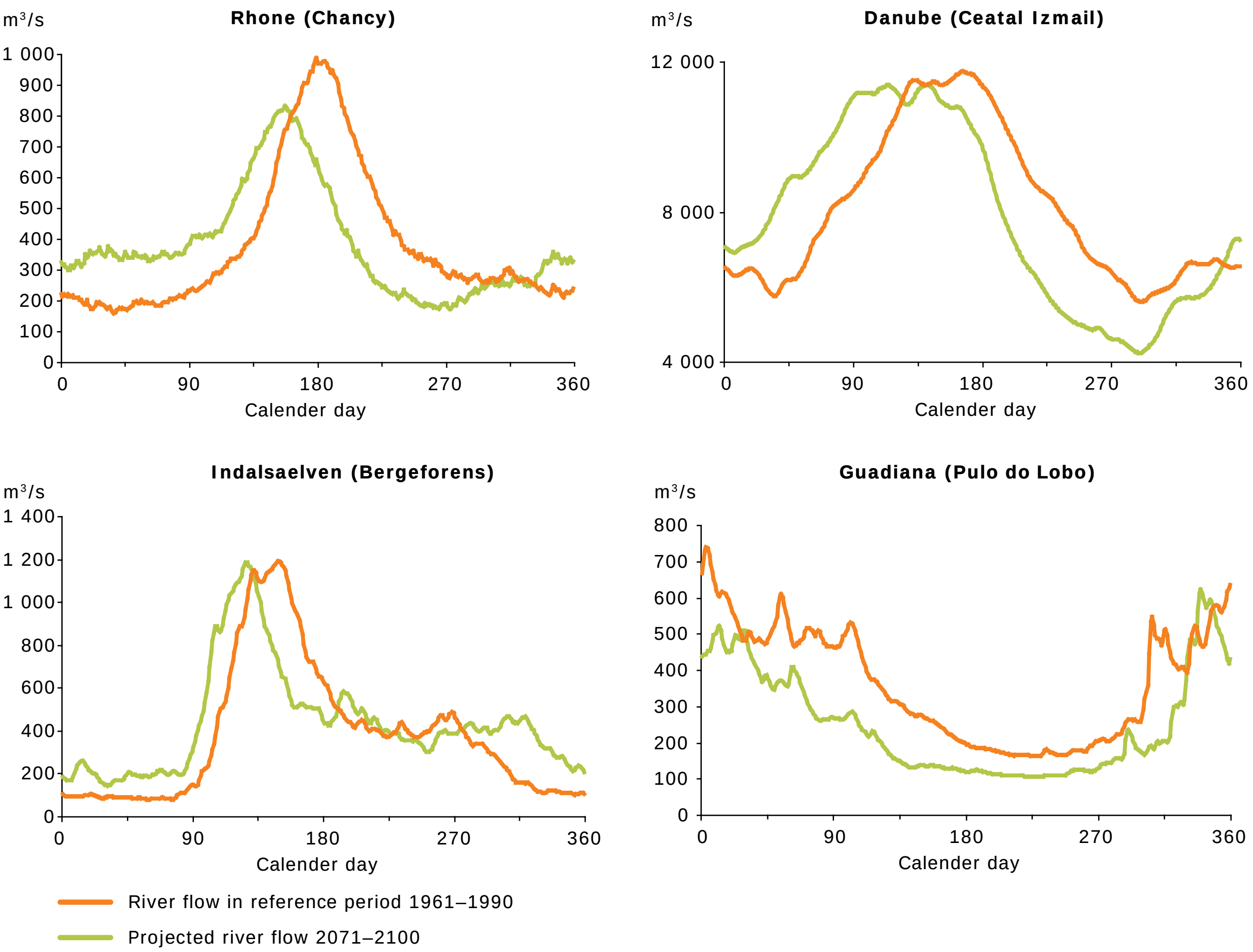
Map 3.6 Projected change in average annual and seasonal river flow



Note: Projected change in mean annual and seasonal river flow between the climate change scenario (SRES A1B, 2071–2100) and the control period (1961–1990). Simulations with LISFLOOD based on an ensemble of 11 RCMs.

Source: Rojas et al., 2012.

Figure 3.9 Projected change in daily average river flow for four rivers



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

Source: Luc Feyen, 2009 (unpublished results). © JRC.

3.3.3 River floods

Relevance

There are many different types of floods. They can be distinguished based on the source of flooding (e.g. rivers and lakes, urban storm water and combined sewage overflow, or sea water), the mechanism of flooding (e.g. natural exceedance, defence or infrastructural failure, or blockage) and other characteristics (e.g. flash flooding, snowmelt flood, or debris flow).

River floods are a common natural disaster in Europe, and — along with storms — the most important natural hazard in Europe in terms of economic damage. They are mainly caused by prolonged or heavy precipitation events or snowmelt. River floods can result in huge economic losses due to damage to infrastructure, property and agricultural land, and indirect losses in or beyond the flooded areas, such as production losses caused by damaged transport or energy infrastructure. They can also lead to loss of life, especially in the case of flash floods, and displacement of people, and can have adverse effects on human health, the environment and cultural heritage.

Past trends

More than 325 major river floods (including flash floods) have been reported for Europe since 1980, of which more than 200 have been reported since 2000 (EM-DAT, 2012). The rise in the reported number of flood events in the recent decade results mainly from better reporting and from land-use changes. Floods have resulted in more than 2 500 fatalities and have affected more than 5.5 million people in the period from 1980 to 2011. Direct economic losses over this same period amounted to more than EUR 90 billion (based on 2009 values).

Map 3.7 shows the occurrence of flood events in Europe from 1998–2009. This picture is incomplete because events with small spatial extent and/or impact are not included. Nevertheless, it becomes clear that large areas throughout Europe have been affected by flooding over the last decade, many of them even multiple times. Flood losses in Europe have increased substantially over recent decades but this trend is primarily attributable to socio-economic factors, such as increasing wealth located in flood zones. The influence of anthropogenic climate change remains inconclusive (Barredo, 2009).

Significant trends in river inundations have been identified in some regional and national studies. For example, significant increases in flood intensities have been identified between 1951 and 2002 in western, southern and central Germany (Petrow and Merz, 2009) as well as in upland catchments in the northern and western United Kingdom (Hannaford and Marsh, 2008). A new analysis of the strong UK floods of 2000 suggests that anthropogenic climate change was a contributing factor (Pall et al., 2011). In the Alps (Renard et al., 2008) and Nordic region (Wilson et al., 2010), snowmelt floods have occurred earlier because of warmer winters. In contrast, no conclusive evidence was found in an analysis of flood trends in Austria (Villarini et al., 2012), and an increasing flood trend in Catalonia is attributed to socio-economic factors (Barnolas and Llasat, 2007).

Projections

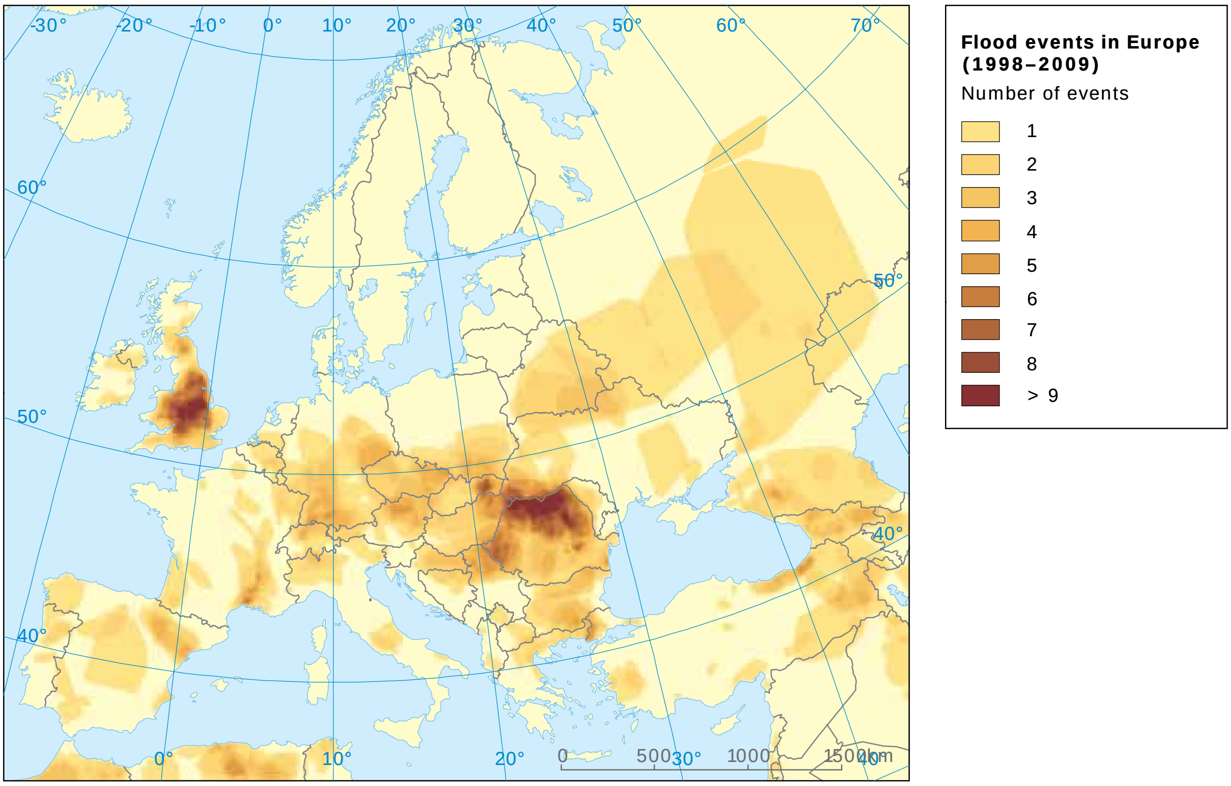
Changes in future flood hazard in Europe have been simulated by a hydrological model driven by an ensemble of climate simulations (Dankers and Feyen, 2009; Flörke et al., 2011). An increasing flood hazard is consistently projected for several of Europe's major rivers across climate models and emissions scenarios (Feyen et al., 2011).

Map 3.8 shows the change in the level of a one-in-a-century flood between the reference

Key messages: 3.3.3 River floods

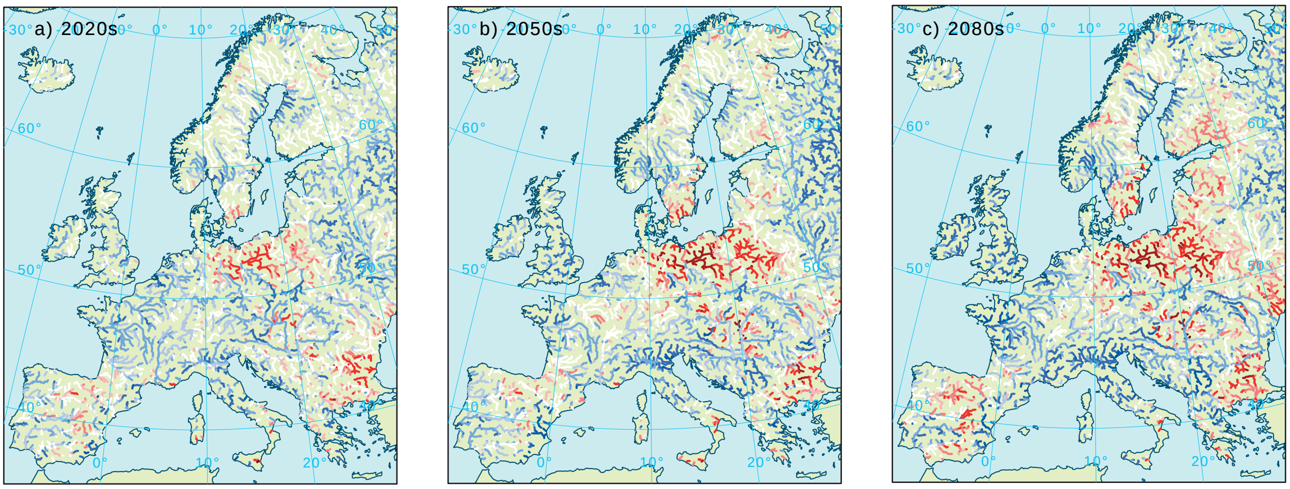
- More than 325 major river floods have been reported for Europe since 1980, of which more than 200 have been reported since 2000.
- The rise in the reported number of flood events over recent decades results mainly from better reporting and from land-use changes.
- Global warming is projected to intensify the hydrological cycle and increase the occurrence and frequency of flood events in large parts of Europe.
- Flash floods and pluvial floods, which are triggered by local intense precipitation events, are likely to become more frequent throughout Europe. In regions with projected reduced snow accumulation during winter, the risk of early spring flooding could decrease. However, quantitative projections of changes in flood frequency and magnitude remain highly uncertain.

Map 3.7 Occurrence of major floods in Europe (1998–2009)



Source: EEA, based on Dartmouth Flood Observatory, 2012.

Map 3.8 Projected change in river floods with a return period of 100 years



Relative change in river floods with a return period of 100 years between future period and 1961–1990 (SRES A1B)

(%) – 60 – 40 – 20 – 10 – 5 5 10 20 40 60

Note: Projected change in the level of a 100-year maximum level of river discharge between the reference period 1961–1990 and the 2020s (left), 2050s (centre) and the 2080s (right) based on an ensemble of 12 RCM simulations with LISFLOOD for the SRES A1B scenario.

Source: Rojas et al., 2012.

period and three future time periods based on the hydrological model LISFLOOD and an ensemble of 12 climate models. Blue rivers indicate an increase in flood level and red rivers a decrease. While the ensemble mean presented in Map 3.8 provides the best assessment of all model simulations together, individual simulations can show important differences from the ensemble mean for individual catchments, partly due to significant decadal-scale internal variability in the simulated climate (Feyen et al., 2011). A decrease in 1-in-a-century floods is projected in large parts of north-eastern Europe due to a reduction in snow accumulation and hence melt-associated floods under milder winter temperatures (Dankers and Feyen, 2009). This projection is consistent with other studies on snow-dominated regions, including parts of Finland (Veijalainen et al., 2010), the Alps and Carpathian Mountains (EEA, 2009b). Flash floods and pluvial floods, which are triggered by local intense precipitation events, are likely to become more frequent throughout Europe (Christensen and Christensen, 2002; Kundzewicz et al., 2006).

3.3.4 River flow drought

Relevance

Lack of water has severe consequences for Europe's citizens and most economic sectors, including agriculture, energy production and industry. An intense drought throughout the Iberian Peninsula during 2004–2005, for example, led to a 40 % decline in cereal production (García-Herrera et al., 2007), whilst low rainfall in 2006 led to a 30 % fall in agricultural production in Lithuania, with an estimated loss of EUR 200 million (European Commission, 2007). In Slovenia, direct losses attributable to drought in 2003 are estimated to be around EUR 100 million (Sušnik and Kurnik, 2005). Furthermore, lack of water detrimentally impacts freshwater ecosystems including vegetation, fish, invertebrates and riparian bird life (EEA, 2009a). Diminished flow also strongly impacts water quality by reducing the ability of a river to dilute pollutants.

Electricity production has already been significantly reduced in various locations in Europe during very warm summers due to limitations of cooling water supply from rivers. Dry periods can also seriously impact the production of hydropower (Lehner et al., 2005), for example in the case of Catalunia where the 2003–2007 drought caused a hydropower reduction of over 40 % (Generalitat de Catalunya, 2010).

Past trends

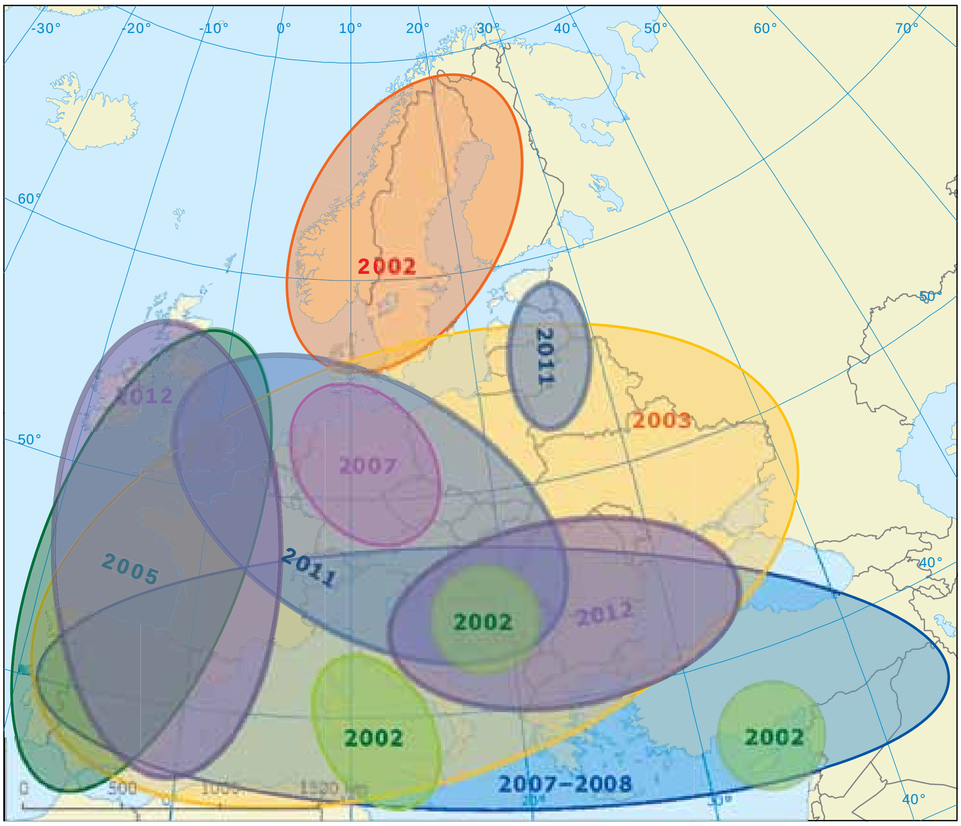
Over the past 40 years, Europe has been affected by a number of major droughts, most notably in 1976, 1989, 1991, and more recently (see Map 3.9), the prolonged drought over large parts of the continent associated with the 2003 summer heat wave and the 2005 drought in the Iberian Peninsula (see also effects on Energy production in Section 4.5). However, there is no evidence that river flow droughts have become more severe or frequent over Europe in general in recent decades (Hisdal et al., 2001; Stahl et al., 2008), nor is there conclusive proof of a general increase in summer dryness (based on the Palmer Drought Severity Index) in Europe over the past 50 years due to reduced summer moisture availability (van der Schrier et al., 2006). Several stations in Europe have shown trends towards less severe low stream flows over the 20th century but this is primarily attributed to an increasing number of reservoirs becoming operational during this period (Svensson et al., 2005).

Whilst public water supplies often have priority over other uses during droughts, restrictions on use can arise, together with a significant cost associated with emergency water supplies. In 2008, Cyprus suffered its fourth consecutive year of low rainfall and the drought situation reached a critical level in the summer months. To ease the crisis, water was shipped in from Greece using

Key messages: 3.3.4 River flow drought

- Europe has been affected by several major droughts in recent decades, such as the catastrophic drought associated with the 2003 summer heat wave in central parts of the continent and the 2005 drought in the Iberian Peninsula.
- Severity and frequency of droughts appear to have increased in parts of Europe, in particular in southern Europe.
- Regions most prone to an increase in drought hazard are southern and south-eastern Europe, but minimum river flows are also projected to decrease significantly in many other parts of the continent, especially in summer.

Map 3.9 Water scarcity and drought events in Europe during the last decade



Water scarcity and drought events in Europe during the last decade

Source: ETC-LUSI; Tallaksen, 2007 (personal communication).

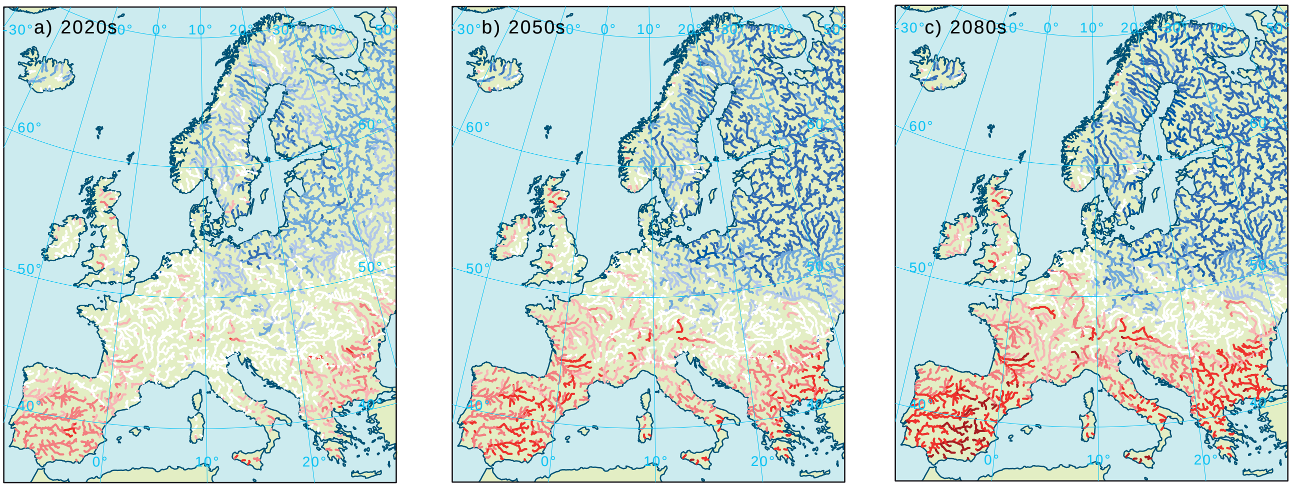
tankers. In addition, the Cypriot Government was forced to apply emergency measures, including the cutting of domestic supplies by 30 %. Similarly, in Catalonia during the spring of 2008 water levels in the reservoirs supplying 5.8 million inhabitants were only at 20 % of capacity. The government planned to ship fresh water in, at an estimated cost of EUR 35 million. After a few shiploads were transported to Barcelona, these transports were stopped because strong rainfall was filling the reservoirs again (Collins, 2009).

Projections

River flow droughts are projected to increase in frequency and severity in southern and south-eastern Europe, Benelux, France, western parts of Germany and the United Kingdom over the coming decades (Rojas et al., 2012) (see Map 3.10). For the near future (2020s, Map 3.10a), the differences to the control period 1961–1990 are rather limited although the general pattern of an increase of minimum flows in Scandinavia and a decrease in southern and south-eastern Europe can already be seen. For Scandinavia and north-eastern Europe the projected minimum flows with a return period of 20 years further increase while almost everywhere else in Europe a moderate to strong decrease is projected. In most of Europe, the projected decrease in summer precipitation accompanied by rising temperatures is projected to lead to more frequent and intense summer droughts (Douville et al., 2002; Lehner et al., 2006; Feyen and Dankers, 2009).This projected decline in the water resource will be reflected not only by reduced river flows, but also by lowered lake and groundwater levels and a drying up of wetlands.

Climate change will affect not only water supply but also water demand. Water demand for irrigation is projected to increase in many regions (see Section 4.1.5), which may further decrease river flow. Initial research suggests that climate change may also have some effect on household water demand (Keirle and Hayes, 2007).

Map 3.10 Projected change in minimum river flow with return period of 20 years



Relative change in minimum river flow with return period of 20 years between future period and 1961–1990 (SRES A1B)

(%) – 60 – 40 – 20 – 10 – 5 5 10 20 40 60

Note: Relative change in minimum river flow for a) 2020s, b) 2050s and c) 2080s compared to 1961–1990 for SRES A1B scenario.

Source: Rojas et al., 2012.

3.3.5 Water temperature

Relevance

Water temperature is one of the parameters that determine the overall health of aquatic ecosystems. Most aquatic organisms have a specific range of temperatures they can tolerate, which determines their spatial distribution. Changes in temperature also determine ice cover periods, thermal stratification of lakes, nutrient availability and the duration of growing seasons that in turn affect species composition and food web structures.

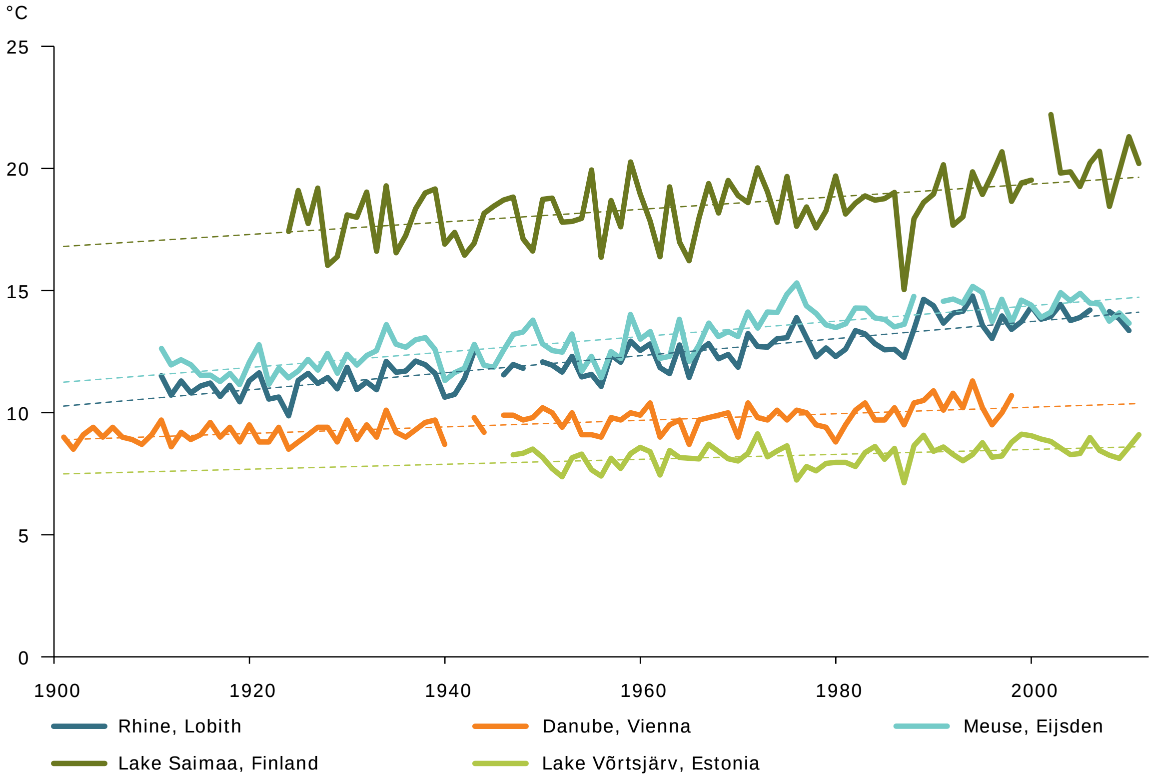
Past trends

The surface water temperatures of major rivers in Europe have increased by 1–3 °C over the last century (Figure 3.10). For example, the average temperature in the Rhine near Basel has risen by more than 2 °C in the last 50 years (FOEN, 2011). The temperature of the downstream part of the Rhine increased by 3 °C between 1910 and 2010. Two thirds of the increase at the downstream Rhine is attributed to the increased use of cooling water and one third to the increase in air temperature as a result of climate change (Bresser et al., 2006). A similar

Key messages: 3.3.5 Water temperature

- Water temperatures in major European rivers have increased by 1–3 °C over the last century. Several time series show increasing lake and river temperatures all over Europe over the last 60 to 90 years.
- Lake and river surface water temperatures are projected to increase with further projected increases in air temperature.
- Increased temperature can result in marked changes in species composition and functioning of aquatic ecosystems.

Figure 3.10 Trends in water temperature of large European rivers and lakes in the 20th century



Note: Annual average water temperature in River Rhine and River Meuse (1911–2010); River Danube (1901–1998), Lake Võrtsjärv (1947–2011), and average water temperature in August in Lake Saimaa, Finland (1924–2011).

Source: River Rhine and River Meuse: Compendium voor de Leefomgeving, 2012; River Danube: Hohensinner, 2006 (personal communication); Lake Saimaa: Johanne Korhonen, 2012 (personal communication); Lake Võrtsjärv: Peeter Nõges, 2012 (personal communication).

increase has been observed in the Meuse. The annual average temperature of the Danube increased by around by 1 °C during the last century. Increases in surface water temperature were also found in some large lakes. Lake Võrtsjärv in Estonia had a 0.7 °C increase between 1947 and 2011, and the summer (August) water temperature of Lake Saimaa, Finland increased more than 1 °C over the last century.

Several time series indicate a general trend of increasing water temperature in European rivers and lakes in the range of 0.05 to 0.8 °C per decade (Dabrowski et al., 2004; George and Hurley, 2004; Pernaravièiûtë, 2004; Bresser et al., 2006). The surface water temperature of some rivers and lakes in Switzerland has increased by more than 2 °C since 1950 (BUWAL, 2004; Hari et al., 2006). In the large lakes in the Alps the water temperature has generally increased by 0.1–0.3 °C per decade: Lake Maggiore and other large Italian lakes (Ambrosetti and Barbanti, 1999; Livingstone, 2003; Anneville et al., 2005; Dokulil et al., 2006).

Projections

Lake surface water temperatures are projected to increase further, in parallel with the projected increases in air temperature. The exact amount of warming depends on the magnitude of global warming, on the region, on the season and on lake properties (Malmaeus et al., 2006; George et al., 2007). Physical modelling studies predict that temperatures will increase more in the upper regions of the water column than in the lower regions, resulting in generally steeper vertical temperature gradients and enhanced thermal stability (Peeters et al., 2002). Such increased lake thermal stability was observed both in Switzerland during the mild 2006/2007 winter (Rempfer et al., 2010) and in Italy during the hot 2009 summer (Nõges et al., 2011). Further impacts of increased lake and river water temperature are described in Section 3.3.6.

3.3.6 Lake and river ice

Relevance

Lake ice reduces underwater light (Leppäranta et al., 2003) and vertical mixing, that is, the exchange of water from different depth layers (Livingstone, 1993; Melles et al., 2007). The existence of lake ice, and the timing of lake ice break-up, is thus of critical ecological importance, influencing for instance the production and biodiversity of phytoplankton (Weyhenmeyer et al., 1999) and the occurrence of winter fish kills (Stefan et al., 2001; Jackson et al., 2007).

Past trends

The duration of ice cover in the northern hemisphere has shortened at a mean rate of 12 days per century over the last 150–200 years, resulting from a 5.8 day later ice cover and a 6.5 day earlier ice break-up on average (Magnuson et al., 2000; EEA, 2008).

There are, however, large differences across regions. At the Hungarian section of the River Danube, the date of first ice appearance has shifted 19–29 days later over the 1876–2011 period, while the date of final ice disappearance shifted 18–23 days earlier (Takács, 2011) (see Figure 3.11a). In Lake Kallavesi, eastern Finland the freezing date has shifted 15 days later in 1833–2011, while the break-up date has shifted 12 days earlier in 1822–2011 (SYKE, 2011) (see Figure 3.11b).

Projections

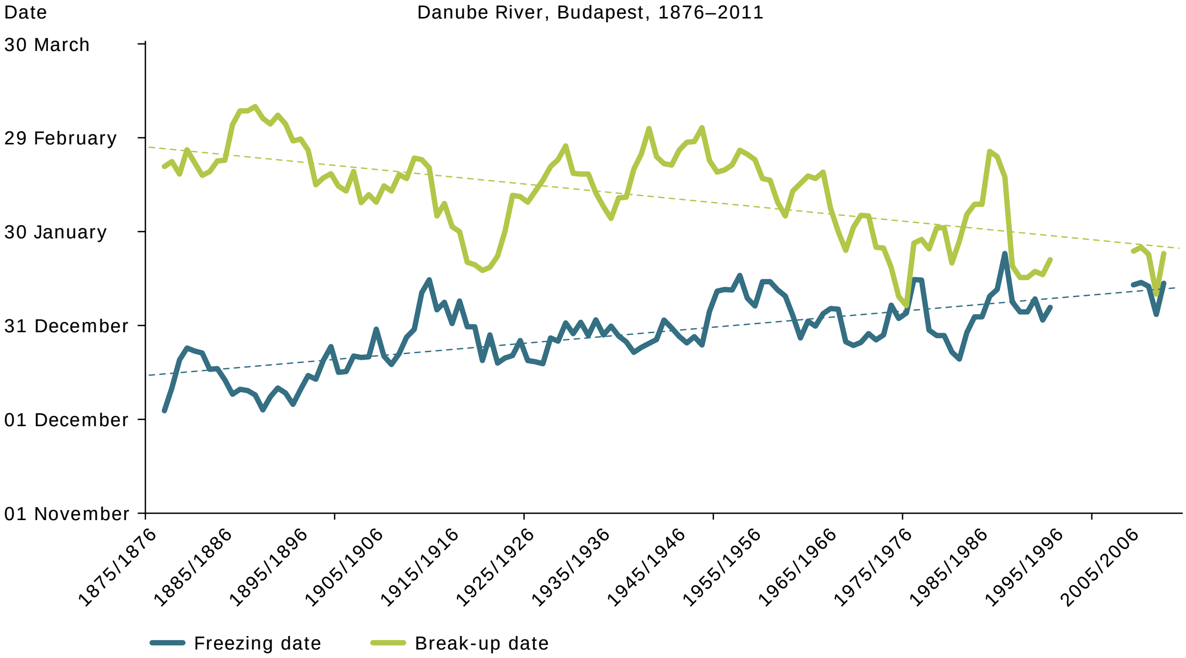
One recent study has simulated changes in lake ice cover throughout the Northern Hemisphere (40–75 °N) based on one global climate model driven by the SRES A2 emission scenario. The results indicate an overall decrease in the duration of lake ice cover of 15–50 days across regions by 2040–2079, compared to the baseline period 1960–1999 (Dibike et al., 2011). The ice cover of lakes in regions where the ice season is already short or where ice cover only occurs in cold winters is generally more strongly affected by increasing temperature than that of lakes in colder regions (Weyhenmeyer et al., 2011). However, the ecological consequences of reduced ice cover are expected to be lower in areas where ice cover normally is less frequent and ecosystems thereby are adapted to less ice or ice-free conditions.

Key messages: 3.3.6 Lake and river ice

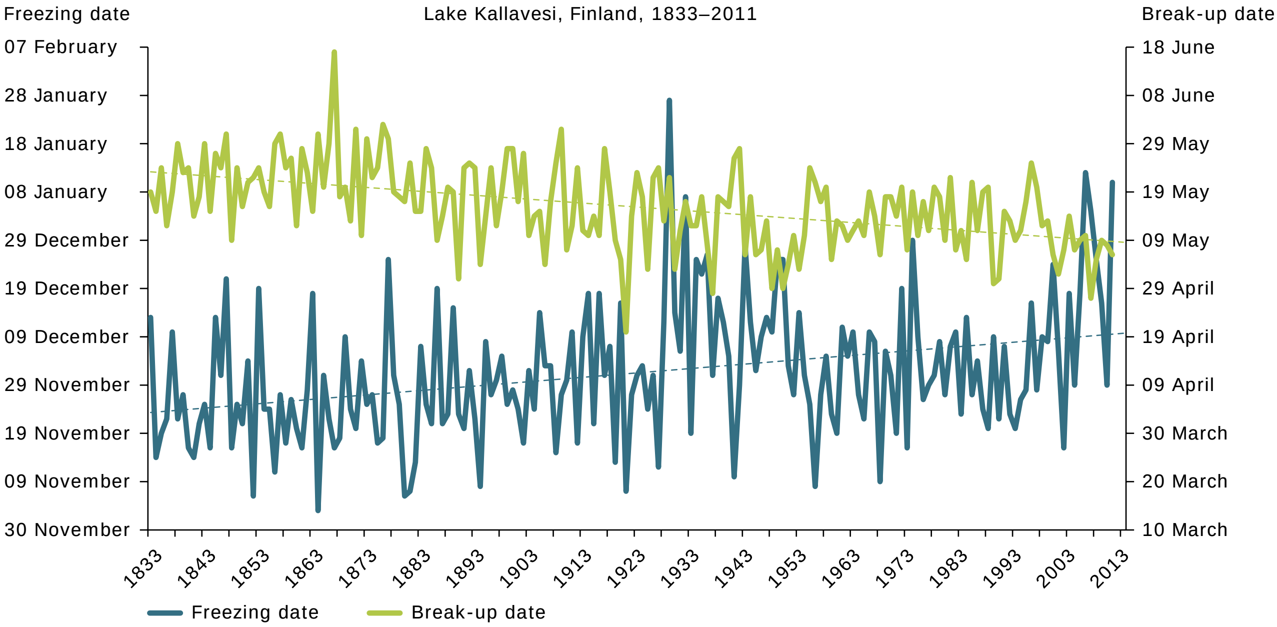
- The existence of ice cover and the timing of ice break-up influence the vertical mixing of lakes and are therefore of critical ecological importance.
- The duration of ice cover on European lakes and rivers has shortened at a mean rate of 12 days per century over the last 150–200 years.
- A further decrease in the duration of lake ice cover is projected with projected climate change.

Figure 3.11 Observed change in duration of lake and river ice cover

a)



b)



Note: Ice break-up dates and freezing dates of a) Danube River, at Budapest, 1876–2011 (5-year running average) and b) Lake Kallavesi, Finland, 1833–2011.

Source: a) Katalin Takács, 2012 (personal communication).

b) SYKE, 2011; Kuusisto, 2012 (personal communication).

3.3.7 Freshwater ecosystems and water quality

This Section presents selected information on the impacts of changes in the indicators presented above for freshwater ecosystems and water quality. This information is not presented in the indicator format because several different impacts are foreseen for aquatic species and ecosystems, and the message cannot simply be conveyed in one indicator. More information can be found in (ETC-ICM, 2010).

Impact of changed river flow regime on freshwater ecosystems

River flow regimes, including long-term average flows, seasonality, low flows, high flows and other types of flow variability, play an important role for freshwater ecosystems. Thus, climate change affects freshwater ecosystems not only by increased temperatures but also by altered river flow regimes (Döll and Zhang, 2010).

Changes in phenology

Increasing temperatures will change the life-cycle events and stimulate an earlier spring onset of various biological phenomena, such as phytoplankton spring bloom, clear water phase, first day of flight for aquatic insects and time of spawning of fish. Prolongation of the growing season can have major effects on species. For example, British Odonata dragonflies and damselflies species have changed their first day of flight by 1.5 day per decade on average over the period 1960 to 2004 (Hassall et al., 2007), and increasing temperatures at Lago Maggiore have resulted in earlier and longer zooplankton blooms (Manca et al., 2007).

Changes in species distribution

Increased water temperatures will favour warm-water species, whereas cold-water species will become more limited in their range. Examples of northward-moving species are non-migratory British dragonflies and damselflies (Hickling et al., 2005) and south European Dragonflies (inbo, 2011). The brown trout in Alpine rivers has been observed to move to higher altitudes (Hari et al., 2006). Extinction of some cold-water aquatic insects has been predicted with reduced meltwater input from disappearing snowpacks and glaciers (Brown et al., 2007).

Facilitation of species invasions

Climate change is facilitating biological invasions of species that originate in warmer regions. For example, the subtropical cyanobacterium Cylindrospermopsis raciborskii thrives in waters that have high temperatures, a stable water column and high nutrient concentrations. This highly toxic species has recently spread rapidly in temperate regions and is now commonly encountered throughout Europe (Dyble et al., 2002). Its spread into drinking and recreational water supplies has caused international public health concerns.

Water quality

Climate change is affecting water quality in various ways. Higher temperatures stimulate mineralisation of soil organic matter, which leads to increased leaching of nutrients, especially nitrogen and phosphorus (Battarbee et al., 2008; Feuchtmayr et al., 2009; Futter et al., 2009). Decreases in stream flow, particularly in summer, will lead to higher nutrient

Key messages: 3.3.7 Freshwater ecosystems and water quality

- Cold-water species have been observed to move northwards or to higher altitudes in response to increased temperatures.
- A longer growth season will change the timing of several life-cycle events.
- Increased water temperatures can lead to earlier and larger phytoplankton blooms.
- The observed changes are projected to continue with further projected climate change.
- A warmer and wetter climate can lead to increased nutrient and dissolved organic carbon concentrations in lakes and rivers but management changes can have much larger effects than climate change.

concentrations due to reduced dilution (Whitehead et al., 2009), whereas increases in floods and extreme precipitation events can increase the nutrient load to surface waters due to increased surface run-off and erosion, (Fraser et al., 1999; Battarbee et al., 2008). In this context, it should be noted that significant management changes can have much larger impacts on nutrient concentrations than climatic changes (Bryhn et al., 2010).

Increases in soil temperature, moisture and intensive rainfall can enhance the concentrations of dissolved organic matter (DOC) (Worrall et al., 2002; Soulsby et al., 2003; Inamdar et al., 2006; Roulet and Moore, 2006). Increased DOC concentration has been observed in lakes and streams in Europe and North America in recent decades, primarily due to a recovery from acid deposition, but climate change may result in additional increases (Monteith et al., 2007). The overall relationship between climate change and DOC concentrations is not clear due to the importance of different processes with opposing effects (Epp et al., 2007; Futter et al., 2007). Enhanced nutrient and DOC concentrations can give increased eutrophication, lower oxygen levels and poorer underwater light conditions.

Algal blooms and water quality

Climate change can enhance harmful algal blooms in lakes, both as a direct result of temperature increase and as a result of climate-induced increases in nutrient concentrations. Increased lake temperature will generally have a eutrophication-like effect (Schindler, 2001), with enhanced phytoplankton blooms (Wilhelm and Adrian, 2008), and increased dominance of cyanobacteria in phytoplankton communities. These changes may restrain the use of lake drinking water and recreation and they may increase the associated health risks (Mooij et al., 2005; Jöhnk et al., 2008; Paerl and Huisman, 2008).

Phytoplankton and zooplankton blooms in several European lakes are now occurring one month earlier than 30–40 years ago, giving rise to the potential for a trophic mismatch between bloom species and other species (Weyhenmeyer et al., 1999; Weyhenmeyer, 2001; Adrian et al., 2006; Nõges et al., 2010).

3.4 Terrestrial ecosystems and biodiversity

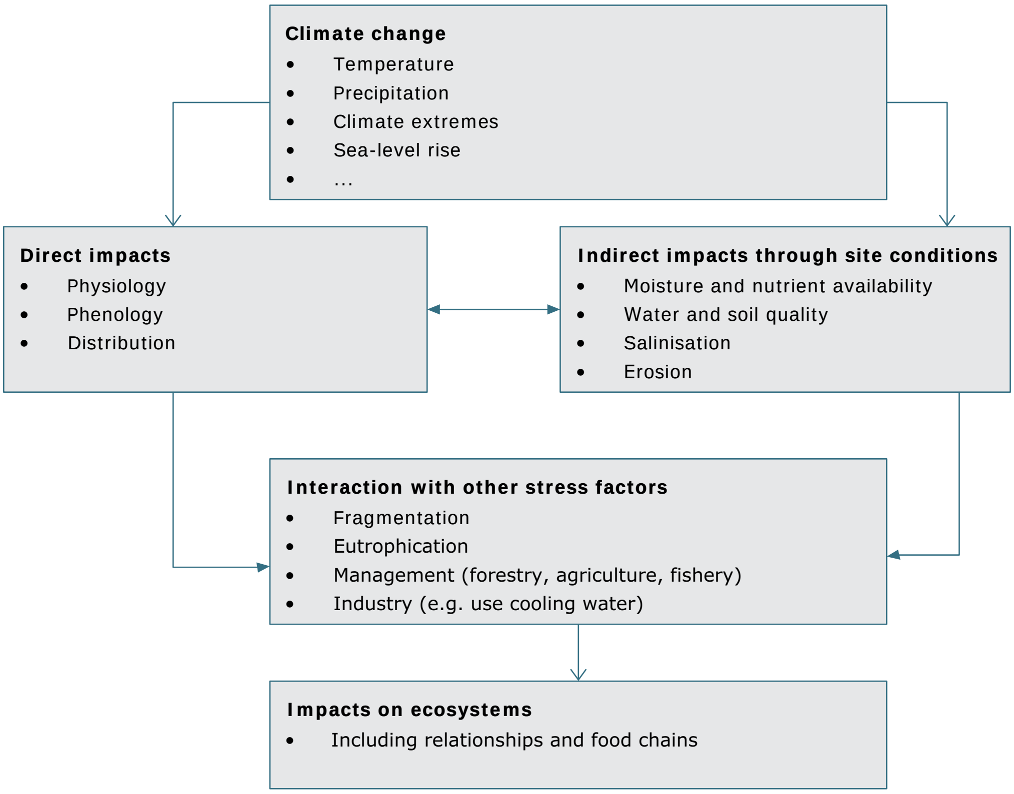
3.4.1 Overview

Climate change affects individual organisms (e.g. plant, fungi and animal species), whole ecosystems and their services in many ways. The direct effects of climate change, such as changes in species phenology and distribution, are moderated by impacts on the habitat and by ecological interactions between species, such as competition and food webs (see Figure 3.12). Furthermore, climate change usually does not act in isolation but together with other factors, such as eutrophication and human land use and management. The principal response mechanisms of species to climate change depend on their adaptive capacity and include phenological and/or physiological adaptation, migration and colonisation of new habitats. All these mechanisms face important constraints in terms of timing and/or effectiveness.

Key messages: 3.4 Terrestrial ecosystems and biodiversity

- The timing of seasonal events in plants and animals is changing across Europe. Between 1971 and 2000, phenological events in spring and summer have advanced on average between 2.5 and 4 days per decade. The pollen season today starts on average 10 days earlier and is longer than it was 50 years ago. Climate change is regarded as the main cause of these changes.
- Breeding seasons of thermophilic insects such as butterflies, dragonflies and bark beetles are lengthening, allowing for extra generations to be produced during the year.
- Many European plant and animal species have shifted their distribution northward and uphill in response to observed climate change.
- The rate of climate change is expected to exceed the ability of many species to adapt and migrate, especially where landscape fragmentation may restrict movement.
- Direct effects on single species are likely amplified by species interactions, such as disruption of present food webs.
- Almost one fifth of habitats and 12 % of species of European interest are potentially threatened by climate change over their natural European range. Bogs, mires and fens are considered to be the most vulnerable habitat types.

Figure 3.12 Effects of climate change on nature and biodiversity



Source: Based on Jelle van Minnen, Netherlands Environmental Assessment Agency.

For example, migration may be constrained by the speed of dispersal mechanisms and by migration barriers, including human habitat fragmentation. If all these response mechanisms fail, the species is likely to gradually disappear from its current range and eventually become extinct.

Measuring the impacts of a changing climate on biodiversity is a considerable challenge. Furthermore, attribution of observed changes in biodiversity to climate change is difficult because of the importance of other drivers, such as habitat fragmentation, degradation and loss (Mantyka-Pringle et al., 2012), invasive alien species, human management and land-use change. Nevertheless, several comprehensive studies have identified climate change as the main driver for changes in the phenology and distribution of plant and animal species across the world (Root et al., 2003; Parmesan, 2006; Amano et al., 2010; Singer and Parmesan, 2010; Chen et al., 2011).

Indicator selection

Climate change directly influences physiological processes of animal and plant species, especially energy and water budgets, and can in extreme cases lead to death by desiccation or freezing. For warm-adapted species, climate change may be more beneficial while for cold-adapted species climate change tends to be more harmful (Hoffmann et al., 2012). To adapt to these changes, species have several options: 1) adapting temporally, i.e. changing their life-cycle within a year (their **phenology**) according to altered climatic conditions throughout the year, 2) adapting spatially, i.e. change the **distribution** ranges to follow suitable climatic conditions, and 3) microevolution by adapting physiologically. As **species interact** with each other, but responses to climate change are more or less idiosyncratic, this can have fundamental impacts on the co-occurrence of species in time and space, potentially disrupting interactions between species.

Ultimately, this is likely to change ecosystem properties and functions. Traditionally, impacts are assessed differently for plant and animal species. We therefore decided to cover the following indicators:

- Plant and fungi phenology;
- Animal phenology;
- Distribution of plant species;
- Distribution and abundance of animal species;
- Species interactions.

Changes in **plant, fungi and animal phenology** have shown to be good indicators for climate change impacts (Gordo and Sanz, 2006a; Estrella et al., 2009), yet also other pressures (such as nitrogen input) may impact phenology (Cleland et al., 2006). Directly or indirectly, climate change can affect species populations in a number of ways, including **species distribution** changes (e.g. due to habitat loss) and range changes (contraction and expansion, relating to their dispersal ability). Under a new climatic regime, therefore, individuals of some species may be able to colonise new, more suitable areas. Such species will frequently include **alien species**, that is those which have been introduced by human agency to regions outside their natural range. Alien species are also being introduced as a result of climate change — for example birds and invertebrates from mainland Europe now being found in southern England and moving north. Alien invasive species have been recognised as one of the most important threats to biodiversity at the global level. They have significant adverse impacts on the goods and services provided by ecosystems, on economy and human health (Millennium Ecosystem Assessment, 2005; Vilà et al., 2010, 2011). The combination of the two pressures of climate change and biological invasions poses new challenges to conservation policies (Burgiel and Muir, 2010), especially as links between them are largely ignored. Climate change can also affect ecological dynamics, the complex **species interactions** and their ecosystem relationships. Changing climatic conditions can lead to mismatching of species' life-cycle events and food sources or decoupled predator-prey relationships, for example through influences on the activity of predators or on trophic interactions between species such as the association between the timing of budburst (food supply), emergence of insect larvae and the egg laying date of birds.

The EC Habitats Directive calls for the regular assessment and reporting of the conservation status of the 1 500 species and the habitats of special European interest listed in the Directive's Annexes I, II, IV and V ([51]). During the reporting period 2001–2006, Member States collected a diverse range of data and provided expert opinion. Data availability and quality is rather heterogeneous during this reporting period ([52]). The reports contain information on the conservation status of species and habitats. They also give an indication whether climate change is considered as an important driver of change in conservation status. The first national reports suggest that 19 % of habitats and 12 % of species of European interest are potentially threatened by climate change over their natural European range (Table 3.2). Bogs, mires and fens are considered to be the most vulnerable habitat types, with up to 50 % potentially negatively affected. This is particularly worrying because bogs and mires are important carbon stores and their degradation releases GHGs into the atmosphere. Of the species groups, amphibians are worst affected, with 45 % of species negatively afflicted by climate in Europe (Araújo et al., 2006).

The Natura2000 network in Europe is the most extensive network of conservation areas worldwide. The principle objective of the EC Habitat Directive (i.e. maintaining certain species and habitats) is static and does not recognise dynamic influences of environmental changes like climate change. An assessment of the effectiveness of conserving European plant and terrestrial vertebrate species under climate change estimates that by 2080, 58 ± 2.6 % of the species would lose suitable climate niches in protected areas. In Natura2000 areas, the losses were even higher, at 63 ± 2.1 % (Araújo et al., 2011).

Data quality and gaps

Generally, observations for popular groups such as vascular plants, birds, other terrestrial vertebrates and butterflies are much better than for less conspicuous and less popular species. Similarly, due to extensive existing networks, a long tradition and better means of detection and rapid responses of the organisms to changes, knowledge on phenological changes are better observed and recorded than range shifts. Projections of climate change impacts on phenology rely crucially on the understanding of current

([51]) In 2007, Member States reported for the first time on the conservation status of habitats and species covered by the Habitats Directive (Article 17 reports). As this reporting period was until 2006, it did not cover Bulgaria and Romania.

([52]) For a more detailed discussion, see http://bd.eionet.europa.eu/article17/chapter2 and http://eea.eionet.europa.eu/Public/irc/eionet-circle/habitatsart17report/library?l=/papers_technical/completeness_coherence_1/_EN_1.0_&a=d.

Table 3.2 Habitats and species groups negatively affected by climate change in at least one EU Member State

Habitat type	% of habitats of this type affected by climate change	Total number of habitats of this type
Bogs, mires and fens	50	12
Dunes	29	21
Forests	22	72
Heathlands	20	10
Sclerophyllous scrub	15	13
Coastal	14	28
Rocky habitats	14	14
Grasslands	10	29
Freshwater	5	19
All habitats	**19**	**218**

Species group	% of species in this group affected by climate change	Total number of species in this group
Amphibians	45	51
Arthropods	29	118
Mammals	26	125
Non-vascular plants	21	38
Molluscs	17	35
Reptiles	13	87
Fish	4	100
Vascular plants	3	602
All species	**12**	**1 158 (*)**

Note: The table states the proportion of habitat types and species groups listed in the Habitat Directive for which at least one Member State identified climate change as a reason for unfavourable trends in the area covered or across the natural range.
(*) In addition to these species groups, two species from the 'others' (i.e. other groups of animals and plants) category were noted as affected by climate change: the red coral (*Corallium rubrum*) and the medicinal leech (*Hirudo medicinalis*).

Source: ETC/BD, 2009.

processes and responses. For most cases, only a few years of data are available and do not cover the entire area of the EU but are restricted to certain well monitored countries with a long tradition in the involvement of citizen scientists. Based on these short time series, the determination of impacts and their interpretation thus has to rely on assumptions, and achieving a qualitative understanding of species' responses is more robust than their quantification (Singer and Parmesan, 2010). One of the greatest unknowns is how quickly and closely species will alter their phenology in accordance to a changing climatic regime (van Asch et al., 2007; Singer and Parmesan, 2010). Even experimental studies seem to be of little help, since they notoriously tend to underestimate the effects of climate change on changes in phenology (Wolkovich et al., 2012).

Observing range shifts (and projecting responses to climate change) crucially depends on good distributional data, which is also better for popular groups of species than for others. There is evidence from Denmark and two African regions that bird biodiversity is a good proxy for total biodiversity in species-rich regions but data from other groups are needed in less species-rich regions (Larsen et al., 2012). There are large differences in the quality of observational data, with better data generally available in northern and western Europe than in southern Europe. Since neither data quality nor lack of data are properly recorded, the true quality of projections of range shifts as well as the likelihood of unobserved range shifts is largely unknown (Rocchini et al., 2011). An extensive meta-analysis of available projections according to different modelling algorithms, drivers, scenarios, downscaling procedures or taxonomic identity is also missing (see also Dormann et al., 2008).

Species distribution models (also known as habitat models, niche models or envelope models) suffer from a variety of limitations because species are currently not in equilibrium with climate, and because species dispersal and biotic interactions are largely ignored (Bellard et al., 2012; Zarnetske et al., 2012). Furthermore, climate change projections for Europe include climate conditions (in particular in southern Europe) for which no analogue climate was available for the model calibration (Pearson and Dawson, 2004; Dormann, 2007; Williams and Jackson, 2007). Especially the latter problem is evident for projections for southern Europe since projections of species distribution models lack information from climates south of the Mediterranean. Therefore, the uncertainty in the Mediterranean region is much higher and projected declines might result from a lack of data from climatic situations not included in the model.

Largely, there are just very coarse methods available for incorporating species interactions, population dynamics and dispersal processes into models of range shifts, despite several recent approaches to incorporate these (Pagel and Schurr, 2012; Schweiger et al., 2012).

3.4.2 Plant and fungi phenology

Relevance

Phenology is the timing of seasonal events such as budburst, flowering, dormancy, migration and hibernation. Some phenological responses are triggered by mean temperature (Urhausen et al., 2011), while others are more responsive to day length (Menzel et al., 2006) or weather extremes (Menzel et al., 2011). Changes in phenology affect the growing season and thus ecosystem functioning and productivity. Changes in phenology are impacting farming (see Section 4.1), forestry (see Section 4.2), gardening and wildlife. The timing of tilling, sowing and harvesting is changing, fruit is ripening earlier due to warmer summer temperatures (Menzel et al., 2006), and grass in municipal parks and on road verges requires more frequent cutting over a longer period. Changes in flowering have implications for the timing and intensity of the pollen season and related health effects (see Section 4.1). The pollen season is advancing as many species start to flower earlier, and the concentration of pollen in the air is increasing (Buters et al., 2010). The increasing trend in the yearly amount of airborne pollen for many taxa is more pronounced in urban than semi-natural areas across the continent (Ziello et al., 2012).

Past trends

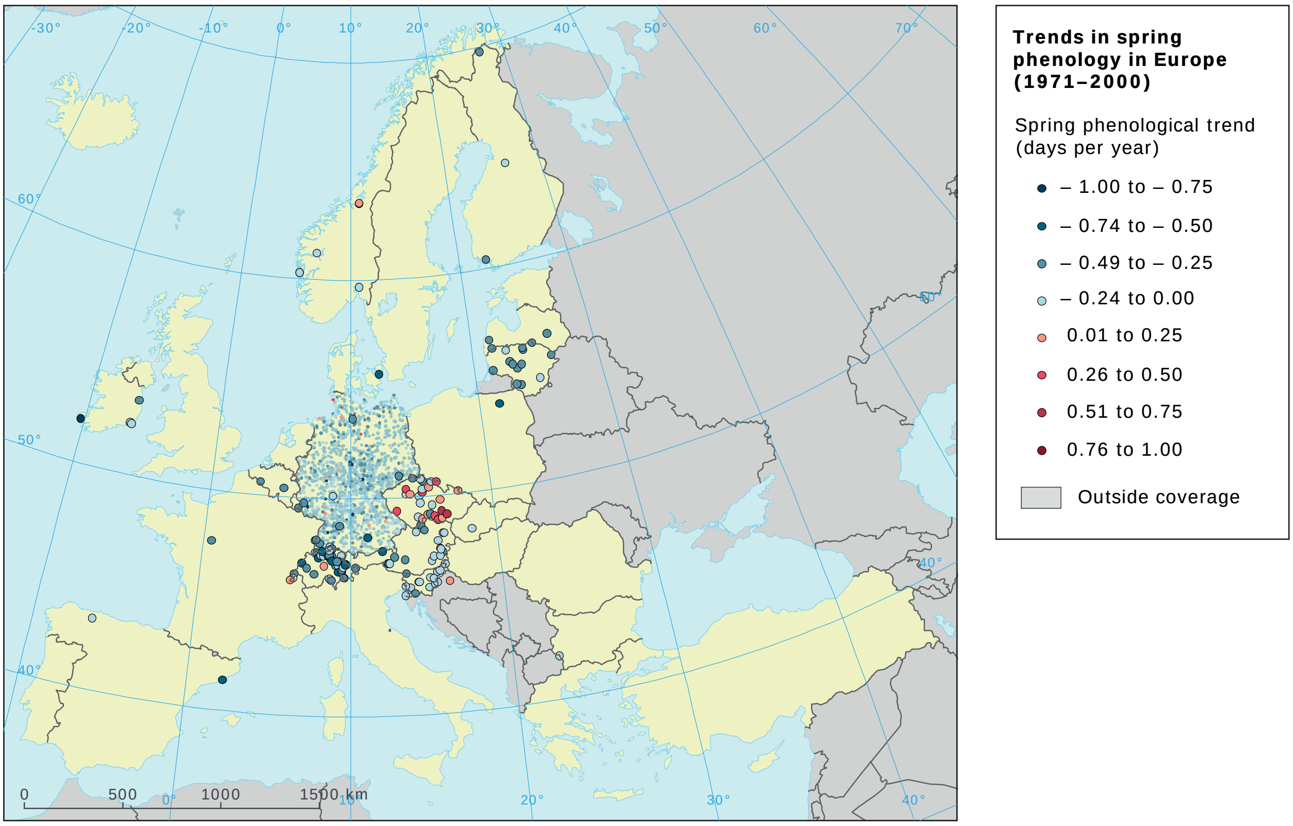
Compared to the 2008 report (EEA, 2008), there is new evidence of climate change impacts on plant and fungi phenology. An analysis of 315 species of fungi in England showed that these have increased their fruiting season from 33 to 75 days between 1950 and 2005 (Gange et al., 2007). Furthermore, climate warming and changes in the temporal allocation of nutrients to roots seem to have caused significant numbers of species to begin fruiting in spring as well as autumn. A study on 53 plant species in the United Kingdom found that they have advanced leafing, flowering and fruiting on average by 5.8 days between 1976 and 2005 (Thackeray et al., 2010). Similarly, 29 perennial plant species in Spain have advanced leaf unfolding on average by 4.8 days, first flowering by 5.9 days, and fruiting by 3.2 days over the period 1943–2003, whereas leaf senescence was delayed on average by 1.2 days (Gordo and Sanz, 2006a). For plants, a medium spring advancement of four to five days per 1 °C increase has been observed in Europe (Bertin, 2008; Estrella et al., 2009; Amano et al., 2010) (see Map 3.11).

Short warm and cold spells also can have a strong effect on phenological events but this depends strongly on their timing and the species (Koch et al., 2009; Menzel et al., 2011). Continental-scale change patterns have been derived from time series of satellite measured phenological variables (1982–2006) (Ivits et al., 2012). North-east Europe showed a trend to an earlier and longer growing season, particularly in the northern Baltic areas. Despite the earlier greening up, large areas of Europe exhibited rather stable season length indicating the shift of the entire growing season to an earlier period. The northern Mediterranean displayed a growing season shift towards later dates while some agglomerations of earlier and shorter growing season were also seen. The correlation of phenological time series with climate data shows a cause-and-effect relationship over the semi-natural areas. In contrast, managed ecosystems have a heterogeneous change pattern with less or no correlation to climatic trends. Over these areas climatic trends seemed to overlap in a complex manner with more pronounced effects of local biophysical conditions and/or land management practices.

Key messages: 3.4.2 Plant and fungi phenology

- The timing of seasonal events in plants is changing across Europe, mainly due to changes in climate conditions. Seventy-eight per cent of leaf unfolding and flowering records show advancing trends in recent decades whereas only 3 % show a significant delay. Between 1971 and 2000, the average advance of spring and summer was between 2.5 and 4 days per decade.
- As a consequence of climate-induced changes in plant phenology, the pollen season starts on average 10 days earlier and is longer than it was 50 years ago.
- Trends in seasonal events are projected to advance further as climate warming proceeds.

Map 3.11 Trends in spring phenology in Europe (1971–2000)



Note: Each dot represents a station. Dot size adjusted for clarity. A negative phenological trend corresponds to an earlier onset of spring.

Source: Estrella et al., 2009.

Projections

Phenology is primarily seen as an indicator to observe the impacts of climate change on ecosystems and their constituent species. Most projections of climate change impacts focus on other ecosystem processes, functions and services of more direct relevance for humans. However, an extrapolation of the observed relationship between temperature and phenological events into the future can provide a first estimate of future changes in phenology. Obviously, there are limits to possible changes in phenology, beyond which ecosystems have to adapt by changes in species composition. One of the few projections is for olives (*Olea europaea*) in the western Mediterranean, where an advancement of flowering by 3–23 days in 2030 compared to 1990 was projected (Osborne et al., 2000). For six dominant European tree species, (Vitasse et al., 2011) showed that flushing is expected to advance in the next decades but this trend substantially differed between species (from 0 to 2.4 days per decade). The more difficult prediction of leaf senescence for two deciduous species is expected to be delayed in the future (from 1.4 to 2.3 days per decade). The authors conclude that earlier spring leafing and later autumn senescence are likely to affect the competitive balance between species.

3.4.3 Animal phenology

Relevance

Climate warming affects the life-cycles of all animal species. Species adapted to warmer temperatures or dryer conditions may benefit from this change, whereas cold-adapted species may encounter increasing pressure on their life-cycles. Mild winters and the earlier onset of spring allow for an earlier onset of reproduction and, in some species, the development of extra generations during the year. In the case of a phenological decoupling between interacting species in an ecosystem (e.g. reduced pressure from parasitoids and predators), certain populations may reach very high abundances that attain orexceed damage thresholds in managed ecosystems (e.g. bark beetles in conifer forests, Baier et al., 2007). Desynchronisation of phenological events may also directly reduce fitness, for example if shortened hibernation times deteriorate body condition (Reading, 2007) or if interactions between herbivores and host plants are lost (Visser and Holleman, 2001). It may also negatively affect ecosystem services such as pollination (Hegland et al., 2009; Schweiger et al., 2010). There is robust evidence that generalist species with high adaptive capacity are favoured, whereas specialist species will be mostly affected negatively (Schweiger et al., 2008, 2012; Roberts et al., 2011).

Past trends

Several studies have convincingly demonstrated a tight dependency of life-cycle traits of animals with ambient temperatures, both in terrestrial and aquatic habitats (Roy and Sparks, 2000; Stefanescu et al., 2003; Dell et al., 2005; Parmesan, 2006; Hassall et al., 2007; Dingemanse and Kalkman, 2008; Schlüter et al., 2010; Tryjanowski et al., 2010). Mostly, the observed warming leads to an advanced timing of life history events. For example, temporal trends for appearance dates of two insect species (honey bee, small white: *Pieris rapae*) in more than 1 000 localities in Spain have closely followed variations in recorded spring temperatures between 1952 and 2004 (Gordo and Sanz, 2006a).

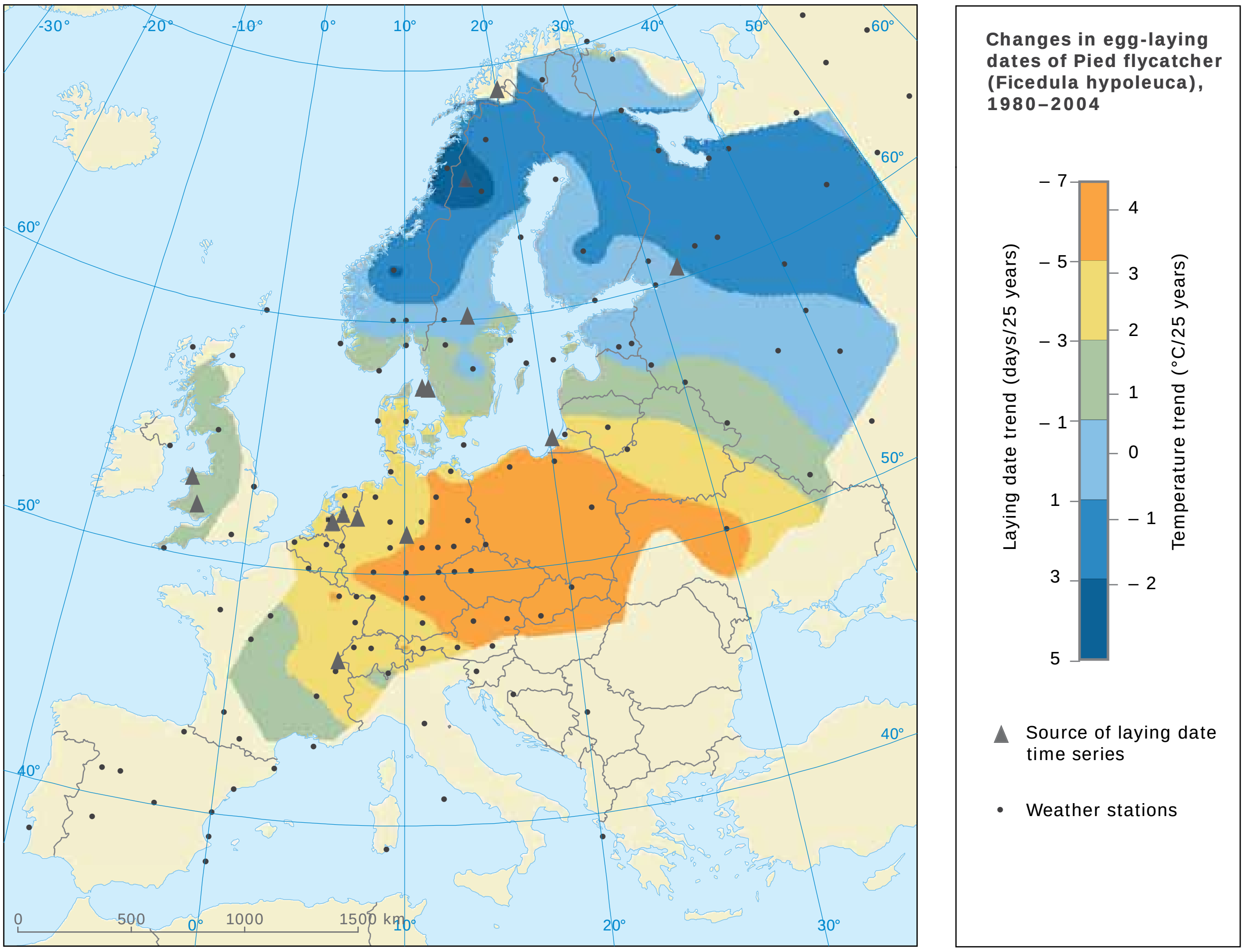
The predicted egg-laying date for the Pied flycatcher (*Ficedula hypoleuca*) showed significant advancement between 1980 and 2004 in western and central Europe, but delays in northern Europe, both depending on regional temperature trends in the relevant season (Both and Marvelde, 2007) (see Map 3.12). Data from four monitoring stations in south to mid-Norway that include nest-boxes of Pied flycatcher from 1992–2011 show in contrary to the regional temperature estimated trends that there are no significant delays in egg-laying date for the Pied flycatcher, but an annual fluctuation making a rather flat curve for the median over these years (Framstad, 2012). A study in the Netherlands covering the period between 1932 and 2004 found that half of the investigated bird species are now overwintering significantly closer to their breeding site than in the past, most likely due to warmer winters (Visser et al., 2009). A long-term trend analysis of 110 common breeding birds across Europe (1980–2005, 20 countries) showed that species with the lowest thermal maxima showed the sharpest declining trends in abundance (Jiguet et al., 2010). In other words, cold-adapted species are losing territory most quickly.

A study from the United Kingdom found that each of the 44 species of butterfly investigated advanced its date of first appearance since 1976 (Diamond et al., 2011). Recent studies on birds, butterflies and amphibians not only confirmed previous findings that there is a coherent fingerprint of climate change in the pattern of phenological changes (Crick and Sparks, 1999; Root et al., 2003; Charmantier et al., 2008), but also indicated that average rates of phenological change have recently accelerated in line with accelerated warming trends (Thackeray et al., 2010). There is also increasing evidence about climate-induced changes in spring and autumn migration, including formerly migratory bird species becoming resident (Gordo and Sanz, 2006b; Jonzén et al., 2006; Rubolini et al., 2007).

Key messages: 3.4.3 Animal phenology

- Many animal groups have advanced their life-cycles in recent decades, including frogs spawning, birds nesting and the arrival of migrant birds and butterflies. This advancement is attributed primarily to a warming climate.
- The breeding season of many thermophilic insects (such as butterflies, dragonflies and bark beetles) has been lengthening, allowing more generations to be produced per year.
- The observed trends are expected to continue in the future but quantitative projections are rather uncertain.

Map 3.12 Trend in egg-laying dates of the Pied flycatcher across Europe (1980–2004)



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

Source: Both and Marvelde, 2007.

Projections

Projections for animal phenology are rarely carried out, except for species of high economic interest (Hodgson et al., 2011). Quantitative projections are hampered by the high natural variability in phenological data, particularly in insects (Baier et al., 2007). The projected future warming is expected to cause further shifts in animal phenology and can lead to an increase of trophic mismatching, unforeseeable outbreaks of species, a decrease of specialist species and changes in ecosystem functioning (van Asch et al., 2007; Singer and Parmesan, 2010).

3.4.4 Distribution of plant species

Relevance

Climate change affects ecosystems in complex ways. The composition of many plant communities is changing (Pompe et al., 2010), often to such an extent that completely new assemblages are appearing (Urban et al., 2012). The extinction risk is particularly large at the trailing edge (i.e. southern or lower altitudinal range margins) of a species (Dirnböck et al., 2011). The ecological implications of these changes and their effects on the provision of ecosystems services are difficult to assess and quantify. However, it is clear that climate change is an important threat for long-term biodiversity conservation. It threatens the ability of meeting the EU policy target to halt biodiversity loss by 2020. The favourable status of Natura 2000 sites is also in danger (Thuiller et al., 2011; Hickler et al., 2012).

Past trends

New results have corroborated and refined earlier knowledge regarding distribution changes of species as a result of climate change. Mountain top floras across Europe have shown a significant change in species composition between 2001 and 2008, with cold-adapted species decreasing and warm-adapted species increasing (Gottfried et al., 2012). Most species have moved upslope on average. These shifts had opposite effects on the summit floras' species richness in boreal-temperate mountain regions (+ 3.9 species on average) and Mediterranean mountain regions (– 1.4 species) (Pauli et al., 2012). In central Norway, an increased species richness was found on 19 of 23 investigated mountains in a 68-year study (Klanderud and Birks, 2003). Lowland species, dwarf shrubs and species with wide altitudinal and ecological ranges showed the greatest increases in abundance and altitudinal advances, while species with more restricted habitat demands have declined. High-altitude species have disappeared from their lower-elevation sites and increased their abundance at the highest altitudes. In the Swiss Alps an upward shift of vascular plants by 13 m was observed based on unpublished data of 'Biodiversity Monitoring Switzerland' ([53]). A study involving 171 forest species in 6 mountain regions in France found significant upward shifts in species' optimum elevation, averaging 29 m per decade, but with a wide range from + 238 m per decade to – 171 m per decade (Lenoir et al., 2008). Land-use changes are the most likely explanation of the observed significant downward shifts in some region (Lenoir et al., 2010). There is further evidence of increases in the distribution range due to climate change for several plant species (Berger et al., 2007; Walther et al., 2007; Pompe et al., 2011).

Projections

Previous modelling exercises projected a high species loss in Alpine species. More recent studies that have considered the large microclimatic heterogeneity in mountain regions suggest that many species would find climatically suitable habitats within reach when forced to migrate under a changing climate (Scherrer and Körner, 2011). Accordingly, mountain flora seems to possess a greater small-scale persistence than previously assumed (Randin et al., 2009). Nevertheless, a recent modelling study comprising 150 high-mountain plant species across the European Alps projects average range size reductions of 44–50 % by the end of the 21st century (Dullinger et al., 2012). An assessment of the impacts of climate change on 2 632 plant species across all major European

Key messages: 3.4.4 Distribution of plant species

- Several European plant species have shifted their distribution northward and uphill. These changes have been linked to observed climate change, in particular to milder winters.
- Mountain ecosystems in many parts of Europe are changing as plant species expand uphill and cold-adapted species are projected to lose climatically suitable areas.
- By the late 21st century, distributions of European plant species are projected to have shifted several hundred kilometres to the north, forests are likely to have contracted in the south and expanded in the north, and about half of the mountain plant species may face extinction.
- The rate of climate change is expected to exceed the ability of many plant species to migrate, especially as landscape fragmentation may restrict movement.

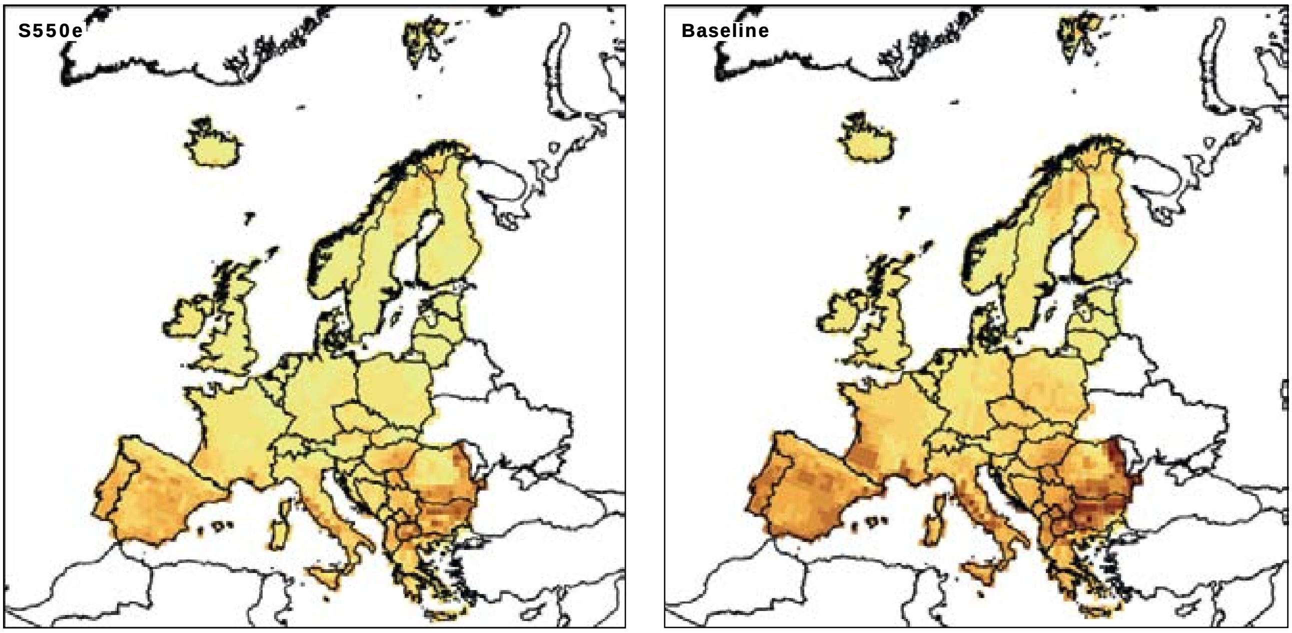
([53]) See http://www.biodiversitymonitoring.ch/en.

mountain ranges under 4 future climate scenarios projected that habitat loss by 2070–2100 is greater for species distributed at higher elevations (Engler et al., 2011). Depending on the climate scenario, up to 36–55 % of Alpine plant species, 31–51 % of sub-Alpine plant species and 19–46 % of montane plant species lose more than 80 % of their suitable habitat. A European-wide study of the stability of 856 plant species under climate change indicated that the mean stable area of species decreases in Mediterranean scrubland, grassland and warm mixed forests (see Map 3.13) (Alkemade et al., 2011). The rate of climate change is expected to exceed the ability of many plant species to migrate, especially as landscape fragmentation may restrict movement (Meier et al., 2012).

The variety of modelling approaches and results do not make clear statements as to where ecosystems and their services are at greatest risk from climate change. Furthermore, most ecological studies assess climate change (or just temperature change) in isolation from concurrent processes, such as increasing atmospheric CO_2 concentration, soil water availability or land-use changes.

The introduction and establishment of invasive alien species is driven primarily by past socio-economic factors (Pyšek et al., 2010; Essl et al., 2011). However, many invasive alien species are predicated to increase their range and abundance in central Europe under a warming climate (Kleinbauer et al., 2010; Pompe et al., 2011) (see Box 3.2).

Map 3.13 Expected average percentage of stable area of 856 plant species for two different climate scenarios by 2100



Expected average percentage of stable area of 856 plant species for two different climate scenarios by 2100

% stable area

0–10 | 10–20 | 20–30 | 30–40 | 40–50 | 50–60 | 60–70 | 70–80 | 80–90 | 90–100

Note: The S550e scenario corresponds to a stabilisation at 550 ppm CO_2-equivalent and a global mean temperature increase of 2 °C, the baseline scenario corresponds to a global mean temperature increase of more than 3 °C.

Source: Alkemade et al., 2011; reprinted with kind permission from Springer Science+Business Media.

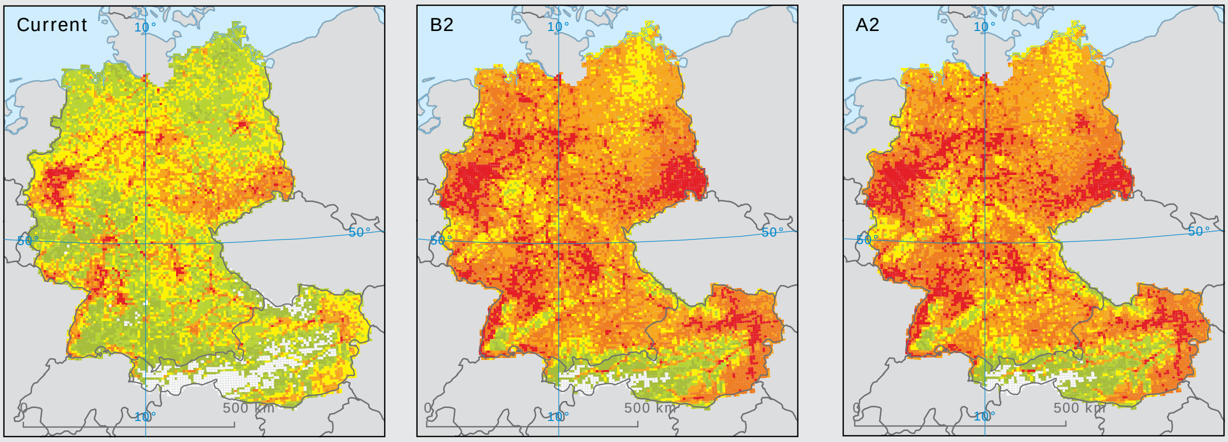
Box 3.2 Alien plant species and climate change — new ranges?

Horticulture and ornamental plant trade are by far the most important pathways of plant introductions to Europe (Hanspach et al., 2008; Hulme et al., 2008; Hulme, 2011). However, climate change mitigation and adaptation measures may also contribute to the introduction of new species, for example through increasing use of dry-adapted species in forestry, and cultivation of energy plants (IUCN, 2009). Furthermore, climate change itself may increase the establishment and reproduction rates and the niche breadth of alien plant species (Walther et al., 2009; Kleinbauer et al., 2010).

An increasing number of warm-adapted alien plant species has recently become established in central Europe, such as palms, cacti and evergreen tree species (Berger et al., 2007; Walther et al., 2007; Essl and Kobler, 2009). One example is the Windmill Palm (*Trachycarpus fortunei*), which was introduced more than a century ago, but established in the wild only recently after average winter temperature increased and severity of cold spells decreased (Berger et al., 2007). Alien plant species have also increased their range by moving uphill (Pauchard et al., 2009).

Most alien plant species originate from warmer regions and will therefore benefit from projected climate change in Europe (Walther et al., 2009; Schweiger et al., 2010; Hulme, 2012). For example, Map 3.14 shows the potential future distribution of 30 major invasive alien plant species for Austria and Germany as projected under different climate change scenarios (Kleinbauer et al., 2010).

Map 3.14 Actual and potential future alien plant invasion hotspots (2081–2090) under two emissions scenarios



Actual and potential future alien plant invasion hotspots (2081–2090) under two emission scenarios

Number of species (out of 30)

0 | 1–5 | 6–10 | 11–15 | 16–20 | 21–25 | > 26 | Outside coverage

Note: Potential future alien plant invasion hotspots in Austria and Germany under climate change, based on 30 invasive alien vascular plant species and the SRES A2 and B2 emissions scenarios. Colours mark number of invasive alien species suitable in an area.

Source: Kleinbauer et al., 2010.

3.4.5 Distribution and abundance of animal species

Relevance

Shifts in the distribution of animal species can have consequences for agriculture (livestock and crops), human health, and for biodiversity and its conservation (Sparks et al., 2007) and ecosystems functions and services. The distribution of many animal species will be particularly affected by climate change if habitat fragmentation impedes their movement to more suitable climatic conditions. Northward and uphill movements are taking place two to three times faster than reported earlier (Chen et al., 2011). An increased extinction risk compared to previous findings is predicted, and is supported by observed responses to climate change (Maclean and Wilson, 2011). A 'biotic homogenisation' of specific ecological communities of European flora and fauna (i.e. losing regional uniqueness and characteristics) is projected (Thuiller et al., 2011).

Past trends

A wide variety of animal species in Europe has moved northward and uphill during recent decades. The distributions of many terrestrial organisms have recently shifted to higher elevations at a median rate of 11 m per decade, and to higher latitudes at a rate of 17 km per decade (Figure 3.13) (Chen et al., 2011). These range shifts are partly attributable to observed changes in climatic conditions but land-use and other environmental changes also play a role (Schweiger et al., 2010, 2012). In Britain, 275 of 329 animal species analysed over the last 25 years have shifted their ranges northwards by 31–60 km, 52 shifted southwards, and 2 did not move (Hickling et al., 2006). However, many species, including butterflies, are failing to move as quickly as might be expected under the current rate of climate change (Warren et al., 2001).

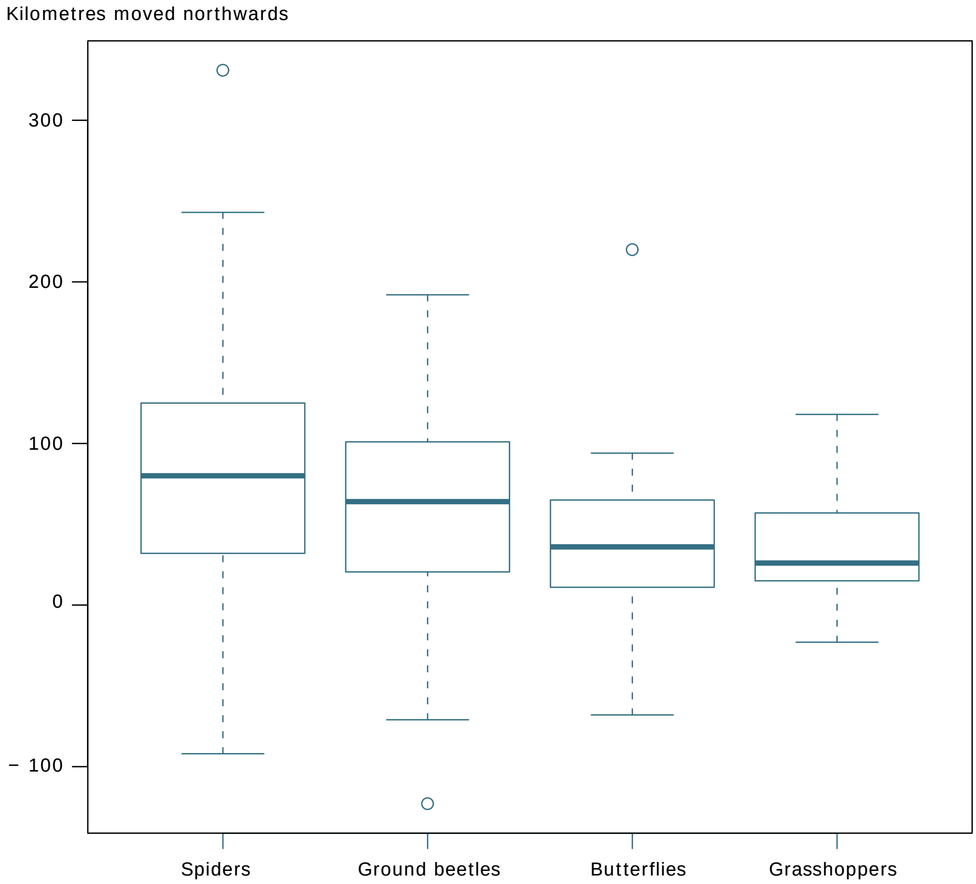
Climate change can benefit some species. One example is the wasp spider (*Argiope bruennichi*), which has multiplied its range in central and northern Europe during the 20th century and is still spreading. This range expansion is at least partly temperature-driven (Kumschick et al., 2011). In Germany, the once rare scarlet darter dragonfly (*Crocothemis erythraea*) has spread from the south, paralleling observed changes in climate, and is now found in every federal state (Ott, 2010). Under a scenario of 3 °C warming above pre-industrial levels by 2100, the ranges of European breeding birds are projected to shift by about 550 km to the north-east, whereby average range size would be reduced by 20 %. Arctic, sub-Arctic, and some Iberian species are projected to suffer the greatest range losses (Huntley et al., 2008).

Climate change has already influenced species richness and composition of European bird communities (Lemoine et al., 2007; Gregory et al., 2009). A study of 122 terrestrial bird species indicated that climate change has influenced population trends across Europe since around 1985, with impacts becoming stronger over time. The study shows that populations of 92 species have declined, largely because of climate change, whereas 30 species have generally increased (Gregory et al., 2009). In a study of 57 non-migratory European butterflies, 36 had shifted their ranges to the north by 35–240 km and only 2 had shifted to the south in the past 30–100 years (Parmesan et al., 1999). The habitat of 16 mountain-restricted butterflies in Spain has decreased by about one third over the last 30 years, and lower altitudinal limits rose on average by 210 m (Wilson et al., 2005).

Key messages: 3.4.5 Distribution and abundance of animal species

- Observed climate change is having significant impacts on European fauna. These impacts include range shifts as well as local and regional extinctions of species.
- There is a clear poleward trend of butterfly distributions from 1990 to 2007 in Europe. Nevertheless, the migration of many species is lagging behind the changes in climate, suggesting that they are unable to keep pace with the speed of climate change.
- Distribution changes are projected to continue. Suitable climatic conditions for Europe's breeding birds are projected to shift nearly 550 km north-east by the end of the 21st century under a scenario of 3 °C warming, with the average range size shrinking by 20 %.
- Habitat use and fragmentation and other obstacles are impeding the migration of many animal species. The difference between required and actual migration rate may lead to a progressive decline in European biodiversity.

Figure 3.13 Observed latitudinal shifts of four species groups over 25 years in Britain



Note: Observed latitudinal shifts of the northern range boundaries of species within 4 exemplar taxonomic groups, studied over 25 years in Britain. (A) Spiders (85 species), (B) ground beetles (59 species), (C) butterflies (29 species), and (D) grasshoppers and allies (22 species). Positive latitudinal shifts indicate movement toward the north (pole); negative values indicate shifts toward the south (Equator). Horizontal lines mark the Median, boxes the 25 to 75 % quartile and whisker the range (up to 1.5 times the interquartile distance). Open Circles are outliers.

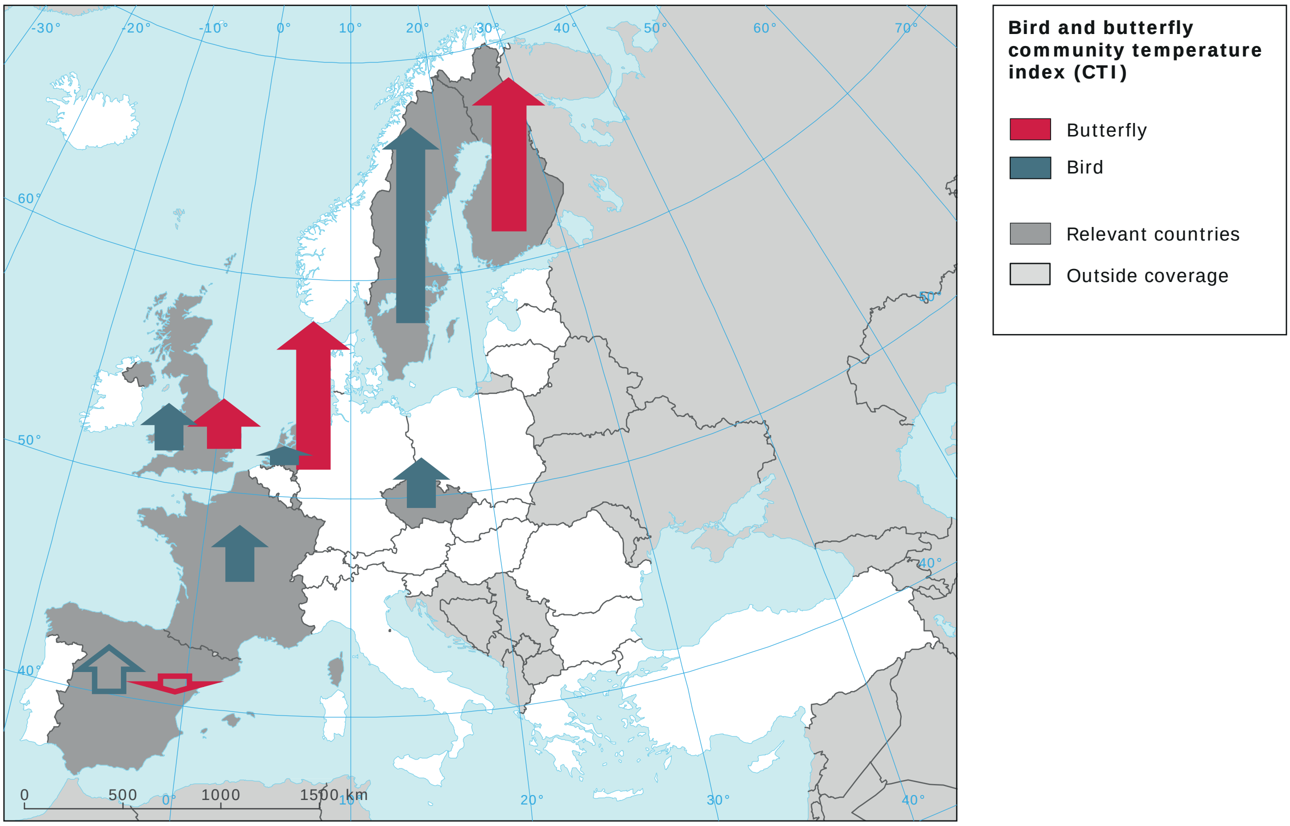
Source: Modified after Chen et al., 2011.

The Community Temperature Index (CTI) is a measure for the rate of change in community composition in response to temperature change. According to changes in the CTI, butterfly communities become increasingly composed of species associated with warmer temperatures. For example, the CTI of butterfly communities across Europe has increased by only 0.014 °C per year from 1970 to 2007. However, temperature has increased by 0.039 °C per year in the same period, that is almost three times faster than the butterfly community could move north (van Swaay et al., 2008). The finding that the movement of animal species is unable to keep pace with climate change has been confirmed in an analysis of the CTI of several thousand local bird and butterfly communities across Europe (see Map 3.15) (Devictor et al., 2012).

The Arctic contribution to global biodiversity is substantial as the region supports globally significant populations of birds, mammals and fish. The Arctic Species Trend Index (ASTI) has been tracking trends in 306 Arctic species. An analysis of the ASTI over 34 years (1970–2004) has shown that the abundance of high Arctic vertebrates declined by 26 % whereas low Arctic vertebrate species increased in abundance. Sub-Arctic species did not show a trend over the whole time period but they seem to decline since the mid-1980s (McRae et al., 2010).

There is some evidence that climate change has already played a role in the spread of alien animal species (see Box 3.3).

Map 3.15 European variations in the temporal trend of bird and butterfly community temperature index



Note: The map shows the temporal trend of bird and butterfly CTI for each country. A temporal increase in CTI directly reflects that the species assemblage of the site is increasingly composed of individuals belonging to species dependent on higher temperature. The height of a given arrow is proportional to the temporal trend and its direction corresponds to the sign of the slope (from south to north for positive slopes). The arrow is opaque if the trend is significant.

Source: Devictor et al., 2012.

Box 3.3 Alien animal species and climate change — new establishments?

There is increasing evidence that some alien species in general and some alien animal species in particular will on average be able to increase their ranges under climate change (Walther et al., 2009). The spread of alien animal species into new regions is favoured by the impact of climate change on ecosystems and landscapes (e.g. rapid climatically driven change in ecosystem composition), by a weakening resistance of native species to alien predators and parasites (e.g. Norway spruce and bark beetle, *Ips typographus*) (Baier et al., 2007), and by decreasing climatic constraints on warm-adapted alien species. However, uncertainty regarding the future behaviour of a particular species under climate change remains high. Because alien species are mostly opportunistic and generalists, they tend to perform better under rapidly changing climate than native species (Hellmann et al., 2008).

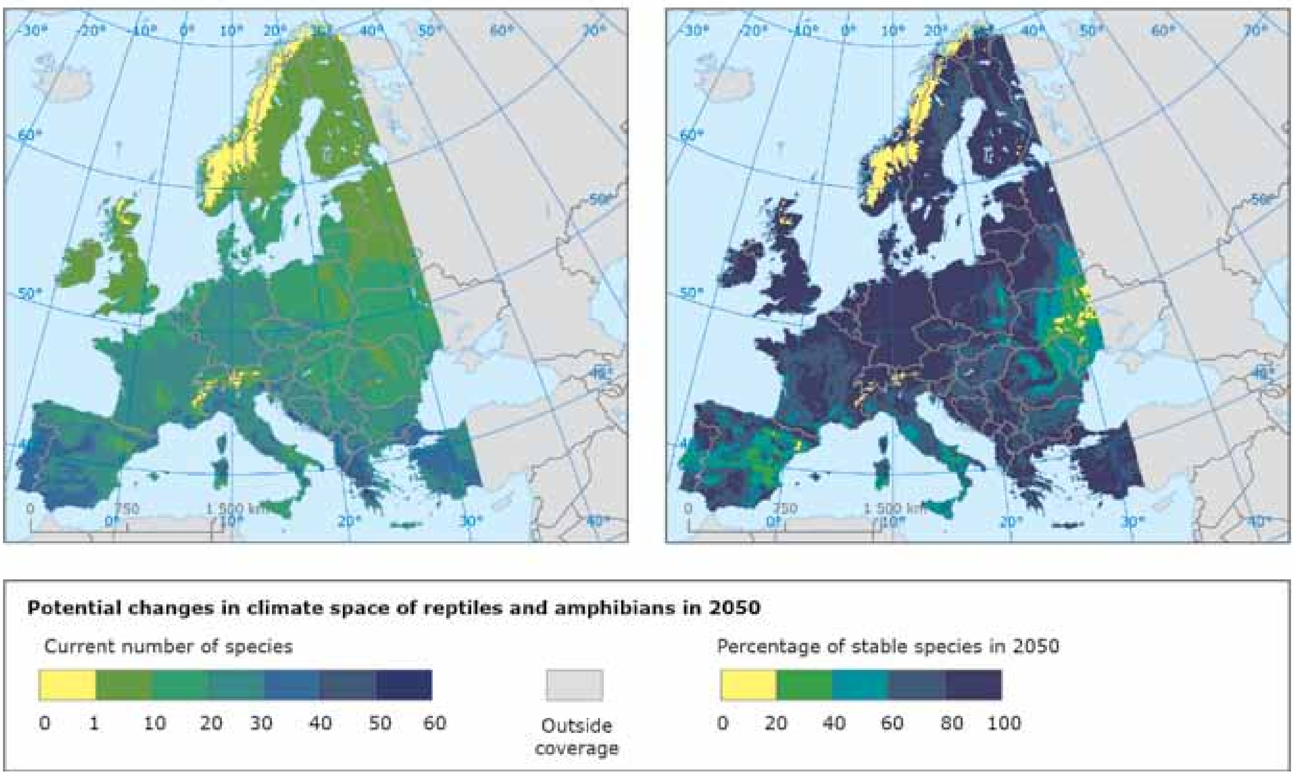
The Red-Eared Slider Turtle (*Trachemys scripta elegans*) is native to eastern North America and was introduced to Europe as a pet in the 1960s (Kraus, 2009). In Europe, it can currently reproduce in the Mediterranean only where temperature, precipitation and solar radiation are suitable but this range is projected to shift further north with climate change (Ficetola et al., 2009). The Pacific oyster (*Crassostrea gigas*) was intentionally introduced to western Europe in the 1960s for commercial harvesting in oyster farms but soon it escaped and established itself close to the farms. Its reproduction depends on water temperatures being between 18 and 23 °C over several weeks. Following unusual warm summer months in 1989–1990, the species spread along the northern Atlantic coasts where increased water temperatures have allowed successful reproduction, larval development and recruitment (Dutertre et al., 2010; Nehring, 2011).

Projections

The northward and uphill movement of many animal species is projected to continue this century. Threatened endemics with specific demands in ecotope or a small distribution range will generally be at greatest risk, in particular if they face migration barriers (Lemoine et al., 2007; Dirnböck et al., 2011). The difficulty of modelling species dispersal is one of the major uncertainties in projections of changes in species distribution. Dispersal is constrained not only by a species' ability to move but also by factors such as habitat fragmentation and the availability and migratory ability of host plants or prey organisms. It is likely that many species will not be able to track climate change because of dispersal constraints (Schweiger et al., 2008, 2012).

The limited dispersal ability of many reptiles and amphibians, combined with the fragmentation of habitats, is very likely to reduce and isolate the ranges of many of those species, particularly in the Iberian Peninsula and parts of Italy (Araújo et al., 2006; Hickling et al., 2006) (Map 3.16). Similar results were found in a comprehensive study that assessed the future distribution of European butterflies in 2050 and 2080 under three different climate change scenarios (Settele et al., 2008). The study shows that climate change poses a considerable additional risk to European butterflies (Map 3.17). The risk varies considerably under different emissions scenarios and assumptions regarding dispersal ability. Under the high-emission SRES A1FI scenario, 24 % of the modelled butterfly species lose more than 95 % of their present climatic niche by 2080 and 78 % lose

Map 3.16 Projected impact of climate change on the potential distribution of reptiles and amphibians in 2050



Note: Projected data based on the Generalised Linear Model map using the HadCM3 A2 scenario for 2020–2050 are compared with the current situation.

Source: Data based on Araújo et al., 2006.

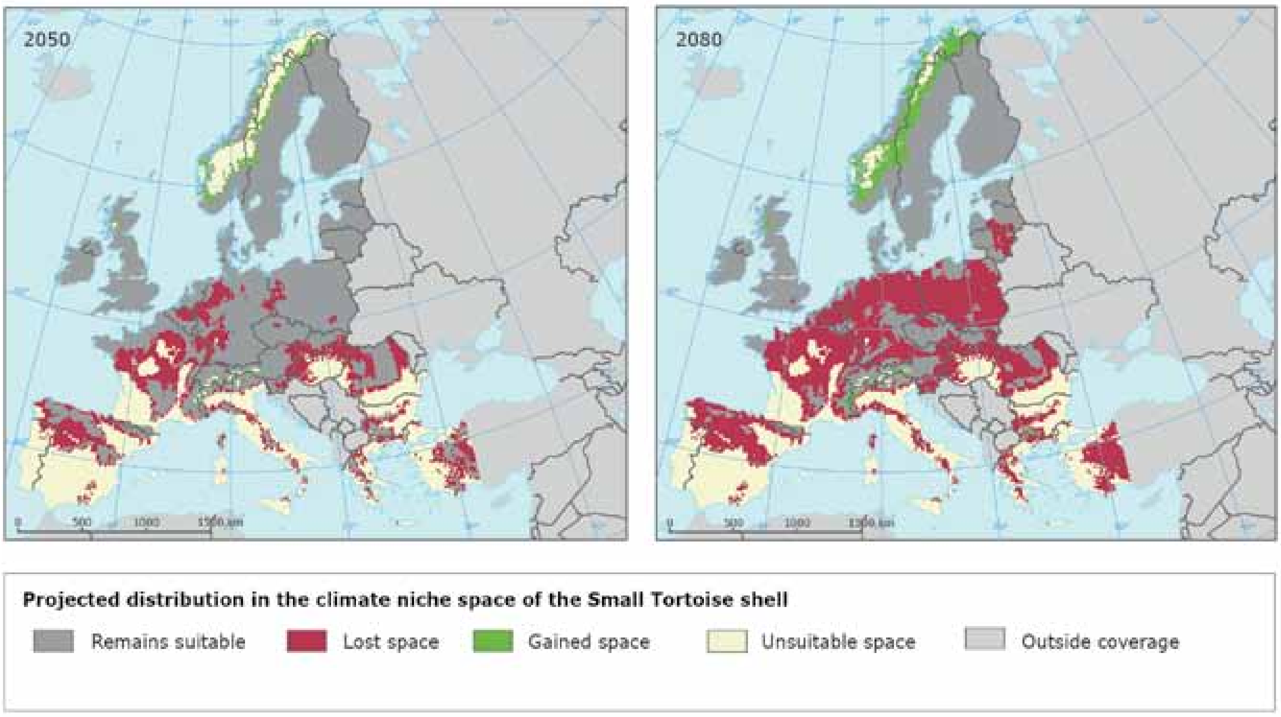
more than 50 %. These numbers are reduced to 3 % and 48 %, respectively, for the low-emission SRES B1 scenario. The risk is much lower, and much more similar across scenarios, by 2050.

A study on the effects of projected climate change on 181 terrestrial mammals in the Mediterranean region projected significant declines in species richness (e.g. 68 % of all mammals) during this century even if movement through fragmented landscapes was possible (Maiorano et al., 2011). A study based on bioclimatic envelope modelling for 120 native terrestrial European mammals under two climate scenarios showed that 1 % or 5–9 % of European mammals risk extinction (Levinsky et al., 2007). Thirty-two to 46 % or 70–78 % may lose more than 30 % of their current distribution (Map 3.18).

Another study simulated phylogenetic diversity for plants, birds and mammals in an ensemble of forecasts for 2020, 2050 and 2080 (Thuiller et al., 2011). The results show that the tree of life faces a homogenisation across the continent due to a reduction in phylogenetic diversity for southern Europe (where immigration from northern Africa was not considered) and gains in high latitudes and altitudes.

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

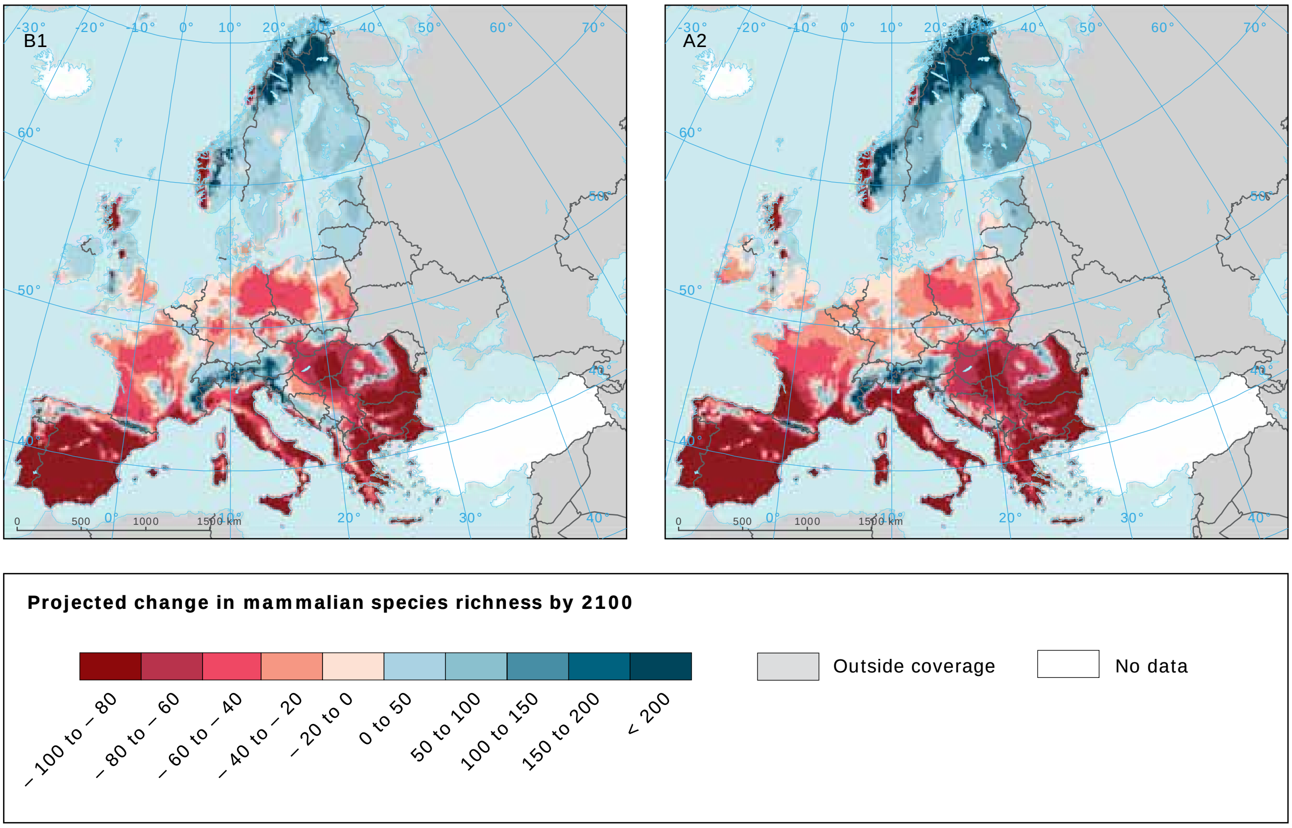
Map 3.17 Projected changes in the climate niche space of the Small Tortoise shell



Note: Future distribution of climate niche space of the Small Tortoise shell (*Aglais urticae*) under the A2 climate change scenario and two future years (2020–2050 left, 2060–2080 right). Dark grey areas show space that remains suitable, dark red areas space that is lost and green areas show space that could be gained under full dispersal. Northern parts of Europe are expected to remain suitable for the Small Tortoiseshell under all scenarios, but large areas of central Europe would become unsuitable. The worst case loss is 55 % of its climatic niche by 2080 under no dispersal or 46 % loss under full dispersal.

Source: Settele et al., 2008. See also http://pensoftonline.net/biorisk/index.php/journal/issue/current/showT.

Map 3.18 Changes in mammalian species richness by 2100



Note: Changes under two climate scenarios B1 (left) and A2 (right) in a 10' resolution.

Source: Levinsky et al., 2007.

3.4.6 Species interactions

Relevance

The effects of climate change on single species will have consequences for all levels of biodiversity, ranging from the genetic level to ecosystems (Walther, 2010). These higher-level impacts are of particular importance since biodiversity, besides being realised as a value in its own right, is increasingly acknowledged as providing indispensable ecosystems services for human well-being (Díaz et al., 2006). Biodiversity can be regarded as 'our collective life insurance', as noted in the 'EU biodiversity strategy to 2020' (European Commission, 2011). The importance of wild species for the functioning of ecosystems is manifold and largely driven by biotic and abiotic interactions. An improved understanding of how climate change will affect these interactions in novel communities established under a novel climate can be utilised to assess the extinction risk of species of particular conservation concern. It will also enhance our abilities to assess and mitigate potential negative effects on ecosystem functions and services. Despite increasing knowledge about effects of climate change on pairwise species interactions and on complete ecological networks, quantitative assessments of these effects are still very uncertain. A robust conclusion from existing observational and theoretical studies is that specialist species are at much higher risk from effects on species interactions than generalist species (Menéndez et al., 2007; Schweiger et al., 2010).

Community changes triggered by climate change can lead to disruptions or alterations of currently existing species interactions and the generation of novel species interactions. Such changes impact on mechanisms such as competition, herbivory, predation, parasitism, pollination and symbiosis by affecting ecological matching among interacting species (Berg et al., 2010; Antoninka et al., 2011). These ecological matches can be defined by spatial or temporal synchronicity of occurrence (Parmesan, 2006; Schweiger et al., 2008; Hegland et al., 2009; Van der Putten et al., 2010), or by energetic, morphological and behavioural demands (Corbet, 2000; Schweiger et al., 2010).

Climate change can also affect disturbance regimes, such as wildfires and storms. Forest fires as an important example of such a disturbance regime are discussed in Section 4.2.3.

Past trends

Direct observations of the effects of recent climate change on competition are scarce and are generally thought not to have led directly to the extinction of species in Europe (Davis, 2003). However, independent studies have shown that observed changes in the distribution and abundance of *Populus* species (a group of trees that are relatively weak competitors) in the Late Glacial (ca. 13 000–10 000 years ago) and in the 20th century could only be explained when the effects of climate change on its competitors were taken into account (Peros et al., 2008; Van Bogaert et al., 2009).

Climate change has already lead to temporal mismatches between species that depend on each other for feeding and for pollination. For example, the egg hatch of the winter moth (*Operophtera brumata*) has advanced more than the budburst date of its larval food plant, the pedunculate oak (*Quercus robur*), over the past two decades, with potentially severe consequences for its fitness (Visser and Both, 2005; Parmesan, 2006; van Asch and Visser, 2007; Both et al., 2009). Similarly, over the last 30 years, the occurrence of the honey bee (*Apis mellifera*) and the Small White butterfly (*Pieris rapae*) in relation to the flowering of crucial host plants has changed

Key messages: 3.4.6 Species interactions

- Climate change is affecting the interaction of species that depend on each other for food or other reasons. It can disrupt established interactions but also generate novel ones.
- Negative effects on single species are often amplified by changes in interactions with other species, in particular for specialist species.
- The impact of species interactions on ecosystems services depends on whether disrupted interactions can be buffered by system-intrinsic properties or by novel organisms.

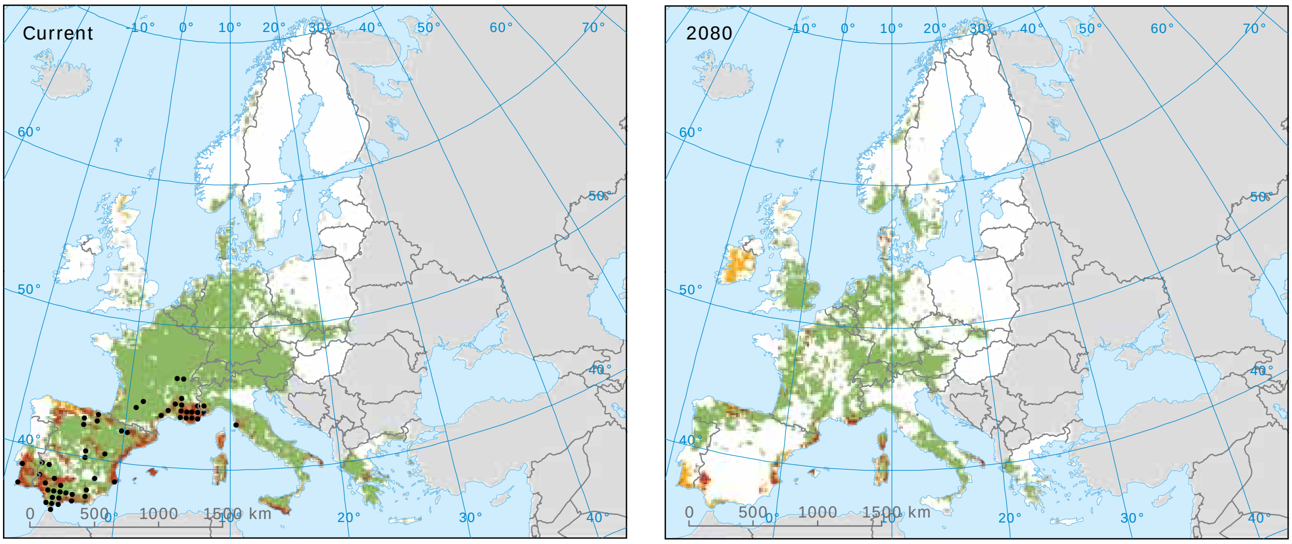
from about 10 days and 5 days later to about 25 days and 15 days earlier, respectively (Gordo and Sanz, 2005). Such temporal mismatches can severely impact pollination activities and the seed set of plants (Kudo et al., 2004). Climate change has also disrupted several predator-prey relationships, such as between insectivorous birds and their insect prey (Visser et al., 2006). In some cases, differential changes in phenology can also strengthen existing or create new predator-prey relationships, as observed by an increased predation pressure of the fat dormouse (*Glis glis*) on several songbirds in the Czech Republic (Adamík and Král, 2008).

Climate change can also generate new interactions in novel communities (Schweiger et al., 2010). In extreme cases, this can lead to severely transformed ecosystems where new species dominate. Such changes are particularly obvious at higher latitudes and altitudes, where growing and reproductive periods are prolonged or where previous thermal constraints are released with climate warming. For instance, the range of the pine processionary moth (*Thaumetopoea pityocampa*) is no longer limited by temperature in many regions, enabling the species to expand its existing range into new areas and causing serious damage in pine forests (Robinet et al., 2007).

Projections

A study on butterflies in Europe showed that most species are not limited by the distribution of their larval host plants and thus appear rather insensitive to spatial mismatching with their hosts under future climate change. However, there are exceptions such as the Portuguese Dappled White butterfly (*Euchloe tagis*), which is projected to lose 20–48 % of its current area based on the loss of suitable climatic conditions by 2080, and 50–74 % when a reduced availability of host plants was also considered (Schweiger et al., 2012) (Map 3.19). These findings highlight the need for a better understanding of ecological interactions that mediate species responses to climate change.

Map 3.19 Projected spatial mismatches of the Portuguese Dappled White butterfly and its host plants



Projected spatial mismatches of the Portuguese Dappled White butterfly (Euchloe tagis) and its host plants

- Suitable climate space for the host plants
- Suitable climate space for the butterfly
- Suitable area for both (butterfly and host plant)
- Currently observed distribution
- Not suitable
- Outside coverage

Note: Spatial mismatches of the Portuguese Dappled White butterfly (*Euchloe tagis*) and its host plants under the BAMBU scenario (climate: A2) for 2050–2080. Green, suitable climate space for the host plants; yellow, suitable climate space for the butterfly; orange, suitable area for both butterfly and host plants; open circles, currently observed distribution. BAMBU: Business-As-Might-Be-Usual scenario.

Source: Schweiger et al., 2012.

3.5 Soil

3.5.1 Overview

Relevance

There has been an increasing awareness of the importance of soil as a regulator of water, the global carbon and nutrient cycles and as a habitat in its own right. Topical debates on issues such as food security, biofuel production and flooding of urban areas have demonstrated the need for better soil management and increased understanding of complex interactions between the key soil functions. This is particularly true when considering additional pressures resulting from climate change.

Soil is the product of the interplay between biological and environmental factors, principally, the geological substrate, living organisms, relief, time and climate. Variations in precipitation levels and temperature regimes determine weathering mechanisms and rates of soil formation. In parallel, climate drives soil-forming processes such as leaching, the mobilisation of clay minerals and nutrient exchange mechanisms, which give soils their characteristic properties. In addition, climate influences the soil by determining the mass and distribution of plant communities and the rate of decay of soil organic matter — the driver of many soil functions. Changes in climatic conditions (e.g. rising temperatures, changing precipitation intensity and frequency) are thus likely to affect soil-related bio-geophysical processes and environmental services that are regulated by soil.

Soil as part of the soil-water-plant system influences plant growth and evapotranspiration through the supply of water to roots, water quality through buffering capacity and transport of excess nutrients or contaminants, run-off through retention capacity, and changes in groundwater recharge. Changes in rainfall intensity and patterns can either increase or decrease soil water contents. Excess water can trigger landslides, or induce saturation overland flow and soil erosion. While increased levels of precipitation can lead to soils accumulating soil organic carbon, the converse will be true for areas where precipitation is reduced; whereas prolonged drought can lead to inhibited microbial activity, which reduces the rate of organic matter breakdown. Loss of organic matter can bring about a loss of fertility and biodiversity, and destruction of soil structure. Loss of soil structure in turn can make soils more susceptible to compaction, or can result in an increased risk of wind erosion, or reduced water retention capacity, with increased flood risk during extreme rainfall events.

In addition, there is an inverse aspect to the soil-climate relationships, as soil can also have an impact on global climate. GHG fluxes from soils are considerable. Natural soil systems tend to act as carbon reservoirs. Soil is the largest terrestrial carbon pool and presents an important factor in future climate change projections. In most ecosystems, the amount of carbon locked in the soil is significantly greater than in above-ground biomass. Permanently frozen soils in the northern polar region contribute significantly to the carbon stock due to cryoturbation, which drags surface organic matter deeper into the soil body, often accumulating on the permafrost table. Extensive peatlands are an additional reservoir. The thawing of the permafrost could lead to a substantial release of GHGs, including CH_4 with a much higher global warming potential than CO_2, into the atmosphere that would further increase global warming (Jones et al., 2010). These important carbon reservoirs need special attention because the boreal and arctic regions where they occur are expected to warm more rapidly than the rest of the world. Drainage

Key messages: 3.5 Soil

- Soil functions and the services soils provide to society are increasingly recognised. Climate is one of the key factors driving soil development; at the same time, soils are important for mitigating climate change through their capacity for storing organic carbon.
- Projections for soil indicators are limited. The expected effects of climate change are complex, and depend on distinct drivers and their interaction. For some indicators, the different aspects of climate change can have opposite effects, which make estimation of future changes particularly difficult.
- European-wide information to help policymakers identify appropriate adaptation measures is limited. This calls for establishing harmonised monitoring networks for collecting data.

can convert peatlands into carbon sources rather than sinks. Likewise, inappropriate cultivation of soils and the application of nitrogen fertilisers can lead to emissions of CO_2 and N_2O.

Selection of indicators

This section presents three indicators that measure important climate-sensitive properties of soils:

- *Soil organic carbon:* Soil organic carbon is potentially impacted by climate change, and changes in soil organic carbon in turn have an impact on climate change.
- *Soil erosion:* Soil erosion by water and wind is already affecting soils across Europe, thereby threatening many of the services soils provide.
- *Soil moisture:* Soil moisture is a key factor for ecosystems, which is determined by soil characteristics, vegetation and climatic factors.

Furthermore, the final Section presents information on the effects of negative precipitation anomalies on a major soil function, biomass production. Another soil-related indicator, which relates to changes in permafrost, is presented in Section 2.3.6.

Uncertainty and data gaps

Quantitative information, from both observations and modelling, on the past trends and impacts of climate change on soil and the various related feedbacks, is very limited. For example, data have been collected in forest soil surveys (e.g. ICP Forests, BioSoil and FutMon projects), but issues with survey quality in different countries makes comparison between countries (and between surveys) difficult (Hiederer and Durrant, 2010). To date, assessments have relied mainly on local case studies that have analysed how soil reacts under changing climate in combination with evolving agricultural and forest practices. Thus, European-wide soil information to help policymakers identify appropriate adaptation measures is absent. There is an urgent need to establish harmonised monitoring networks to provide a better and more quantitative understanding of this system. Currently, EU-wide soil indicators are (partly) based on estimates and modelling studies, most of which have not yet been validated. Nevertheless, in absence of quantification, other evidences can indicate emerging risks. For example, shifting tree lines in mountainous regions as a consequence of climate change may indicate an extinction risk of local soil biota (see Box 3.4).

Finally, when documenting and modelling changes in soil indicators, it is not always feasible to track long-term changes (signal) given the significant short-term variations (noise) that may occur (e.g. seasonal variations of soil organic carbon due to land management). Therefore, detected changes cannot always be attributed to climate change effects, as climate is only one of the soil-forming factors. Human activity can be more determining, both in measured/modelled past trends (baseline), and if projections including all possible factors were to be made. The latter points towards the critical role of effective land use and management in mitigating and adapting to climate change.

3.5.2 Soil organic carbon

Relevance

Biomass is generated by photosynthesis binding CO_2 from the atmosphere. If not harvested, this biomass becomes incorporated into the soil after the death of the plant and through root senescence. The dead plant material is decomposed with the help of micro-organisms and CO_2 is again released into the atmosphere. Part of the carbon is converted into stable (humic) soil organic matter. However, if soil is water-saturated due to poor drainage, the breakdown of carbon is slowed down and only highly specialised microorganisms are able to decompose carbon, releasing CO_2 and CH_4. Nevertheless, wet soils and peatlands act overall as important carbon reservoirs.

Low levels of organic carbon in the soil are generally detrimental to soil fertility, water retention capacity and resistance to soil compaction. Increases in surface water run-off can lead to erosion while lack of cohesion in the soil can increase the risk of erosion by wind. Other effects of lower organic carbon levels are a reduction in biodiversity (see Box 3.4) and an increased susceptibility to acid or alkaline conditions.

Past trends

Around 45 % of the mineral soils in Europe have low or very low organic carbon content (0–2 %) and 45 % have a medium content (2–6 %) (Louwagie et al., 2009). Map 3.20 shows that low levels are particularly evident in southern Europe where 74 % of the land is covered by soils that have less than 2 % of organic carbon in the topsoil (0–30 cm) (Zdruli et al., 2004). However, areas of low organic carbon can be found almost everywhere, including in some parts of more northern countries such as Belgium, France, Germany, Norway and the United Kingdom. More than 50 % of EU soil organic carbon stocks are to be found in peatlands (Schils et al., 2008).

In general, most soils across Europe are likely to be accumulating carbon. Except under drainage conditions, grassland soils accumulate carbon, although there is a high uncertainty as to the rate. Croplands generally act as a carbon source, although existing estimates are varied. Forest soils generally accumulate carbon (estimates range from 17 to 39 million tonnes per year (Schils et al., 2008)). However, estimates of European CO_2, CH_4 and N_2O fluxes between 2000 and 2005, using both top-down estimates based on atmospheric observations and bottom-up estimates derived from ground-based

Key messages: 3.5.2 Soil organic carbon

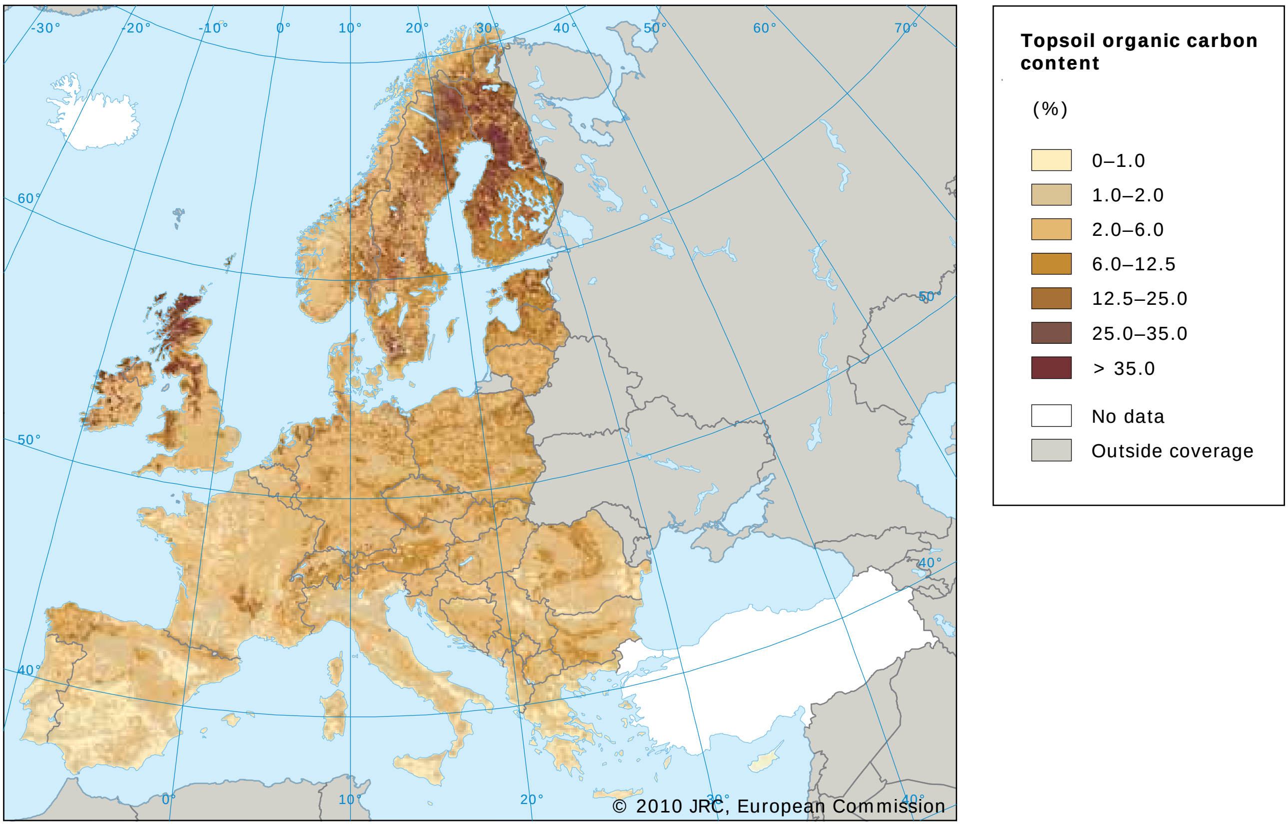
- Soil carbon stocks in the EU-27 are around 75 billion tonnes of carbon; around 50 % of which is located in Ireland, Finland, Sweden and the United Kingdom (because of the large area of peatlands in these countries).
- The largest emissions of CO_2 from soils are due to conversion (drainage) of organic soils, and amount to 20–40 tonnes of CO_2 per hectare per year. The most effective option to manage soil carbon in order to mitigate climate change is to preserve existing stocks in soils, and especially the large stocks in peat and other soils with a high content of organic carbon.
- On average, soils in Europe are most likely to be accumulating carbon. Soils under grassland and forests are a carbon sink (estimated up to 80 million tonnes of carbon per year) whereas soils under arable land are a smaller carbon source (estimated from 10–40 million tonnes of carbon per year).
- The effects of climate change on soil organic carbon and soil respiration are complex, and depend on distinct climatic and biotic drivers. However, they lack rigorous supporting datasets.
- Climate change is expected to have an impact on soil carbon in the long term, but changes in the short term will more likely be driven by land management practices and land use change.

measurements, suggest that CH_4 emissions from livestock and N_2O emissions from arable agriculture are fully compensated by the CO_2 sink provided by forests and grasslands (Schulze et al., 2009).

Projections

Soil organic carbon levels are determined mainly by the balance between net primary production (NPP) from vegetation and the rate of decomposition of the organic material. While climate change is expected to have an impact on soil carbon in the long term, changes in the short term will more likely be driven by land management practices and land-use change, which can mask the evidence of climate change impact on soil carbon stocks. Figure 3.14 provides a flowchart with possible pathways for soil organic carbon (SOC) and CO_2 development in temperate mineral soils, depending on the distinct climatic and biotic drivers. However, the effects of climate change on soil are complex and lack rigorous supporting datasets.

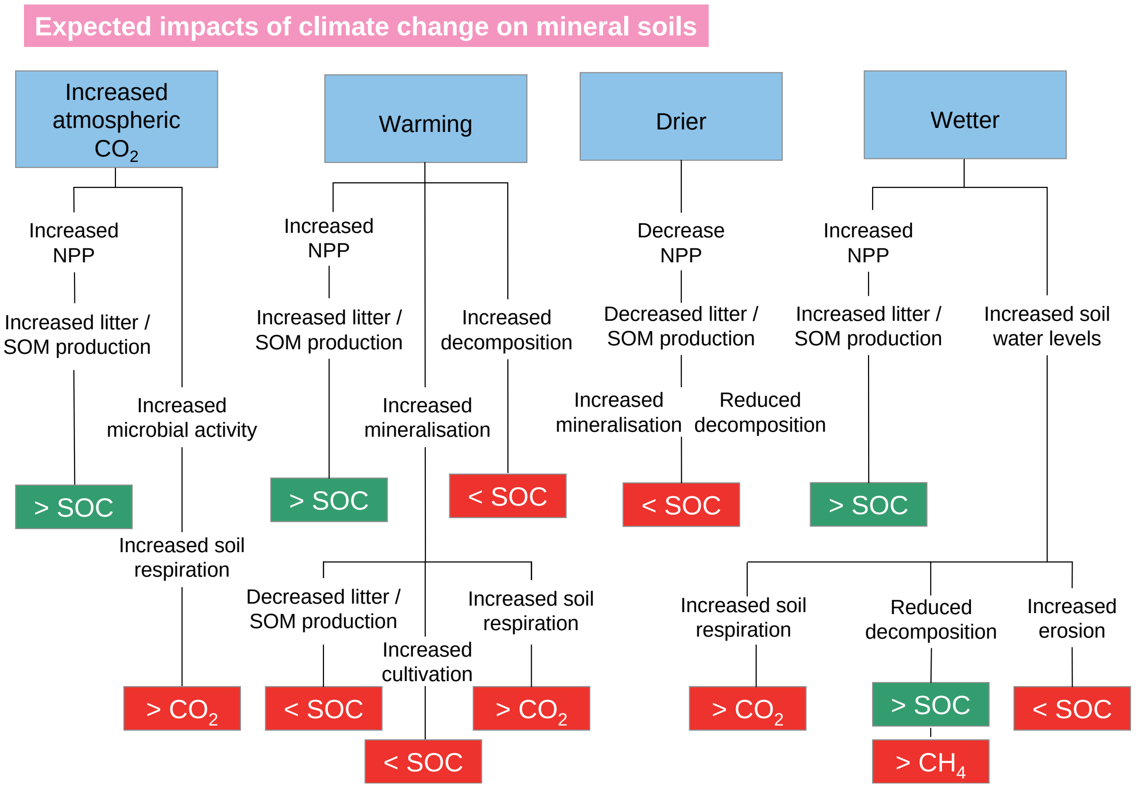
Map 3.20 Variations in topsoil organic carbon content across Europe



Note: The darker regions correspond to soils with high values of organic carbon. The darkest colours, especially in Estonia, Fennoscandinavia, Ireland and the United Kingdom, denote peatlands.

Source: European Soil Database v2.0 (soil), Global Historical Climatology Network (http://www.ncdc.noaa.gov/oa/climate/ghcn-daily) (climate), Corine Land Cover 1990 and USGS Global Land Cover Characterization (http://edc2.usgs.gov/glcc/glcc.php) (land cover); see (Jones et al., 2005, 2012).

Figure 3.14 Qualitative impacts of climatic and biotic variables on temperate mineral soils



Note: SOC: soil organic carbon; SOM: soil organic matter; NPP: net primary productivity; CO_2: carbon dioxide; CH_4: methane. Decomposition is the post-mortem breakdown of organic matter into constituent elements or secondary substances through chemical reactions and biological activity. Mineralisation is the conversion of an element from an organic to an inorganic state as a result of microbial activity.

Box 3.4 The impacts of climate change on soil biota and biodiversity

Soil biodiversity is vulnerable to impacts of climate change on terrestrial systems. However, quantifying the possible effects is problematic given the difficulties in measuring, mapping and monitoring soil biotic communities.

A recent meta-analysis of responses of soil biota to global change, based on manipulative experiments (Blankinship et al., 2011), noted that rising CO_2 concentration will positively affect microflora and -fauna, while mesofauna tend to respond negatively. The effect of the amount of precipitation is positively correlated with the abundance of soil biota, but differs between ecosystems (soil biota abundance affected in forests, but not in grasslands or heathlands). Warming will negatively affect the abundance of soil biota in sites characterised by low mean annual temperature and mean annual precipitation (see Figure 3.14).

There is some preliminary evidence that species are migrating to previously colder regions owing to warmer temperatures and an earlier start to spring. In mountainous regions, where evidence suggests that the tree line is migrating upwards, we can assume that the below-ground ecoregions will follow since soil biota are intimately tied to plant communities (Sylvain and Wall, 2011). However, the amount of habitat for those species adapted to living above the tree line will become reduced as the mountain summits provide an upper limit to the amount of vertical migration that can occur. Observations and quantifications of this vertical migration for vascular plants have found migration rates of between 1 and 4 vertical metres every 10 years. Rates for soil biota are expected to be similar.

3.5.3 Soil erosion

Relevance

Soil erosion by water has substantial on-site as well as off-site effects. By removing fertile topsoil, erosion reduces soil productivity and, where soils are shallow, may lead to the loss of the entire soil body. Soil removed by run-off, for example during a large storm, will create mudflows that will accumulate below the eroded areas, in severe cases blocking roadways or drainage channels and inundating buildings. Erosion can lead to restrictions on land use and land value, damage to infrastructure, pollution of water bodies, and negative effects on habitats and biodiversity.

Based on potential loss of wheat yields, a conservative estimate of the consequence of erosion by water for the EU-27 (excluding Greece, Cyprus and Malta), reveals that agricultural production equivalent to a value of EUR 3.5 billion could be under threat. If the economic loss of soil carbon is also added, the figure would be even higher. In 2011, the removal of topsoil by strong winds after ploughing in very dry conditions in Germany caused a traffic accident that killed 10 people and injured at least 100 others; this is an indirect effect of wind erosion (see Section 4.6).

Climate change will influence soil erosion processes, mainly triggered by extreme rainfall events and droughts. Excess water due to intense or prolonged precipitation can cause tremendous damage to soil through sheet wash, gully erosion and even landslides. However, if soils are managed well, resistance to erosion by water and/or wind can be improved considerably.

Past trends

Systematic and harmonised data on trends in soil erosion across Europe are lacking. EU-wide estimates of erosion are based on modelling studies, most of which have not yet been validated. A recent exercise has estimated that the surface area in the EU-27 (excluding Greece, Cyprus and Malta ([54])) affected by water erosion is 130 million ha. Almost 20 % is subjected to soil loss in excess of 10 tonnes/ha/year (Bosco et al., forthcoming; Jones et al., 2012) (Map 3.21). Most models contain a rainfall erosivity factor and a soil erodibility factor that reflect average precipitation conditions. Typical values for these factors may inadequately represent the impact of extreme rainfall. Therefore, the uncertainty of modelled erosion risk is high, especially at local level.

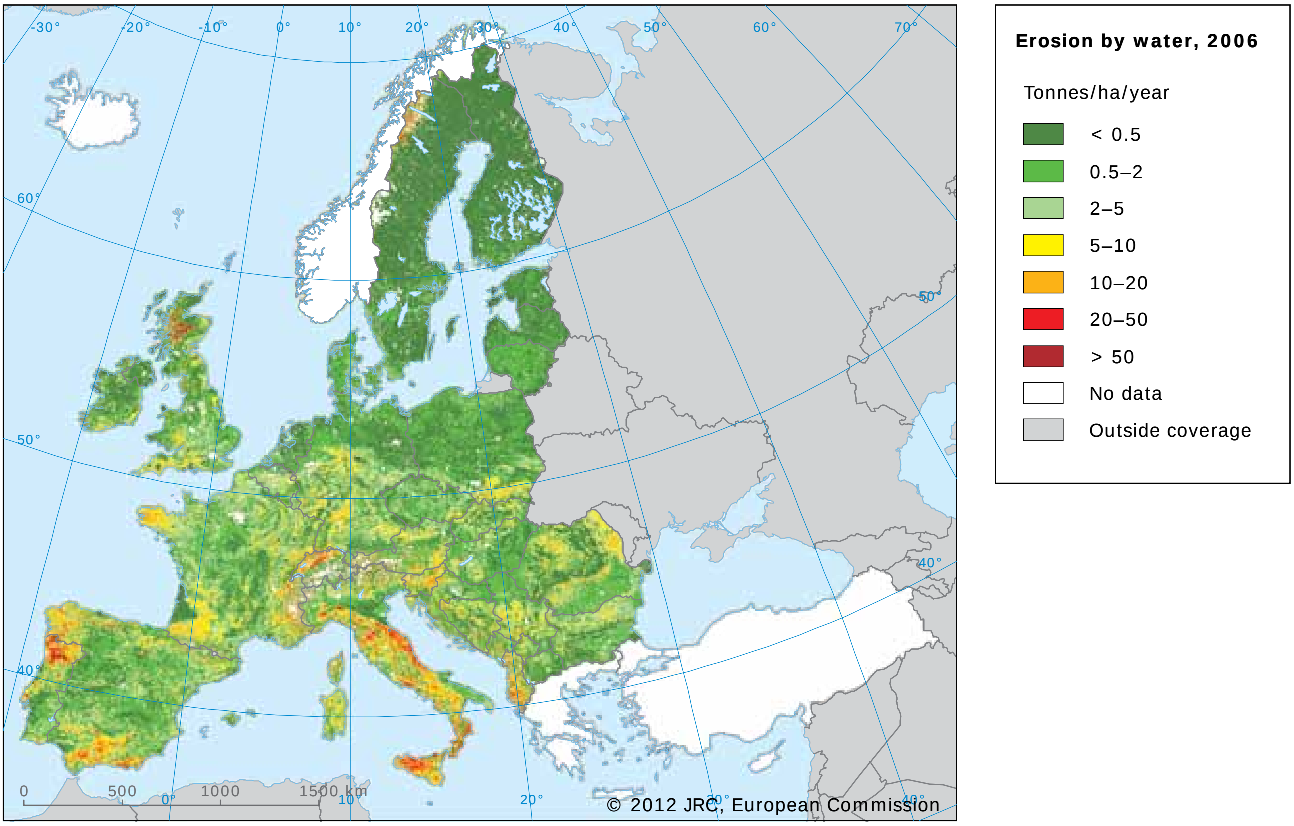
The situation for wind erosion is similar to erosion by water in that systematic data collections are limited. Wind erosion is estimated to be a serious problem in many parts of eastern England, north-west France, northern Germany, parts of the Iberian Peninsula and eastern Netherlands (Map 3.22).

Key messages: 3.5.3 Soil erosion

- 105 million ha, or 16 % of Europe's total land area (excluding Russia) were estimated to be affected by water erosion in the 1990s.
- Some 42 million ha. of land were estimated to be affected by wind erosion, of which around 1 million ha. were categorised as being severely affected.
- A recent new model of soil erosion by water has estimated the surface area affected in the EU-27 at 130 million ha. Almost 20 % is subjected to soil loss in excess of 10 tonnes/ha/year.
- Increased variations in rainfall pattern and intensity will make soils more susceptible to water erosion, with off-site effects of soil erosion increasing.
- Increased aridity will make finer-textured soils more vulnerable to wind erosion, especially if accompanied by a decrease in soil organic matter levels.
- Reliable quantitative projections for soil erosion are not available

([54]) Lacking Corine Land Cover data for 2006.

Map 3.21 Estimated soil erosion by water in Europe

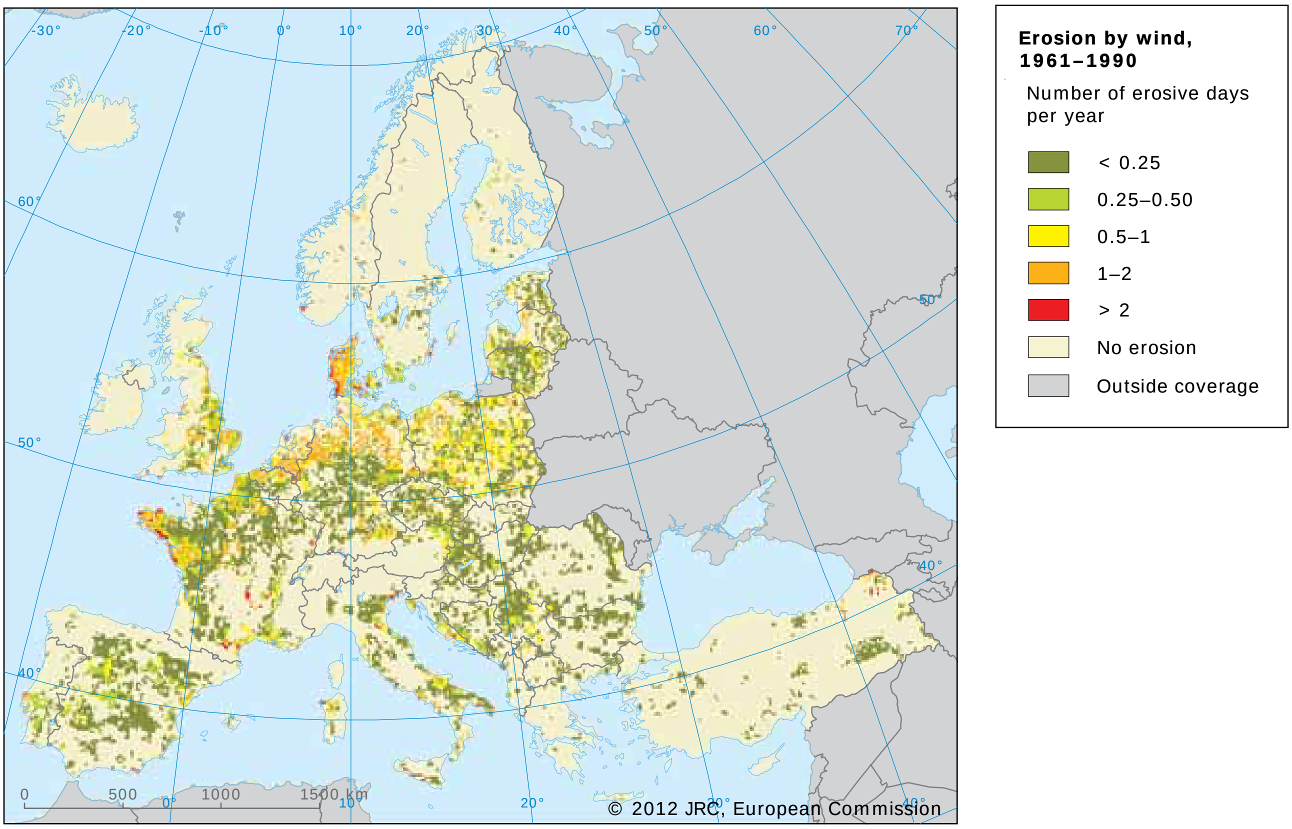


Note: Calculated by the Revised Universal Soil Loss Equation (RUSLE).

While the overall patterns of erosion are generally sound, the validation of erosion data can be challenging. The data presented are currently being validated through comparisons with national datasets and expert judgement. In this sense, zooming in on a specific locality can give the impression of a situation that differs from reality. In addition, the model used in this exercise does not consider localised intense precipitation.

Source: European Soil Database v2.0 (soil), E-OBS (http://www.agu.org/pubs/crossref/2008/2008JD010201.shtml) (climate), Corine Land Cover 2006 (land cover); see Bosco et al., forthcoming; Jones et al., 2012.

Map 3.22 Estimated number of days for wind erosion



Note: Calculations are based on wind velocity and soil texture.

While the overall patterns of erosion are generally sound, the validation of erosion data can be challenging. The data presented are currently being validated through comparisons with national datasets and expert judgement. In this sense, zooming in on a specific locality can give the impression of a situation that differs from reality.

Source: European Soil Database v2.0 (soil), PRUDENCE (prudence.dmi.dk) (climate), Corine Land Cover 2000 (land cover).

Projections

Soil erosion rates and extent are expected to reflect changing patterns of land-use and climate change. Variations in rainfall patterns and intensity (see Section 2.2.5), and in storm frequency and intensity may affect erosion risk either directly, through the physical displacement of soil particles, or indirectly, through removing protective plant cover. However, reliable quantitative projections are currently not available.

Drier regions are likely to be more susceptible to wind erosion than wetter regions. In this context it is interesting to compare Map 3.22 and Map 3.24. The apparent inability of ecosystems to recover from repeated drought may result in increased risk of wind erosion.

3.5.4 Soil moisture

Relevance

The ability of soil to retain moisture is a significant aspect in the water cycle and is crucial for primary production (see Section 4.1). The amount of water held in soil is intrinsically linked to our climate and depends largely on texture, structure and the amount of soil organic matter. Variations in any of these variables will affect soil water retention characteristics and ultimately soil functions (e.g. groundwater recharge).

By absorbing many times its weight in water, soil organic matter in mineral soils can contribute to the mitigation of flooding following extreme rainfall events while storing water in the event of more frequent and severe droughts (Reicosky, 2005; Louwagie et al., 2009). At low soil carbon contents, an increase in carbon content leads to an increase in water retention in coarse soils and a decrease in fine-textured soils. At high carbon contents, an increase in carbon content results in an increase in water retention for all soil textures (Rawls et al., 2003).

While water-holding capacity is an intrinsic soil property based on clay content, structure and organic matter levels, water content is highly dynamic and is the balance between rainfall and evapotranspiration. Changes in temperature and precipitation patterns and intensity will affect evapotranspiration, soil moisture and infiltration rates. Conversely, there is also observational evidence that soil moisture deficit exacerbates hot extremes in south-eastern Europe (Hirschi et al., 2011).

Past trends

There is no clear indication on past trends for water retention across the EU due to a lack of systematic and harmonised data. Several models have been used to assess soil moisture, but these are often reliant on secondary input data (i.e. observed precipitation and temperature). Direct observations of spatially explicit distribution of soil moisture across Europe are just evolving. Satellite-borne sensors, such as the European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission or EUMETSAT's ASCAT Scatterometer, are able to make global observations of surface soil moisture (Map 3.23). Such data, along with numerical modelling techniques, have the potential to be used in deriving composite maps of soil moisture levels down to a depth of 1–2 m, the so-called root zone. Thus, this information could help in assessing the impacts of climatic variations, including droughts, on for example ecosystem production.

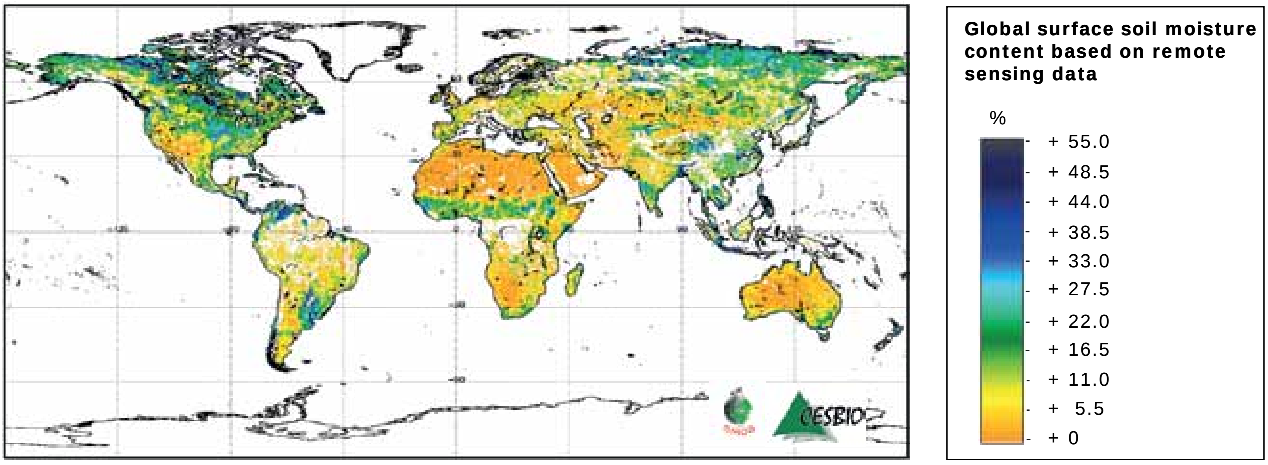
Projections

Projections indicate greater droughts in some areas, which might lead to substantial reductions in summertime soil moisture, and marked increase in rainfall in others (Calanca et al., 2006). In particular in the Mediterranean area of southern Europe, soil water content is expected to decline, and saturation conditions are expected to be increasingly rare and restricted to periods in winter and spring (García-Ruiz et al., 2011). Harmonised time series data on relevant soil properties should be developed as should models to assess key parameters such as subsoil available water capacity and topsoil moisture levels. Satellite information should be integrated with representative observed data, also for projections.

Key messages: 3.5.4 Soil moisture

- Soil water retention is a major soil hydrological property that governs soil functioning in ecosystems and greatly affects soil management.
- There is no clear indication on past trends for water retention across the EU due to a lack of systematic and harmonised data.
- Water retention capacity and soil moisture content will be affected by rising temperatures and by a decline in soil organic matter due to both changes in climate and land management.
- Projections (for 2071–2100) show a general reduction in summer soil moisture over most of Europe, significant reductions in the Mediterranean region, and increases in the north-eastern part of Europe.
- Maintaining water retention capacity and porosity are important to reduce the impacts of intense rainfall and droughts, which are projected to become more frequent and severe.

Map 3.23 Global surface soil moisture content based on remote sensing data



Note: SMOS provides a global image of surface soil moisture every three days; this map covers the period 8–15 June 2010. Yellow colours indicate drier soil surfaces; blue colours denote wetter conditions. SMOS can measure soil moisture levels to an accuracy of 4 % at a spatial resolution of 50 km — about the same as detecting a teaspoonful of water mixed into a handful of dry soil.

Source: European Space Agency (ESA) (http://www.esa.int/SPECIALS/smos/SEMSKJ6CTWF_0.html and http://www.cesbio.ups-tlse.fr/SMOS_blog/wp-content/uploads/2012/02/reprocessed-global-2012.png).

3.5.5 Biomass production and recurrent negative precipitation anomalies

Soil degradation processes are global phenomena that cause a reducing biophysical capacity in the land to sustainably produce ecosystems services and economic value. They are linked to complex patterns of land use and climatic variations. Observed changes in primary productivity of ecosystems are a strong indication of the onset or increasing vulnerability to soil degradation. As discussed in Section 3.5.2, organic matter is an important driver of several soil functions. A reduction in the production of biomass will have an impact on soil organic matter levels and related nutrient cycles. In particular the parallel reduction in the vegetative cover and plant roots will increase the risk of both wind and water erosion.

Climatic conditions and intensive agriculture make the Mediterranean region particularly vulnerable to soil degradation. Ever more demanding land use leads to water scarcity, limiting several ecosystem services normally provided by soil. Amplified variability of aridity limits the ability of intensively used human-environment systems to recover from specific pressures such as salinisation, drought and fire (see Section 4.1). In turn, this leads to an increase in soil degradation and, in extreme cases, desertification.

Map 3.24 presents areas affected by three recurrent negative precipitation anomalies over a period of 10 years, and as such provides a first indication of areas under risk of soil degradation. Many soil types in the Mediterranean region already show symptoms of degradation (i.e. shallow depth, low soil organic carbon content, prone to erosion, low fertility, increased salinity and forest fires) which, together with the hot, dry climate of the region, hampers the assessment of ongoing land degradation.

While the effects of reduced biomass production may be dramatic in the Mediterranean region, the consequences on soil resources may also be evident in more temperate or humid regions. Recent observations suggest that Mediterranean ecosystems are generally resilient and resistant to droughts. However, where human activity becomes too intense, degradation is more pronounced and can possibly become irreversible. Map 3.24 illustrates that, even after recurrent droughts, the Mediterranean environment recovers well, apart from areas that are under intense agricultural use and where the erosion risk is already high (see Map 3.21).

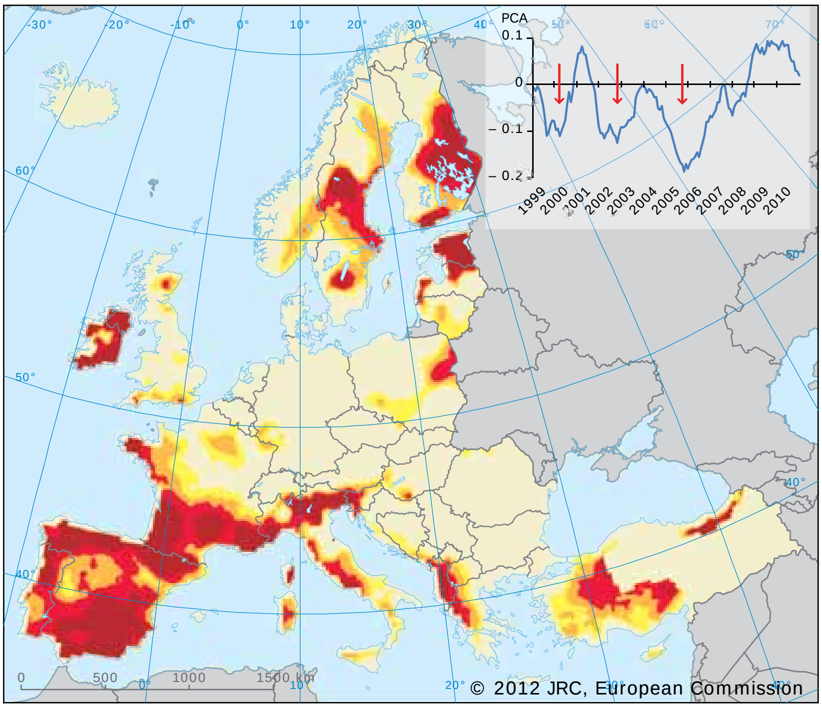
Projections are very limited. Increases in the recurrence of extreme events, such as droughts, combined with risks, such as forest fires, and an expansion of intensive land use will probably induce higher levels of degradation, including soil erosion and, in turn, reduce the quality and availability of natural resources and ecosystems services.

Key messages: 3.5.5 Biomass production and recurrent negative precipitation anomalies

- Biomass production is a major soil function and its decline can be used as a proxy for soil degradation.
- Recurrence of negative precipitation anomalies is leading to an increased risk of soil degradation due to the reduction of biomass, which is the main source of soil organic matter and protects soils from erosion.
- Soil degradation processes are already intense in several parts of the Mediterranean and in some parts of central-eastern Europe.
- In many cases, increased human pressure aggravated by climate change impacts can lead to irreversible soil degradation processes with adverse social, economic and environmental effects.
- Increase in recurrence of extreme climate events, such as droughts, combined with specific hazards, such as fires and both natural and human-induced salinity, and/or an expansion of intensive land use or land-use change, will probably induce higher levels of land degradation.

Map 3.24 Areas affected by three drought events and the effect of these events on ecosystem productivity

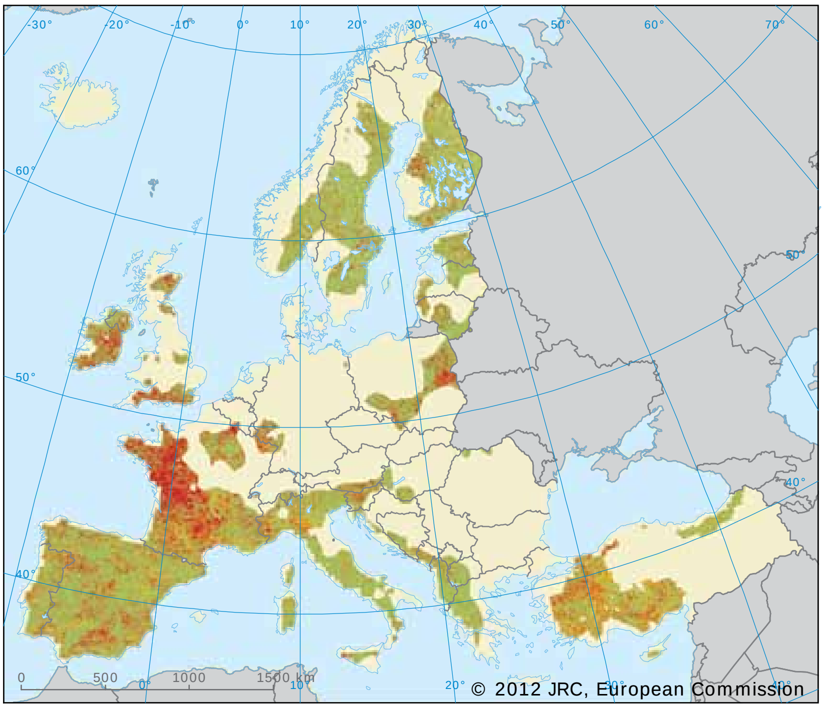
a)



Areas affected by three recent drought events (2000, 2003 and 2006)

- Weak
- Moderate
- Medium
- Strong
- No effect
- Outside coverage

b)



Effect of three recent drought events (2000, 2003 and 2006) on ecosystem productivity

- Strong negative
- Negative
- No effect
- No recent drought
- Outside coverage

Note: a) Areas affected by three recurrent negative precipitation anomalies (drought events, as indicated in the graph: 2000, 2003 and 2006 during the period 1999–2010 based on the standardised precipitation index, a statistical correlation to recurrent anomalies through principal component analysis (PCA) of time series climatic data). The prevalence of recurrent negative precipitation anomalies in the Mediterranean area is very apparent. Such anomalies can also affect areas with traditionally humid climates.

b) The effect of these events on ecosystem productivity based on a change index: the steadiness index. This index addresses both the long-term trend and the net change of primary production calculated from satellite time series over the period in which the recurrent negative precipitation anomalies occurred (1999–2010). The areas in red denote regions with a stronger likelihood of decreased productivity relative to the ecosystem capacity.

Source: Ivits, 2012 (personal communication).

4 Climate impacts on socio-economic systems and health

4.1 Agriculture

4.1.1 Overview

Relevance

The cultivation of crops, their productivity and quality, are directly dependent on different climatic factors. Climate change is already having an impact on agriculture (Peltonen-Sainio et al., 2010; Olesen et al., 2011), and has been attributed as one of the factors contributing to stagnation in wheat yields in parts of Europe despite continued progress in crop breeding (Brisson et al., 2010). Climate change is expected to continue to affect agriculture in the future (Olesen et al., 2011), and the effects will vary greatly in space across Europe (Trnka, Olesen, et al., 2011), but they may also change over time (Trnka, Eitzinger, et al., 2011). It is generally accepted that productivity will increase in northern Europe due to a lengthened growing season and an extension of the frost-free period (Olesen and Bindi, 2002). In southern Europe, climate change is likely to negatively affect the productivity of crops and their suitability in certain regions primarily due to extreme heat events and an overall expected reduction in precipitation and water availability (Iglesias et al., 2010). Year-to-year variability in yields is generally expected to increase throughout Europe, due to extreme climatic events and other factors, including pests and diseases (Ferrise et al., 2011; Kristensen et al., 2011).

There is a large variation across the European continent in climatic conditions, soils, land use, infrastructure, and political and economic conditions, which greatly influence the responsiveness to climatic change (Olesen et al., 2011; Trnka, Olesen, et al., 2011). Intensive farming systems in western and central Europe generally have a low sensitivity to climate change, because a given change in temperature or rainfall has modest impact, and because farmers have resources to adapt by changing management (Reidsma et al., 2010). However, there may be considerable difference in adaptive capacity between cropping systems and farms depending on their specialisation and other farm characteristics (Reidsma and Ewert, 2008).

Selection of indicators

The following indicators were chosen to evaluate selected impacts of climate change on agriculture:

- *Growing season for agricultural crops:* This indicator determines the suitability for growing agricultural crops as determined by temperature.
- *Agrophenology:* This indicator traces changes in the timing of the cycle of agricultural crops.
- *Water-limited crop productivity:* This indicator considers potential changes in crop productivity

Key messages: 4.1 Agriculture

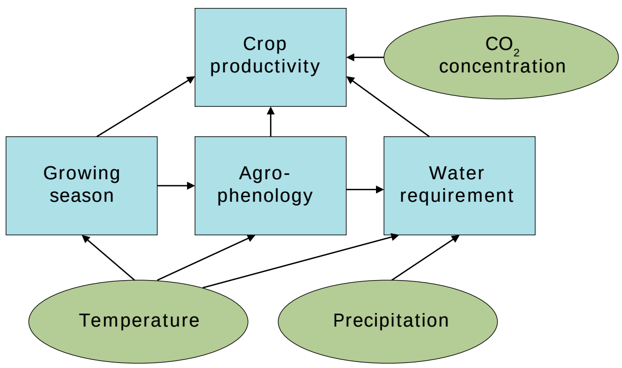
- An increase in the duration of the thermal growing season has led to northward expansion of areas suitable for several crops.
- Changes in crop phenology have been observed, such as advancement of flowering and harvest dates in cereals. These changes are expected to continue in many regions, leading to reductions in grain yield.
- Recent heat waves and droughts have greatly reduced the yield of some crops. The projected increase in the occurrence of such events would be particularly detrimental for crop production in central and southern Europe, where such events will occur more frequently and add to current stresses.
- Climate change is projected to improve the suitability for growing crops in northern Europe and to reduce crop productivity in large parts of southern Europe. Projections based on different climate models agree on the direction of the change, but with some variation in its magnitude.

caused by changes in temperature, rainfall and atmospheric CO_2 concentration.

- *Water requirement for irrigation:* This indicator estimates the water needs for maintaining maximum crop yields, thereby assessing the adaptation needs of agricultural water supply.

The indicators were chosen based on various criteria, including the availability of relevant data across Europe and the ability to identify the main drivers of agricultural change to inform the design of adaptation policy. Figure 4.1 illustrates the links between these indicators and the driving climatic and atmospheric variables. Impacts on livestock are not explicitly included in this report for two reasons. First, effects on livestock are mostly indirect through feed production, and as such effects are covered with the indicators covering water-limited crop productivity and water requirement for irrigation. Second, there is little direct evidence of climate change effects on livestock, except for changes in livestock diseases related to climate change, and this has not been included as an indicator.

Figure 4.1 Links between climatic drivers and agricultural indicators



Data quality and data needs

Effects of climate change on the growing season and crop phenology can be monitored directly, partly through remote sensing (growing season) and partly through monitoring of specific phenological events such as flowering. There is no common monitoring network for crop phenology in Europe, and data on this therefore has to be based on various national recordings, often from agronomic experiments (Olesen et al., 2012). Crop yield and crop requirements for irrigation are not only affected by climate change, but also by management and a range of socio-economic factors. The effects of climate change on these factors therefore have to be estimated indirectly using agrometeorological indicators and through statistical analyses between climatic variables and factors such as crop yield.

The projections of climate change impacts and adaptation in agriculture rely heavily on modelling, and it needs to be recognised that there is often a chain of uncertainty involved in the projections going from emission scenario, through climate modelling, downscaling and to assessments of impacts using an impact model (Olesen et al., 2007). The extent of all these uncertainties is rarely quantified, even though some studies have assessed uncertainties related to individual components. The crop modelling community has only recently started addressing uncertainties related to modelling impacts of climate change on crop yield and effect of possible adaptation options (Rötter et al., 2011), and so far only few studies have involved livestock systems. Future studies also need to better incorporate effects of extreme climate events as well as biotic hazards (e.g. pests and diseases).

4.1.2 Growing season for agricultural crops

Relevance

The thermal growing season is a basic agrological indicator for where and when crops can potentially be grown, assuming sufficient water, radiation and suitable soils. The duration of the growing season is for a large part of Europe defined by the duration of the period with temperatures above a certain threshold. The duration of the frost-free season is considered the period favourable for growth of many plant species (e.g. for flowering). However, active growth of plants requires higher temperatures, and for most of the temperate crops grown in Europe a threshold temperature of 5 °C can be used (Trnka, Olesen, et al., 2011).

Past trends

Increasing air temperatures are significantly affecting the duration of the growing season over large areas of Europe (Scheifinger et al., 2003). Many studies report a lengthening of the period between the occurrence of the last spring frost and the first autumn frost. This has occurred in recent decades in several areas in Europe and more generally in the Northern Hemisphere (Trnka, Brázdil, et al., 2011). Studies of changes in the growing season based on remote sensing show a diverse spatial pattern in Europe (Schwartz et al., 2006). Across all of Europe, the delay in end of the season of the period 1992–2008 by 8.2 days was more significant than the advanced start of the season by 3.2 days (Jeong et al., 2011).

An analysis of the frost-free period in Europe between 1975 and 2010 shows a general and clear increasing trend. The trend is not uniformly spread over Europe. The highest rates of change (larger than 0.8 days per year) were recorded along the Atlantic shores, in the British Isles, Denmark, central parts of Europe, central Italy, central and southern Spain, and in Turkey (Map 4.1). There are also areas in Europe with an apparent trend for reductions in the frost-free period; however, these trends are not significant.

Projections

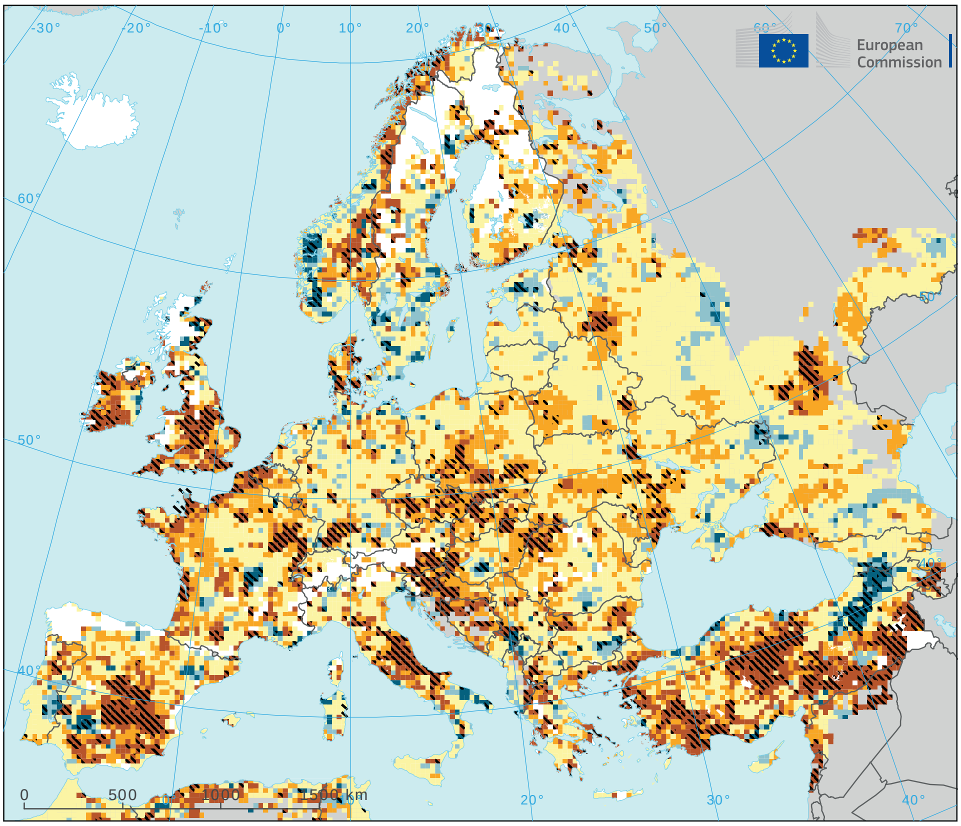
A warming of the climate is expected mainly to result in an earlier start of the growing season in spring and a longer duration in autumn (Jeong et al., 2011). A longer growing season allows the proliferation of species that have optimal conditions for growth and development and can thus increase their productivity or number of generations (e.g. crop yield, insect population). This will in many cases also allow for introduction of new species previously unfavourable due to low temperatures or short growing seasons. This is relevant for introduction of new crops, but will also affect the spreading of weeds, insect pests and diseases (Roos et al., 2010).

A further lengthening of the growing season as well as a northward shift of species is projected as a result of the projected further increase in temperature across Europe (Olesen et al., 2011). The date of last frost in spring is projected to advance by about 5–10 days by 2030 and by 10–15 days by

Key messages: 4.1.2 Growing season for agricultural crops

- The thermal growing season of a number of agricultural crops in Europe has lengthened by 11.4 days on average from 1992 to 2008. The delay in the end of the growing season was more pronounced than the advance of its start.
- The growing season is projected to increase further throughout most of Europe due to earlier onset of growth in spring and later senescence in autumn.
- The projected lengthening of the thermal growing season would allow a northward expansion of warm-season crops to areas that were not previously suitable.

Map 4.1 Change in the number of frost-free days per year during the period 1975–2010



Rate of change of growing season length, 1975–2010

Frost-free days/year

- < – 0.8
- – 0.8 to – 0.4
- – 0.4 to 0.4
- 0.4 to 0.8
- > 0.8

Statistical significance

- 0.10

- No data
- Outside coverage

Source: MARS/STAT database.

2050 throughout most of Europe (Trnka, Olesen, et al., 2011). The suitability for growing certain crops will also depend on the total amount of heat received during the growing season expressed as a temperature sum. Projections show the greatest absolute increases in temperature sum in southern Europe, whereas relative changes are much larger in northern than in southern Europe (Trnka, Olesen, et al., 2011).

The extension of the growing season is expected to be particularly beneficial in northern Europe, where new crops could be cultivated and where water availability is generally not restricting growth (Olesen et al., 2011). In parts of the Mediterranean area the cultivation of some crops may shift from the summer season to the winter season, which could offset some of the negative impacts of heat waves and droughts during summer (Minguez et al., 2007). Other areas of Europe, such as western France and parts of south-eastern Europe, will experience yield reductions from hot and dry summers without the possibility of shifting the crop production into the winter seasons.

4.1.3 Agrophenology

Relevance

Changes in crop phenology provide important evidence of responses to recent regional climate change (Menzel et al., 2003). Although phenological changes are often influenced by management practices, in particular sowing date and choice of cultivar, recent warming in Europe has clearly advanced a significant part of the agricultural calendar. Specific stages of growth (e.g. flowering, grain filling) are particularly sensitive to weather conditions and critical for final yield. The timing of the crop cycle (agrophenology) determines the productive success of the crop. In general, a longer crop cycle is strongly correlated with higher yields, since a longer cycle permits better use of the available thermal energy, solar radiation and water resources.

Past trends

Changes in the phenological phases of several perennial crops in Europe, such as the advance in the start of the growing season of fruit trees (2.3 days/10 years), cherry tree blossom (2.0 days/10 years) and apple tree blossom (2.2 days/10 years), in line with increases of up to 1.4 °C in mean annual air temperature have been observed in Germany during 1961–2000 (Chmielewski et al., 2004). Sowing or planting dates of several agricultural crops have been advanced, for example by 5 days for potatoes in Finland (1965–1999), 10 days for maize and sugar beet in Germany (1961–2000) and 20 days for maize in France (1974–2003) (IPCC, 2007).

An analysis of the modelled flowering date for winter wheat in Europe between 1975 and 2010 shows a general and clear increasing trend, which is most pronounced in north-western Europe (Map 4.2). In parts of Europe the modelled flowering date has advanced by 0.3–0.5 days per year. This modelled advance in flowering date probably exceeds what is observed in reality, as day length responses in the plants and farmers' choices of cultivars with longer growth duration will reduce this response.

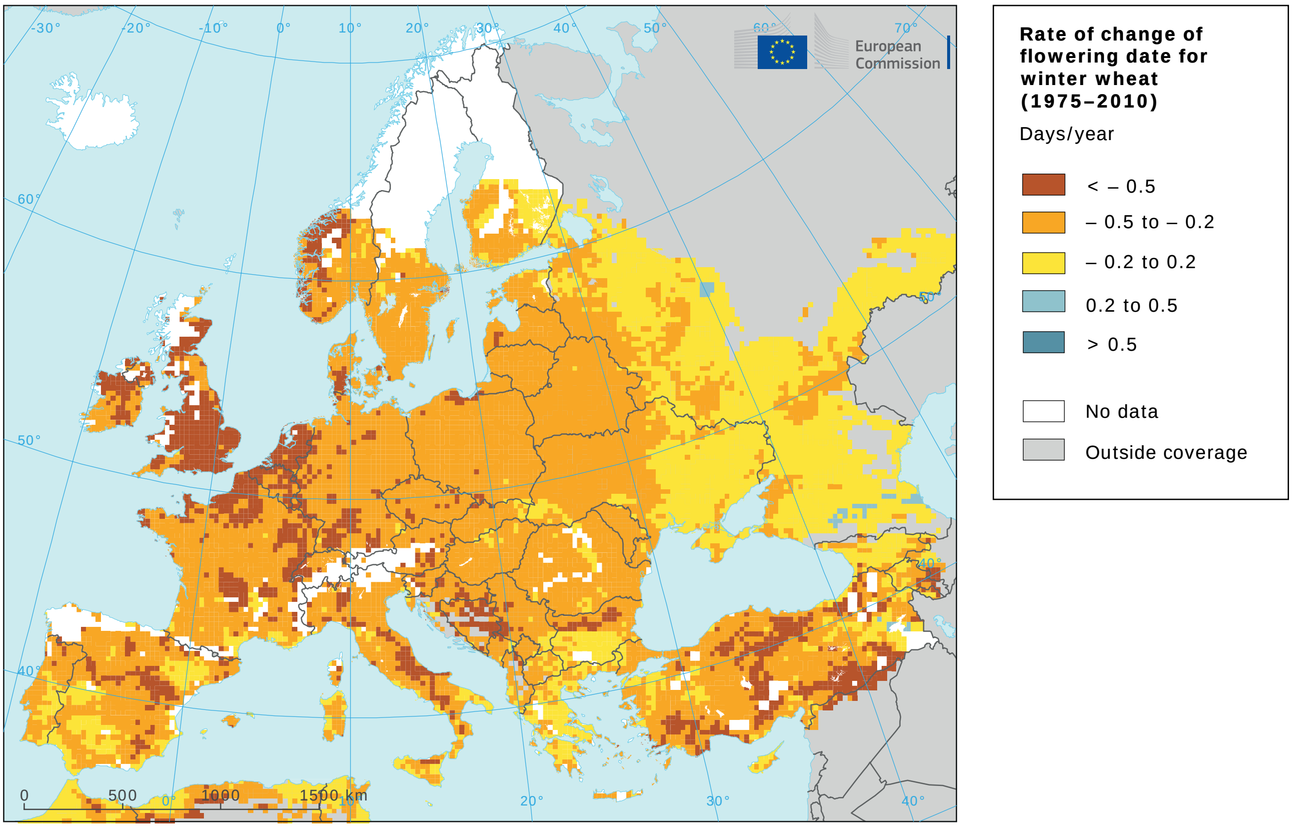
Projections

With the projected warming of the climate in Europe, further reductions in the number of days required for flowering in cereals and maturity may be expected throughout Europe (Map 4.3). The modelled changes in flowering dates in Map 4.3 include the expected effects of changes in cultivar choice on flowering and maturity dates. Since many plants (including cereals) in Europe require long days to flower, the effect of warming on date of flowering is smaller than would otherwise be expected. The flowering date for winter wheat is projected to show the greatest advance in western parts of Europe, but with a large uncertainty due to uncertainty in the underlying climate change projections. The advance in maturity date is larger than the advance in flowering date, leading to a shortening of the grain filling period, which will negatively affect yields. An independent study with a different phenology model and other climate change projections found similar advances in flowering date for winter wheat for England and Wales (14–16 days by 2050) (Semenov, 2009).

Key messages: 4.1.3 Agrophenology

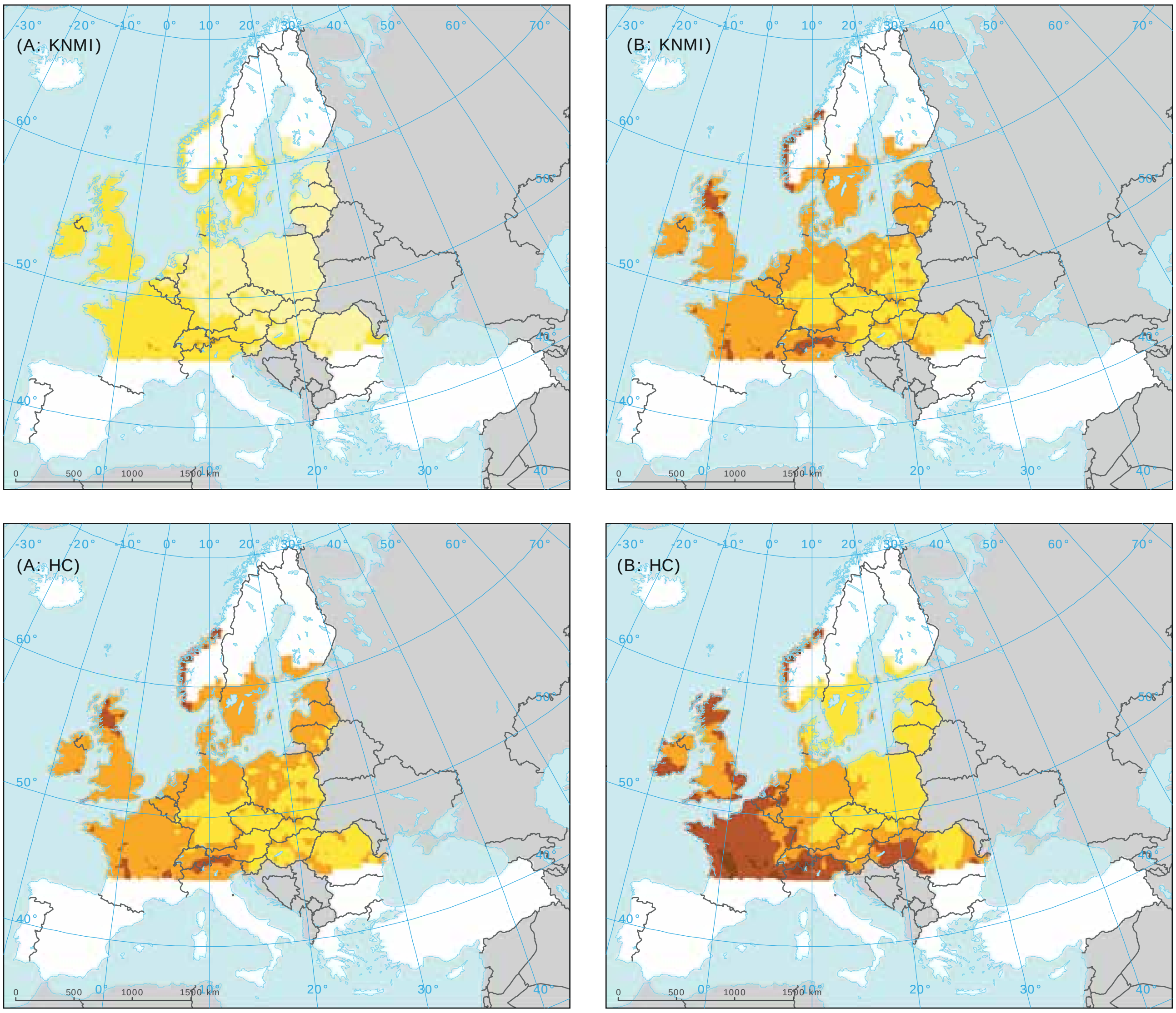
- Flowering of several perennial crops has advanced by about two days per decade in recent decades.
- Changes in timing of crop phenology are affecting crop production and the relative performance of different crop species and varieties.
- The shortening of crop growth phases in many crops is expected to continue. The shortening of the grain filling phase of cereals and oilseed crops can be particularly detrimental to yield.

Map 4.2 Change of flowering date for winter wheat (1975–2010)



Source: MARS/STAT database.

Map 4.3 Projected change in dates of flowering and maturation for winter wheat



Projected change in dates of flowering (A) and maturation (B) for winter wheat

Days

– 25 to – 20 | – 20 to – 15 | – 15 to – 10 | – 10 to – 5 | – 5 to 0 | 0 to 5 | No data or no cropping baseline | Outside coverage

Note: Model estimated mean change in dates of flowering and full maturation for winter wheat for the period 2031–2050 compared with 1975–1994 for the RACMO (KNMI) and HadRCM3 (Hadley Centre.HC) projections under the A1B emission scenario.

Source: Fels-Klerx et al., 2012.

4.1.4 Water-limited crop productivity

Relevance

Crop biomass production derives from the capture and conversion of solar energy through the process of photosynthesis. However, this process may be restricted by low (or high) temperatures or by water limitations. (Trnka, Olesen, et al., 2011) developed a simple index by which the effective annual radiation for plant growth was estimated by summing daily contributions of solar radiation on days with mean temperature above 5 °C, minimum temperature above 0 °C and sufficient soil water for supporting crop transpiration. In practice the response depends on soil type that may have large differences in capacity for storing soil moisture and on possibilities for supplementary irrigation. Crop yield also depends on the timing of the crop growth and yield formation. Yields in cereal and oilseed crops respond particularly to the duration of the grain filling period (Kristensen et al., 2011). The impacts of unfavourable meteorological conditions and extreme events vary considerably, depending on the timing of occurrence and the development stage of the crops (Moriondo et al., 2011). Changes in the occurrence of extreme events such as heat waves, droughts, heavy precipitation and floods will greatly affect crop yield leading to increased variability and economic consequences (Ciscar et al., 2011).

Past trends

A global analysis of yields of cereal crops (wheat, maize and barley) has shown yield decreases due to increasing mean temperatures (Lobell and Field, 2007). Similar effects have been observed for various countries in Europe (Kristensen et al., 2011). Increasing temperatures have also been attributed as one of the main causes for the lack of yield increase of winter wheat in France despite improvements in crop breeding (Brisson et al., 2010). Grain yields in maize have been steadily increasing in northern Europe, whereas yields in southern Europe seem to have been stagnating. There is also a tendency for increasing variability of grain yields in France and Italy, linked to occurrence of heat waves and droughts (Olesen et al., 2011). These climatic extremes affected the crop production in large areas of southern and central Europe in 2003 and 2007. In contrast to cereals and oilseed crops, potato and sugar beet seem to have responded positively to the increasing temperatures by increasing yields, most likely due to longer growing seasons (Peltonen-Sainio et al., 2010).

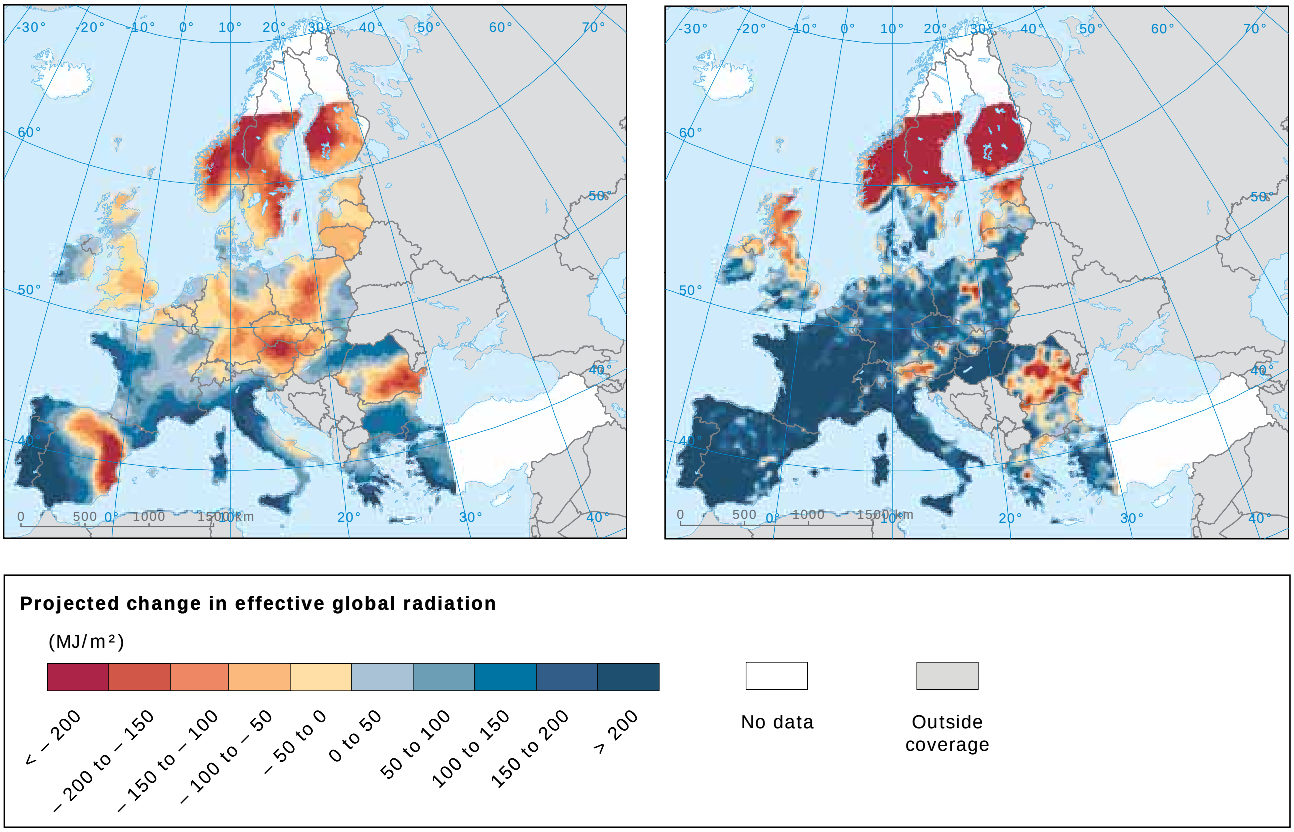
Projections

The impact of future changes in climate on crop yield depends on the characteristics of the climatic change within a region as well as on a combination of other environmental, economic, technological and management factors (Reidsma et al., 2010). The index of effective solar radiation sum has been developed as a proxy for the effects of environmental changes on crop productivity (Trnka, Olesen, et al., 2011)), and it integrates the daily solar radiation on those days where neither temperature nor soil moisture is limiting for growth. This index estimates the potential for rain-fed crop production using a standard soil across the entire continent, although this may be greatly modified by local soil conditions. Map 4.4 shows the projected changes in effective radiation sum for the 2040s for climate projections from two different climate models. Both projections show reduced production potential in large parts of southern Europe and increases in the far north, but they differ substantially for areas in-between. A broader analysis of climate change scenarios for agricultural productivity in Europe has provided a clear picture of deterioration of agroclimatic conditions from increased drought

Key messages: 4.1.4 Water-limited crop productivity

- Yields of several crops (e.g. wheat) are stagnating, whereas yields of other crops (e.g. maize in northern Europe) are increasing; both effects are partly due to the observed climatic warming.
- Extreme climatic events, including droughts and heat waves, have negatively affected crop productivity during the first decade of the 21st century, and this is expected to further increase yield variability under climate change.
- Crop yields will be affected by the combined effects of changes in temperature, rainfall and atmospheric CO_2 concentration. Future climate change can lead to yield decreases or increases, depending on crop type and with considerable regional differences across Europe.

Map 4.4 Projected changes in effective solar radiation from two climate models



Note: Mean changes in effective solar radiation (MJ/m²), which is an indicator for water-limited crop productivity, for the period 2031–2050 compared with 1975–1994 for the RACMO (KNMI) and HadRCM3 (Hadley Centre.HC) projections under the A1B emission scenario.

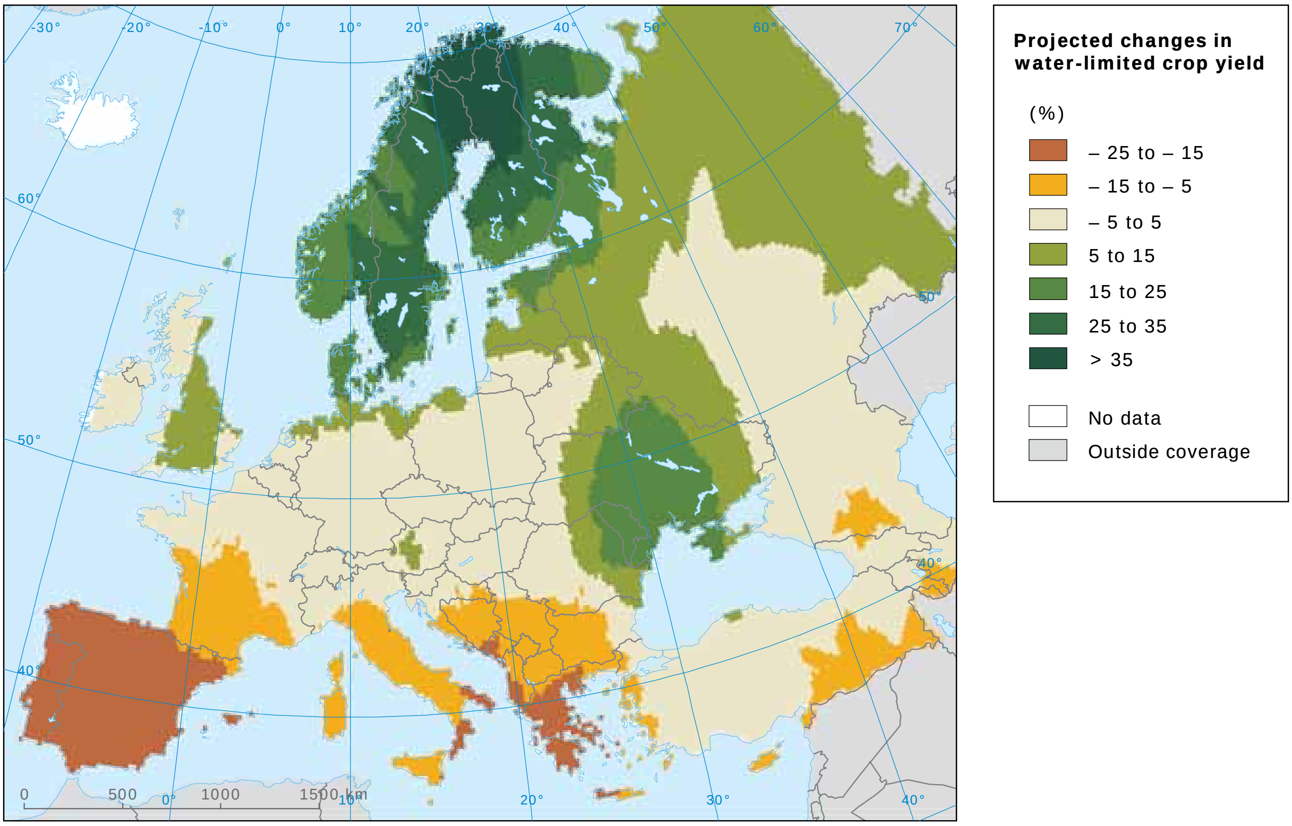
Source: J.E. Olesen, 2012 (personal communication).

stress and a shortening of active growing season across large parts of southern and central Europe (Trnka, Olesen, et al., 2011). Results also suggest a risk of an increasing number of unfavourable years for agricultural production in many European climatic zones, resulting in increased variability of crop yield from droughts and heat waves.

The estimates shown in Map 4.4 do not consider the effects of enhanced atmospheric CO_2 levels on crop productivity. The ClimateCrop model was applied to explore the combined effects of projected changes in temperature, rainfall and CO_2 concentration across Europe, considering certain management changes thus incorporating effects of adaptation. The mean projected changes in Map 4.5 show the same overall picture as Map 4.4 of decreases in yields along the Mediterranean and large increases in Scandinavia. However, throughout large parts of western and central Europe mean changes in crop yields are likely to be small.

Map 4.6 shows changes in water-limited wheat production in Europe by 2030 for climate projections from two different climate models (Donatelli et al., 2012). The results that also include effects of enhanced CO_2 concentrations indicate that different climate models can lead to large differences in projected impacts, with both yield increases and decreases possible in northern and southern Europe. The same study showed large differences in simulated yield changes between different crops, climate model projections and time horizons. Neither of these model estimates considers adaptation to climate change, such as changes in crop species and varieties and changes in crop management. It is therefore likely that negative yield impacts will be smaller and positive effects bigger following adaptation in the farming systems.

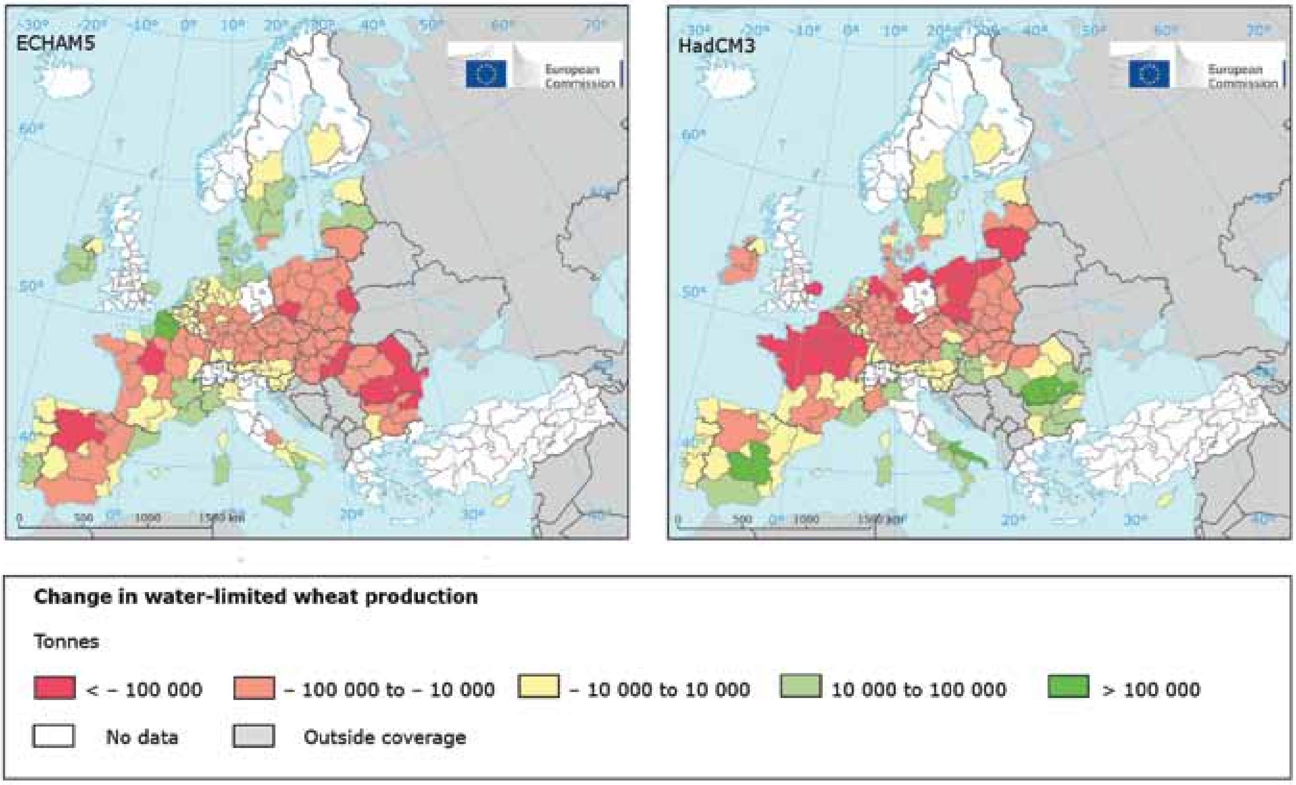
Map 4.5 Projected changes in water-limited crop yield



Note: Mean relative changes in water-limited crop yield simulated by the ClimateCrop model for the 2050s compared with 1961–1990 for 12 different climate models projections under the A1B emission scenario.

Source: Iglesias et al., 2011.

Map 4.6 Simulated change in water-limited wheat production for 2030 based on two climate models



Note: Simulated change in water-limited wheat production for 2030 compared with 2000 for the A1B emission scenario using a cold (ECHAM5) (left) and a warm (HADCM3) (right) climate change projection.

Source: Donatelli et al., 2012.

4.1.5 Irrigation water requirement

Relevance

Water is essential for plant growth and there is a relationship between plant biomass production and transpiration, with the water-use efficiency (biomass production per unit water transpired) being affected by crop species as well as management. Increasing atmospheric CO_2 concentration will lead to higher water use efficiency through reductions in plant transpiration (Kruijt et al., 2008) and increased photosynthesis (Ainsworth and Long, 2005). Higher temperatures and lower relative humidity leads to higher evaporative demands, which reduces the water-use efficiency. The resulting effect of climate change on water-use efficiency is therefore a combination of changes in temperature and atmospheric CO_2 concentration as well as changes in crop choice and management. The water demand by crops must be met through rainfall during the growing period, from soil water storage or by irrigation. In drought prone areas, increasing demands for water by industrial and urban users intensify the competition for water for irrigation in agriculture (Iglesias et al., 2007).

Past trends

Consistent observations of water demand for agriculture do not currently exist for Europe but past trends can be estimated on the basis of meteorological data. Map 4.7 estimates the change in the water balance, which is the difference between a reference evapotranspiration and the rainfall. This indicator provides only a rough proxy for changes in irrigation demand, because actual irrigation demand is determined by the crops grown, the type of irrigation applied and the local soil conditions. In the period considered (1975–2010), the Iberian Peninsula and Italy experienced an increase in the volume of water required for irrigation, if yields of irrigated crops were to be maintained, whereas parts of south-eastern Europe have experienced a decrease.

Projections

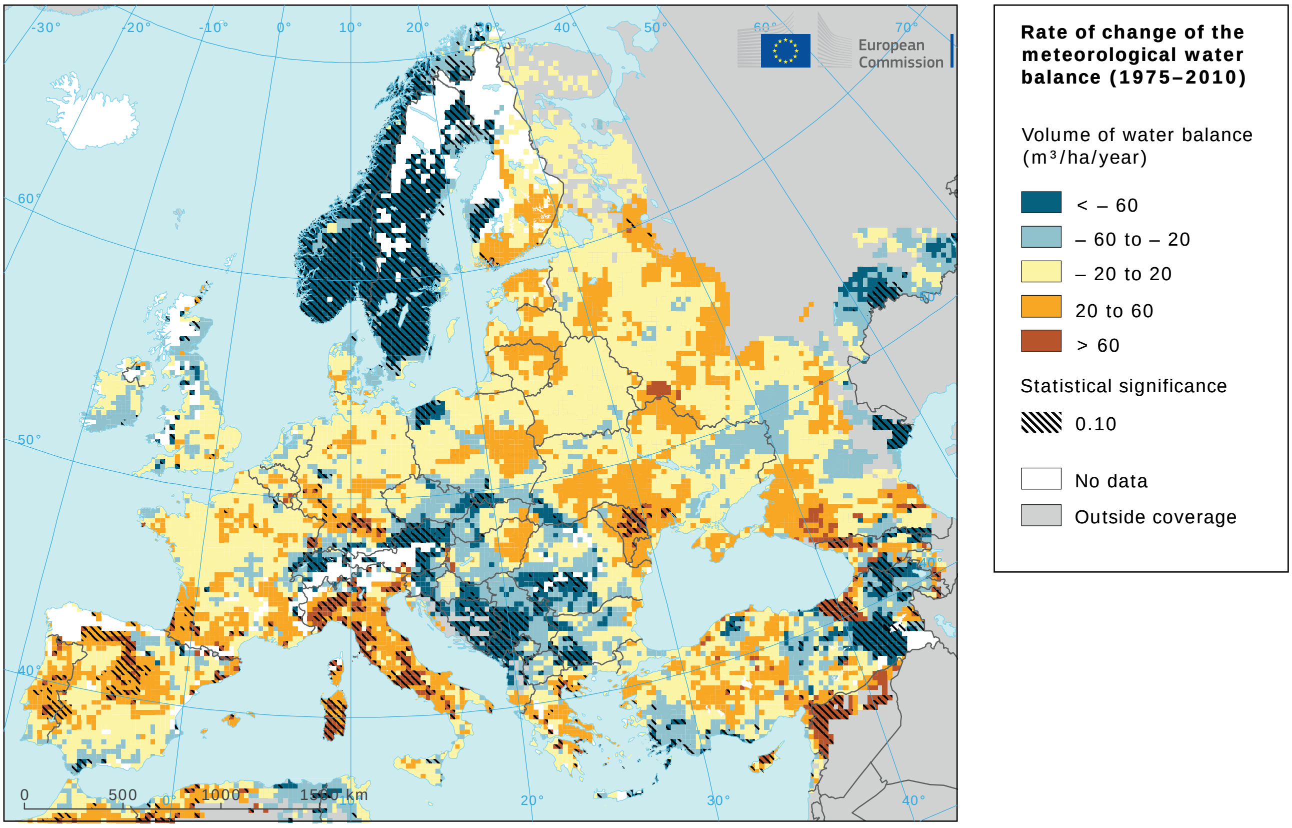
No projections of changes in irrigation demand are available for Europe. Many climate change projections show a consistent increase in the number of dry days in spring and summer in much of southern and central Europe (Trnka, Olesen, et al., 2011). In some of the severe climate change scenarios the increase in the number of dry days in summer even extends far into northern Europe. The increasing temperatures will increase the evaporative demand, which would be further increased if the higher frequency of dry days leads to lower relative humidity and reduced cloud cover. These effects will only be partly compensated by the reduced crop transpiration under higher CO_2 concentrations (Olesen et al., 2007).

The expected increasing evapotranspiration will put pressure on the use of irrigation in drought-prone areas. Irrigation in Europe is currently concentrated along the Mediterranean, where some countries use more than 80 % of total freshwater abstraction for agricultural purposes (EEA, 2009). The increasing demand for irrigation will therefore increase the competition for water, in particular where total water availability declines due to reduced precipitation. Assuming that urban water demands would have preference over agricultural purposes, the proportional reduction of water availability for irrigation in many European basins is larger than the reduction in annual run-off (Map 4.8) (Iglesias et al., 2012). Projections for the Mediterranean region show a considerable decline in water availability, which in some areas makes current irrigation practices impossible in the future.

Key messages: 4.1.5 Irrigation water requirement

- In the Iberian Peninsula and Italy, an increase in the volume of water required for irrigation from 1975 to 2010 has been estimated, whereas parts of south-eastern Europe have recorded a decrease.
- The projected increases in temperature will lead to increased evapotranspiration rates, thereby increasing crop water requirements across Europe.
- The impact of increasing water requirements is expected to be most acute in southern Europe, where the suitability for rain-fed agriculture is projected to decrease and irrigation requirements are projected to increase.

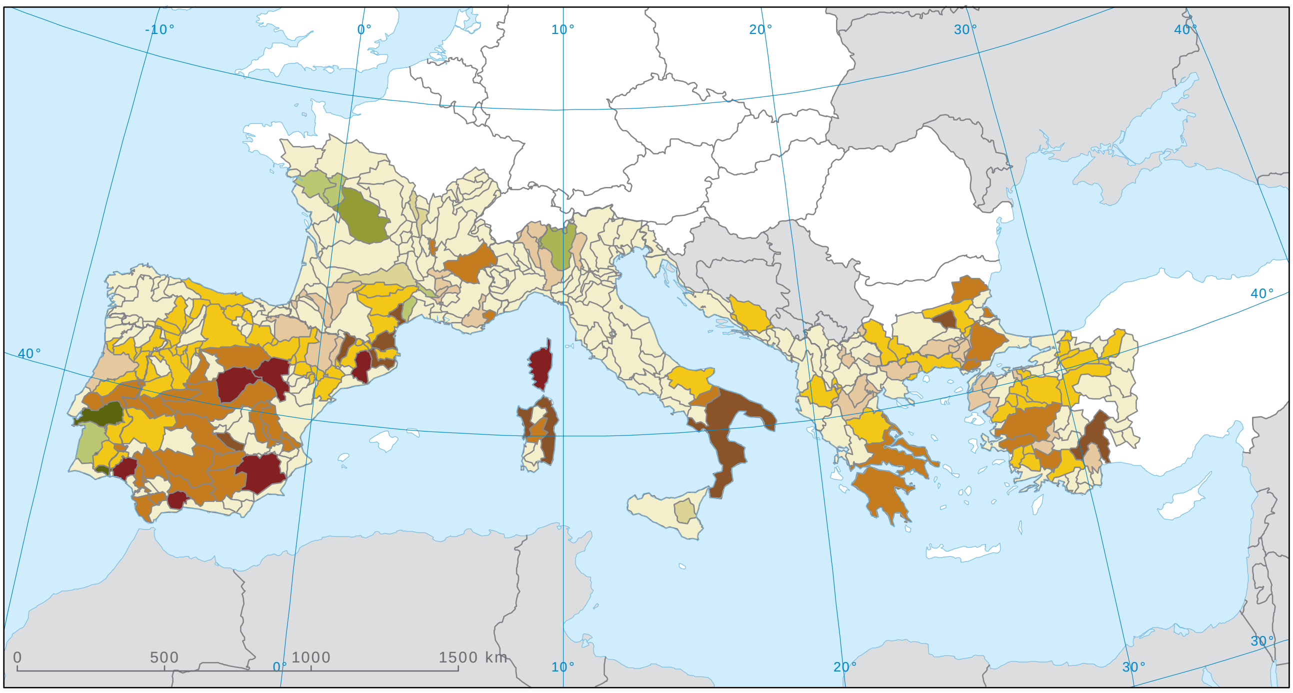
Map 4.7 **Rate of change of the meteorological water balance (1975–2010)**

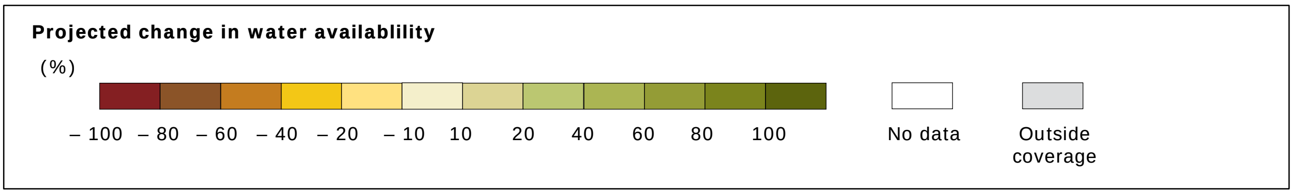


Note: The map provides an estimate of the increase (brown in map) or decrease (blue in map) of the water volume required for irrigation assuming that all other factors are unchanged and given that there is an irrigation demand.

Source: MARS/STAT database.

Map 4.8 Projected change in water availability for irrigation in the Mediterranean region by 2071–2100





Note: Relative change in water availability for irrigation as projected under the A1B emission scenario by the HIRHAM (DMI) regional climate model for 2071–2100 relative to 1961–1990.

Source: Iglesias et al., 2012.

4.2 Forests and forestry

4.2.1 Overview

Relevance

Forests are defined as ecosystems dominated by trees and other woody vegetation. They cover more than 40 % of all land area in Europe and are as such one of the main terrestrial ecosystems. Forestry describes the management of forest land including cultivation, maintenance and development of forests.

Forests provide a wide range of benefits and services to their owners, managers and beneficiaries (Forest Europe, UNECE and FAO, 2011). Forests in Europe provide societies with products such as timber, wood fibre and energy, with recreational opportunities as well as multiple ecosystem services, including biodiversity, clean water and air (Bredemeier, 2011). Forests are the most species-rich terrestrial ecosystem and they are a main element of European nature. Because of their structural complexity, they provide ideal habitats for a high number of plants, birds and animals. In mountain areas, forests protect settlements and infrastructure from, for example, landslides and avalanches. Forests regulate water flows and reduce floods, and protect from wind, sand drift and noise. Forests offer good protection from soil erosion and degradation, which is important especially in mountainous, hilly and semi-arid areas. Forests play an important role for climate regulation and for the global C cycle as they store a considerable amount of terrestrial carbon. Forests and forestry play a key role in the long-term mitigation of and adaptation to climate change. Both forest management and land use are central elements in the existing climate regime and in negotiations of future climate policies. Furthermore, forest-related jobs and revenues contribute to national economies, which may be threatened by climate change (Hanewinkel et al., 2012).

Climate and weather have a strong influence on the processes that control forest structure and function, and thus on forest health. Climate change is projected to impact on forests by increasing threats such as pest outbreaks, fires and drought. Increased temperatures, changes in precipitation amounts and patterns, and changed composition of the atmosphere are all expected to have impacts on forests. Total seasonal precipitation as well as its pattern of variability are both of major importance for forestry systems (Olesen and Bindi, 2002; Lindner et al., 2010). Extreme events including droughts, flooding, storms and heat waves are expected to become more frequent in parts of Europe (see Sections 2.2 and 3.4).

Various extreme climatic events like the 2003 drought in large parts of Europe and severe windstorms already had strong negative impacts on forests (Ciais et al., 2005; Usbeck et al., 2010). Storms, droughts and heat waves can lead to higher rates of tree mortality, and make forests more susceptible to secondary damages, such as insect and fungal infestations. Forests are strongly affected by a range of insects and invasive species. Insect and pathogen outbreaks are generally facilitated by a warming climate. As forest ecosystems change and move in response to climate changes, they are expected to become more vulnerable to disturbances. Since the latitudinal (and altitudinal) distribution of forest species is strongly determined by climatic conditions, a changing climate will have an impact on which tree species can survive, and where.

Key messages: 4.2 Forests and forestry

- Forests provide multiple goods and services, including wood supply, carbon accumulation, ecosystems services, water purification, protection against natural hazards and recreational services.
- Forests in Europe have been accumulating carbon (C) at a rate of more than 100 million tonnes (Mt C) per year from 1990 to 2010.
- Climate change is expected to have major impacts on forest ecosystems. Rising atmospheric CO_2 concentration, higher temperatures and changes in precipitation are likely to have significant effects on the vegetation period, growth, health and distribution of trees as well as on forest ecosystems, and thus on the goods and services provided by forests.
- Climate change may also enhance the frequency of favourable conditions for forest fires extending the fire season in both time and space.
- An increase in storms, droughts and heat waves can lead to higher rates of tree mortality, and make forests more susceptible to secondary damages, such as insect and fungal infestations.

Impacts of climate change, combined with increasing atmospheric CO_2 concentrations, on forests vary across regions. In some areas, forests may grow faster as a result of increased availability of CO_2 and higher temperature (and concurrent increases in nitrogen availability). In others areas, especially those receiving less precipitation, forests may suffer and experience decreased growth. Climate change may also enhance the frequency of favourable conditions for forest fires extending the fire season in both time and space. The unique adaptation of boreal forests makes them more sensitive to temperature fluctuations than temperate or other forests. Even a slight increase in mean annual temperature is enough to affect many species' growth and regeneration. The boreal forest is likely to decrease in area, biomass and carbon stock, with a significant disruption at its southern boundary but the northern border line will move further north (Olsson, 2009; Hanewinkel et al., 2012).

Selection of indicators

This section presents the following indicators that capture climate-sensitive characteristics of forests that are relevant for forest management:

- *Forest growth:* This indicator describes the extent of forests (i.e. their area) as well as the growing stock (i.e. the volume of the aboveground biomass of all living trees). The definitions refer to the Forest Europe definitions (Forest Europe, UNECE and FAO, 2011). These definitions are currently being refined by the European National Forest Inventory network (ENFIN) to allow for better comparison of forest-related information across Europe.

- *Forest fires:* This indicator monitors the areas burnt by forest fires, which are experienced in many European countries, in particular in southern Europe. Climate change may lead to more forest fires due to warmer and drier weather, and possibly increases in lightning storms (a natural cause of fires).

Forest carbon stock would be another potential indicator related to forests. The forests in EEA Europe contain more than 26 000 Mt C; about half of that amount is stored in soils (Forest Europe, UNECE and FAO, 2011). Furthermore, temperate and boreal forests are the main terrestrial carbon sink worldwide (Houghton, 2003). Biomass growth in European forests (including also countries beyond the EEA region) is estimated to sequester about 10 % of the GHG emissions from that region. Climate-driven changes in the forest carbon stock are a potential feedback mechanism that could either accelerate or slow down anthropogenic climate change. A comprehensive assessment of the state of Europe's forests, including their carbon stock, has recently been completed (Forest Europe, UNECE and FAO, 2011). This assessment concluded, among others, that the carbon stock of European forests is currently growing, at a rate of more than 100 Mt C per year between 1990 and 2010. This increase is due to changes in forest management and environmental changes including climate, CO_2, and nitrogen deposition. In order not to repeat information ready available elsewhere, this EEA report does not present an indicator on forest carbon stock but refers to the original study for more detailed information. Finally, an indicator on *forest health* could be conceived (Moore and Allard, 2008) but such information is not currently available across Europe.

Data quality and data needs

Forest areas of most European countries are inventoried by National Forest Inventories (NFIs) as well as by the monitoring activities of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests ([55])). Time series of forest data go back to more than 100 years for some European countries. Independent periodic assessments of forest area, growing stock and increment as well as carbon stock are conducted through systematic observation with statistically designed sampling based on the NFIs. The quality of the data is high. However, the estimates of the inventory of each country may differ due to differences in the definition of the variables. Harmonisation efforts are ongoing to make the forest information comparable and representative of the forests in Europe. The work is conducted by the ENFIN in COST Actions E43 and FP1001 (McRoberts et al., 2010).

It is very difficult to separate the impacts of climate change on forests and forestry from non-climate influences (e.g. related to management) in observational data. Therefore, efforts to understand the impacts of climate change on forests and forestry are largely based on controlled experiments in laboratories and on small forest plots, and on model simulations.

([55]) See http://icp-forests.net.

Information on forest fires is collected in the European Fire Database at the JRC. The European forest fire database is an important component of the European Forest Fire Information System (EFFIS). Forest fire data are provided each year by individual EU Member States through several EU regulations, and additional data coming from other European countries have been checked, stored and managed by JRC within EFFIS. The quality of the data is high. A time series on forest fires exists back to 1980 for the five European countries most affected by forest fires. Currently, the database covers data from 22 countries in Europe and contains over 2 million individual fire event records.

4.2.2 Forest growth

Relevance

Tree growth is controlled by complex interactions between climate and non-climate factors, with forest management having a significant effect. Trees have long been known to respond to changes in climate: variations in tree ring widths from one year to another are recognised as an important source of climatic information although difficult to interpret. Climate change is expected to influence forest composition and productivity (see Table 4.1). Increases in atmospheric CO_2, changes in temperature and the availability of water will affect the relative health and productivity of different species in complex ways. CO_2 has a direct impact on tree function and forest productivity. An increased concentration in the atmosphere stimulates photosynthesis and likely results in an increase in growth rates and leaf area, if other factors are not limiting. Increased temperatures generally speed up plant growth, rates of decomposition and nutrient cycling, though other factors like availability of water also influence these processes. Higher temperatures lengthen the growing season by advancing its start in spring and delaying its end in fall.

Climate change is expected to present several threats to forest growth and productivity such as increased frequency and severity of summer drought with impacts on drought-sensitive tree species, in particular on shallow, freely draining soils (Houghton, 2003; Melillo et al., 2011). Indirect effects on forest productivity are expected through changes to the frequency and severity of pest and disease outbreaks, increasing populations of damaging insects and mammals, and the impact of existing and new invasive species. Concurrent changes in nitrogen and sulphur deposition and increased levels of ozone pollution are also expected to have an impact. Nitrogen deposition can stimulate forest growth but it can also increase the susceptibility of trees to drought, diseases, pests and frost by causing acidification and nutrient imbalances, thus decreasing forest vitality. Based on the current understanding of these processes, the individual effects of climate and non-climate changes are difficult to disentangle.

Past trends

Since the 20th century, the annual increment of forests in Europe (in terms of area and growing stock) has increased due to advances in forest management practices, genetic improvement and, in central Europe, the cessation of site-degrading practices. Abandoned farmland in high and mid latitudes is reverting to forest, which store much more carbon than the previous cropland.

Forests and other wooded land cover approximately 190 million ha (1.9 million km^2) in the EEA region, and this area has increased over the last decades (Forest Europe, UNECE and FAO, 2011). Forest biomass has also grown over the past two decades,

Key messages: 4.2.2 Forest growth

- The area covered by forests and other wooded land in Europe (39 EEA countries) has increased for many decades.
- Forest biomass in the EEA region is growing, and the average growth rate has increased from 1990 to 2010.
- In some central and western areas of Europe, forest growth has been reduced in the last 10 years due to storms, pests and diseases.
- Future climate change and increasing CO_2 concentrations are expected to affect site suitability, productivity, species composition and biodiversity, and thus have an impact on the goods and services that the forests provide. In general, forest growth is projected to increase in northern Europe and to decrease in southern Europe.

Table 4.1 Impacts and consequences of climate change on forest growth and forest conditions

Climate effects	Impacts	Consequences
Increased CO_2 concentrations, longer growing season	Increased productivity of some species, e.g. for biomass production	Increased timber supply
Reduced snowfall	Decrease in snow damage Increase in wet snow damages	
Increase in average winter temperature	Winter chilling requirements for flowering and seed germination not met, incomplete winter hardening Reduction in winter cold damage Reduction in cold-associated mortality of insect pest, deer populations Potential for range of new species	Reduced natural regeneration Serious winter tree damage Increased tree damages
Higher earlier spring temperatures	Earlier budburst and potentially increased damages by late frosts	Reduced high-quality timber supply
Decrease in spring and summer rainfall	Drought during tree growth period Threat to newly planted trees Increase in forest fires Limiting current tree species range	Reduced tree growth, serious damage to trees Tree damage; increased tree vulnerability to insect attack; increased risk of soil erosion Changes in tree composition and thus in the range of goods and services
Increased winter rainfall	Waterlogging of soils, killing of tree roots	Reduction of rooting depths Increased vulnerability to droughts and storms
Reduced soil moisture	Changes in species suitability	
Increased frequency of high or extreme temperature episodes	Damaging effects of pests	Tree damage and mortality: loss of timber quality and quantity
Changes in temperature, rainfall and frequency of extreme weather events	Loss of biodiversity	Loss of biodiversity and habitats
Increase in storm events	Wind throws	Loss of quality timber supply, of recreational areas, gaps favouring regeneration
Droughts	Serious damages to trees and stands	Reduced timber volume and reduced high-quality timber supply; higher susceptibility to pests and pathogens; higher mortality; effects on nutrient cycling, habitats and fauna
Extreme weather events	Migration of tree species/loss of native tree species Potential reduction of some of the damaging effects of pests	Loss of biodiversity and habitats Reduced tree damage and yield losses (either quantity or quality)

Source: Compiled from Brown et al., 2012.

at an accelerating rate, as a consequence of a number of factors. A time series for 17 EEA countries shows an increase in growing stock from 85 million m^3 (5.4 $m^3 ha^{-1}$) in 1990 to 110 million m^3 (5.9 $m^3 ha^{-1}$) in 2010 (Forest Europe, UNECE and FAO, 2011). This has been explained primarily by the growth of young forests in Europe, which have not reached maturity, and by the increasing carbon concentration in the atmosphere. Furthermore, several studies have already noted longer growing seasons in several species, shifts in tree line and changes in species distribution (see Section 3.4.3). However, in some central and western forest areas of Europe, forest growth has been reduced in the last 10 years due to storms, pests and diseases.

Projections

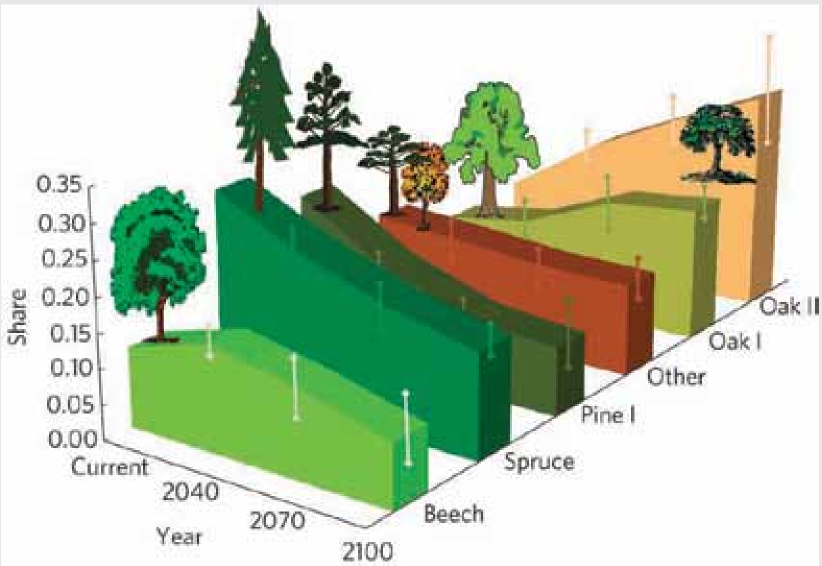
Many aspects of projected climate change will impact forest growth and productivity (Solberg et al., 2009). Increasing CO_2 in the atmosphere might act as a fertiliser for plants and enables them to use water more efficiently, but this effect seems to be strongly dependent on local conditions such as moisture stress and soil nutrient availability and it might be limited to young trees. Nitrogen deposition may enhance forest growth in particular areas where plant-available nitrogen is still the limiting factor depending on soil, climate, vegetation, deposition history and use. However, nitrogen deposition can also enhance the risk of forest decline, if critical loads are exceeded. The concentrations of nitrogen oxides due to fossil fuel combustion are still high in spite of increased use of catalytic convertors. The high concentrations of reduced nitrogen from intensive agriculture, like ammonia are still a matter of concern for forests in the air causing eutrophication (Sutton, 2011). Increases in ground-level ozone are likely in some regions due to warmer temperatures, which would cause a decrease in forest health and growth, which in turn has critical implications for forest distributions and future rates of carbon sequestration (Matyssek et al., 2012).

In general, forest productivity is projected to increase in areas with increased water availability, if appropriate tree species are growing there, while it is projected to decrease where water is scarce and projected to decline further. Wherever droughts increase, forest productivity is expected to decrease. Overall, climate change is projected to have a positive effect on the growing stocks in northern Europe and a negative effect in some regions in southern Europe. However, quantitative projections are not currently available as existing studies on future climate impacts on forests focus on effects on individual species. Box 4.1 provides quantitative projections of forest composition and their economic impacts.

Box 4.1 Projected changes in forest composition and their economic impacts

Climate change is expected to strongly affect the biological and economic viability of different tree species in Europe. A recent modelling study assessed the impacts of projected climate change on forest composition across Europe as well as the economic consequences in terms of annual productivity and land value (Hanewinkel et al., 2012). The major commercial tree species in Europe, Norway spruce, shifts northward and to higher altitude. It loses large parts of its present range in central, eastern and western Europe under all climate scenarios (SRES A1B, A1FI, and B2). Depending on the emission scenario and climate model, between 21 % and 60 % (mean: 34 %) of European forest lands will be suitable only for a Mediterranean oak forest type with low economic returns by 2100, compared to 11 % in the baseline period 1961–1990. Further information on major groups of tree species is provided in Figure 4.2. As a result of the decline of economically valuable species, the value of forest land in Europe is projected to decrease between 14 % and 50 % (mean: 28 % for an interest rate of 2 %) by 2100. The economic loss is estimated at several hundred billion EUR.

Figure 4.2 Projected change in the share of major tree species in Europe



Note: The bars reflect the standard deviation resulting from four different climate model realisations of the SRES A1B emission scenario. The relative size of the icons corresponds to the relative height of mature trees of the species groups. For additional information see the original reference. Europe refers to the area covered by the ENSEMBLE climate projections.

Source: Hanewinkel et al., 2012. © Nature Publishing Group. Reprinted with permission.

4.2.3 Forest fires

Relevance

Forest fires are an integral part of forest ecosystem dynamics in many ecosystems where they are an essential element of forest renewal. They help control insect and disease damage and eliminate litter that has accumulated on forest floors. At the same time, forest fires are an important disturbance agent in many forested landscapes. Fire risk depends on many factors such as weather, vegetation (e.g. fuel load and condition), topography, forest management practices and socio-economic context, to mention the main ones. Extreme fire episodes and devastating fire seasons of recent years in Europe were in most cases driven by severe fire weather conditions. Although most of the wild fires in Europe are ignited by humans (either accidently or intentionally), it is widely recognised that weather conditions and accumulation of fuel play a dominant role in affecting the changes in fire risk over time. Thus climate change is expected to have a strong impact on forest fire regimes in Europe.

Past trends

Historical fire series are available in Europe and regularly updated within EFFIS. However, the time period covered is not the same for all countries and only in a few case series is longer than 25 years available. A long time series of forest fire data is available for five particularly affected countries in southern Europe (Greece, Spain, France, Italy and Portugal). The total burnt area per year in the five southern Member States since 1980 is shown on Figure 4.3. Since the area of each country is different, and the area at risk within each country is also different, comparisons among countries cannot be absolute.

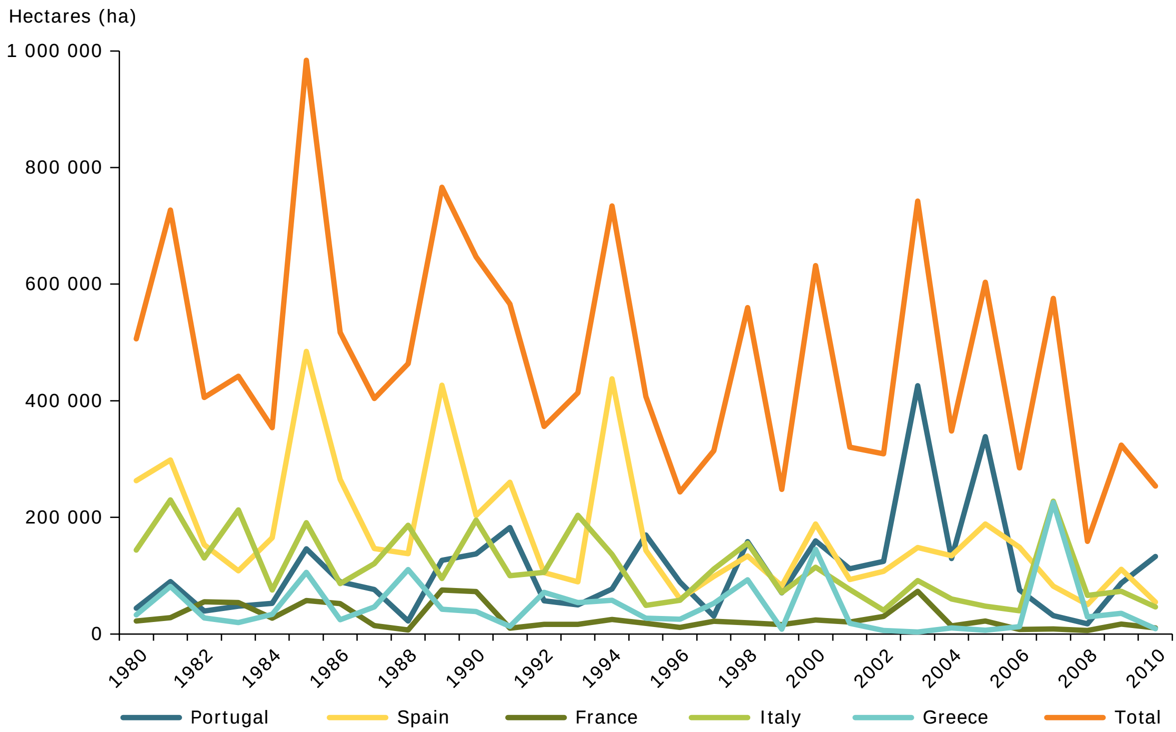
The statistics vary considerably from one year to the next, which clearly indicates how much the burnt area depends on seasonal meteorological conditions. Some multi-annual periodicity in the burned area trend can also be partially attributed to the dead biomass burning/accumulation cycle typical of the fire-prone regions. The historical trend of number of fires is more controversial to analyse because fire frequency is strongly affected by the significant changes that occurred in past years in the statistical reporting systems of the countries. Reported fire frequency in southern European countries has increased during the 1990s to then stabilise for around one decade and slightly decrease during recent years.

To complement the information from past forest fires, past trends of fire danger have also been analysed processing series of meteorological fire danger indices, which are routinely used to rate the fire potential due to weather conditions. The Canadian Fire Weather Index (FWI) is used in EFFIS to rate the daily fire danger conditions in Europe. FWI can be transformed with a simple equation into a daily severity rating index which is deemed to be linearly related with fire suppression difficulties (Van Wagner, 1987). Daily severity values can be averaged over the fire season obtaining a Seasonal Severity Rating (SSR) index, which allows objective comparison of fire danger from year to year and from region to region. Although the index is dimensionless and mainly used for comparison purposes, SSR values above 6 may be considered in the extreme range. Weather input to compute SSR are the same as for FWI (air temperature, relative humidity, wind, precipitation). Other driving factors of fire regimes, such as land-use changes or fuel dynamics, are not taken into account by SSR which is based on weather parameters. However, the fundamental role played by weather in affecting the

Key messages: 4.2.3 Forest fires

- Fire risk depends on many factors, including climatic conditions, vegetation (e.g. fuel load and condition), forest management practices and other socio-economic factors.
- The number of fires in the Mediterranean region has increased over the period from 1980 to 2000; it has decreased thereafter.
- In a warmer climate, more severe fire weather and an expansion of the fire-prone area and longer fire seasons, as a consequence, are projected, but with considerable regional variation.
- The impact of fire events is particularly strong in southern Europe on already degraded ecosystems.

Figure 4.3 Burnt forest area in five southern European countries (1980–2010)



Source: Schmuck et al., 2011.

year-by-year variation of fire incidence in Europe has been clearly demonstrated (Camia and Amatulli, 2009).

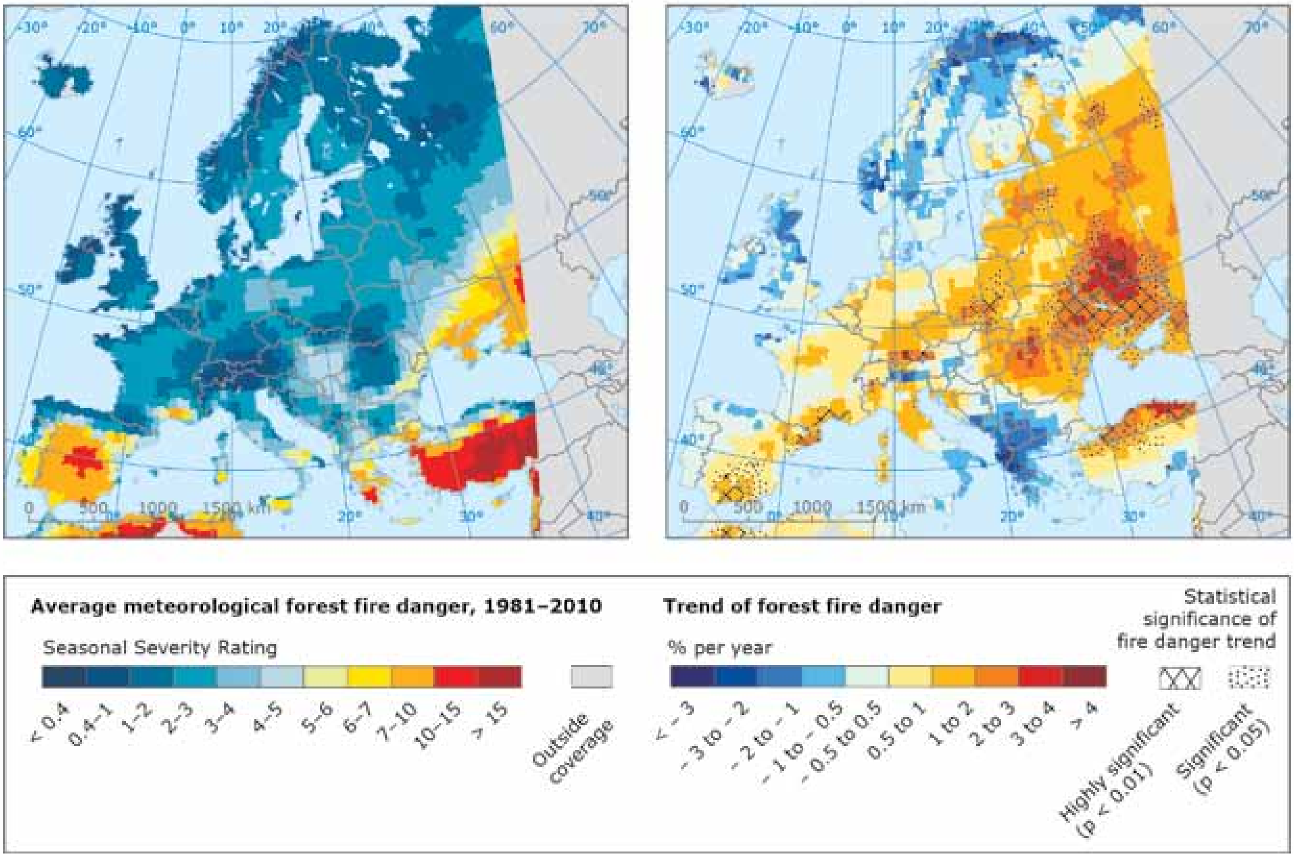
Annual SSR values for the period 1981 to 2010 were computed based on daily weather data using the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim dataset. Map 4.9 shows the SSR values averaged over the entire period (left map) and the corresponding trend derived from linear interpolation of the annual values (right map).

Projections

Climate change projections suggest substantial warming and increases in the number of droughts, heat waves and dry spells across most of the Mediterranean area and more generally in southern Europe (see Section 2.2). These projected climate changes would increase the length and severity of the fire season, the area at risk and the probability of large fires, possibly enhancing desertification.

Map 4.10 compares modelled fire danger projections for baseline (1961–1990) and projected (2071–2100) climate conditions. The results suggest that climate change would lead to a marked increase of fire potential in south-eastern and south-western Europe; in relative terms the increase in SSR would be particularly strong in western-central Europe.

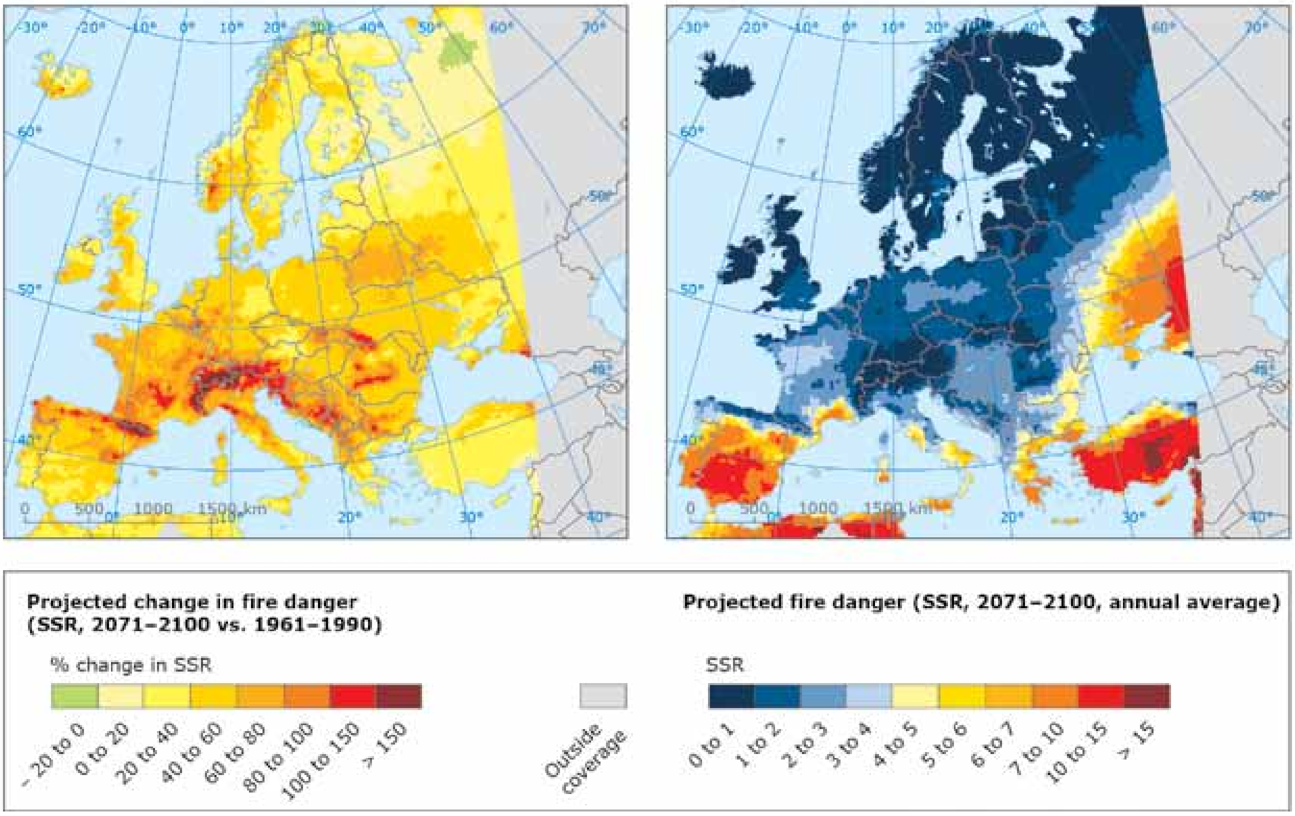
Map 4.9 State and trend of fire danger for the period 1981–2010



Note: Fire danger is expressed by the Seasonal Severity Rating (SSR). Daily severity values can be averaged over the fire season using the SSR index, which allows objective comparison of fire danger from year to year and from region to region. The coarse scale of the map does not allow accounting for specific conditions of given sites, as for example in the Alpine region, where the complex topography may strongly affect local fire danger.

Source: A. Camia, 2012 (personal communication), based on Camia et al., 2008.

Map 4.10 Projected changes in fire danger



Note: Fire danger is expressed by the Seasonal Severity Rating (SSR). Based on projections by the Regional Climate Model (RCM) RACMO2 driven by the Global Climate Model (GCM) ECHAM5 for the SRES A1B emission scenario.

Source: A. Camia, 2012 (personal communication), based on Camia et al., 2008.

4.3 Fisheries and aquaculture

Relevance

Industries related to the capture of wild fish as well as marine aquaculture are sensitive to climate change. This section gives an overview of the observed and projected impacts of climate change on fisheries and aquaculture. Due to the scarcity of quantitative information, this information is not presented as an indicator.

The total fisheries catch of the EU, concentrated mainly in the north-east Atlantic, is the third largest fishery in the world. Commercially relevant wild fish stocks are subject to high levels of exploitation, in many cases at levels that exceed their reproductive capacity. In Europe's seas, overfishing is a problem, with 30 % of commercial stocks (those which are assessed) being fished outside safe biological limits. Recently, scientists have also brought attention to the likely effects of climate change on fish stocks. Stocks are thought to respond to warming conditions both physiologically and ecologically. Warming waters are expected to affect fish distribution, migration patterns, phenology (timing), food availability (see Section 3.1) and recruitment. In response, the geographical distribution and productivity of fish stocks could be changing (Simpson et al., 2011). It is furthermore speculated, that ocean acidification (see Section 3.1) may eventually impact on the lowest levels of the food web which ensures availability of food for fish, and hence impact fish productivity. The high levels of fish exploitation, however, mean that it is very difficult to distinguish between changes due to fisheries and those due to ocean warming.

Although marine aquaculture depends critically on coastal habitats that will be affected by climate change, it is still very difficult to distinguish between possible climate change effects, natural variability in the environment around cages, and technological improvements that generally support the development of the industry. The industry's concerns are related to changes in the frequency and strength of storms which may pose a risk to infrastructure such as salmon cages and to sea-level rise-induced changes in shoreline morphology which may change the location of habitats suitable for the industry. The emergence, spread and severity of diseases, parasites and pathogens, and the spread of nuisance and non-native species could also potentially be damaging. In Ireland and the United Kingdom, rising temperatures may create the opportunity to rear species adapted to warmer water. However, market forces are seen as the more important factor to determine whether existing farmed species will be displaced by new ones (Callaway et al., 2012).

Past trends

Climate change has had a number of effects in the north-eastern Atlantic, where 72 % of commonly observed species have responded to warming waters by changing their abundance and/or distribution (see Figure 4.4). Traditionally, exploited fish such as cod have moved further northwards in the region, particularly in the North Sea most likely as a result of a shift in the thermal regime of the North Sea.

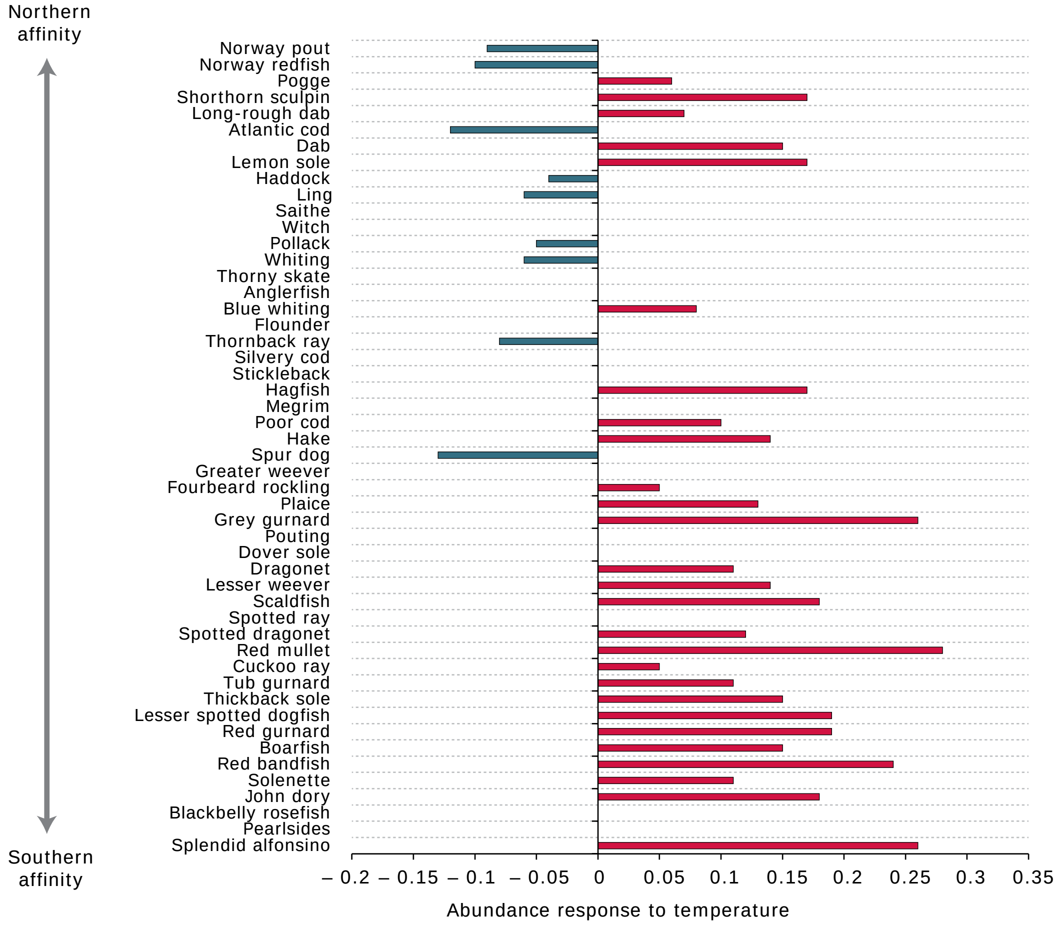
Furthermore, warming seas have allowed potentially new exploitable stocks to move into some areas. While warming can lead to an increase in fish biodiversity in a region, there is often a concurrent decrease in the size structure of the fish population. For example, in the North Sea the relatively small species sprat, anchovy and horse mackerel have increased in recent decades, whereas the larger species cod and plaice have decreased at their southern distribution limit (Perry, 2005). This change may have important socio-economic consequences as the stocks moving out of the North Sea tend to have a higher value than the stocks moving into it.

As catch of wild fish species has been decreasing while the demand for fish and fish products has increased, a large increase in the total European

Key messages: 4.3 Fisheries and aquaculture

- The effects of climate change, in particular of ocean warming, on wild fish distributions and aquaculture are difficult to distinguish from those of high exploitation rates or technological developments.
- Wild fish stocks seem to be responding to changing temperatures and food supply by changing their geographical distribution.
- Future climate change is likely to lead to an increased catch potential in the Arctic, and to a decreased or constant catch potential in other European seas.
- Climate change can influence where aquaculture is possible, which species are raised, and the efficiency of the production.

Figure 4.4 Observed change in the distribution of demersal fish in response to observed rise in sea surface temperatures



Note: Changes in abundance in response to observed temperature change are relative changes (unitless).

Source: Simpson et al., 2011. Reprinted with permission from Elsevier.

aquaculture production has been observed over the past 15 years (EEA, 2010). Today EU and European Free Trade Association (EFTA) aquaculture production is at a level of 1.8 million tonnes of fish, shellfish and crustaceans, generating a turnover of EUR 3.2 billion and 65 000 jobs. Often aquaculture production is situated in coastal communities that rely almost solely on income from that industry, and hence these communities are vulnerable to changes that affect the industry.

Projections

Projections of changes in total catch of marine fish and invertebrates as a consequence only of temperature changes has shown the potential of a large-scale redistribution of global catch potential with an increase in high latitude regions and a decline in the tropics. The exclusive economic zone (EEZ) regions with the highest increase in catch potential by year 2055 include Alaska (USA), Greenland, Norway and Russia, whereas the biggest loss would occur in Chile, China, Indonesia and USA (excluding Alaska and Hawaii) (Cheung et al., 2009; 2012). Hence, the biggest loss in catch potential is likely to occur outside Europe, but it would affect parts of the world that are particularly vulnerable to such changes because of the high importance of fisheries to national economies and diets, and limited societal capacity to adapt to potential impacts and opportunities (Allison et al., 2009). Large differences in changed catch potential are likely to occur within Europe, with the greatest increase in the Arctic.

Climate change may create new opportunities for aquaculture, in particular by raising warm-water species in previously unsuitable locations. Changes in aquaculture, however, also strongly depend on market forces and consumers' tastes, which may have a stronger influence on production than temperature and technological advancements.

4.4 Human health

4.4.1 Overview

Relevance

Climate change is already contributing to the global burden of disease and premature deaths. Nearly all environmental and social impacts of climate change may ultimately affect human health through altering weather patterns, changes in water and air quality, food quantity and quality, ecosystems services, livelihoods, infrastructure and migration (Figure 4.5). Climate change can affect existing health risks both positively and negatively, and it may introduce new health risks to previously unaffected regions. The potential health benefits from milder winters in some regions are however not expected to outweigh the risk of negative health effects through direct and indirect, immediate and delayed risks of climate change (McMichael et al., 2012). Two European research projects ([56]) estimated substantial health and welfare costs of climate change in Europe (Kovats et al., 2011) (see Section 5.5.2 for further information).

Climate change may exacerbate existing environmental problems, such as particulate emissions and high ozone concentrations, pose additional challenges to providing sustainable water and sanitation services, and increase a risk of water- and food-borne diseases, as well as affect the distribution of infectious diseases and their vectors (Confalonieri et al., 2007). Nearly half of over 50 infectious diseases that the EU Member States are currently required to report can be directly or indirectly affected by climate change; other climate-sensitive diseases, including Chikungunya fever, Lyme borreliosis, tick-borne encephalitis, and visceral leishmaniasis are considered emerging infectious diseases due to climate change (Lindgren et al., 2012).

All people are affected by climate change, but the health effects depend largely on their vulnerability (e.g. age, pre-existing diseases) and their ability to adapt, linked to ecological, social, economic and cultural factors, including education and access to healthcare among others (EEA, 2010a). Vulnerable population groups include the elderly and children, the urban poor, traditional societies, subsistence farmers, and coastal populations (WHO, 2011a).

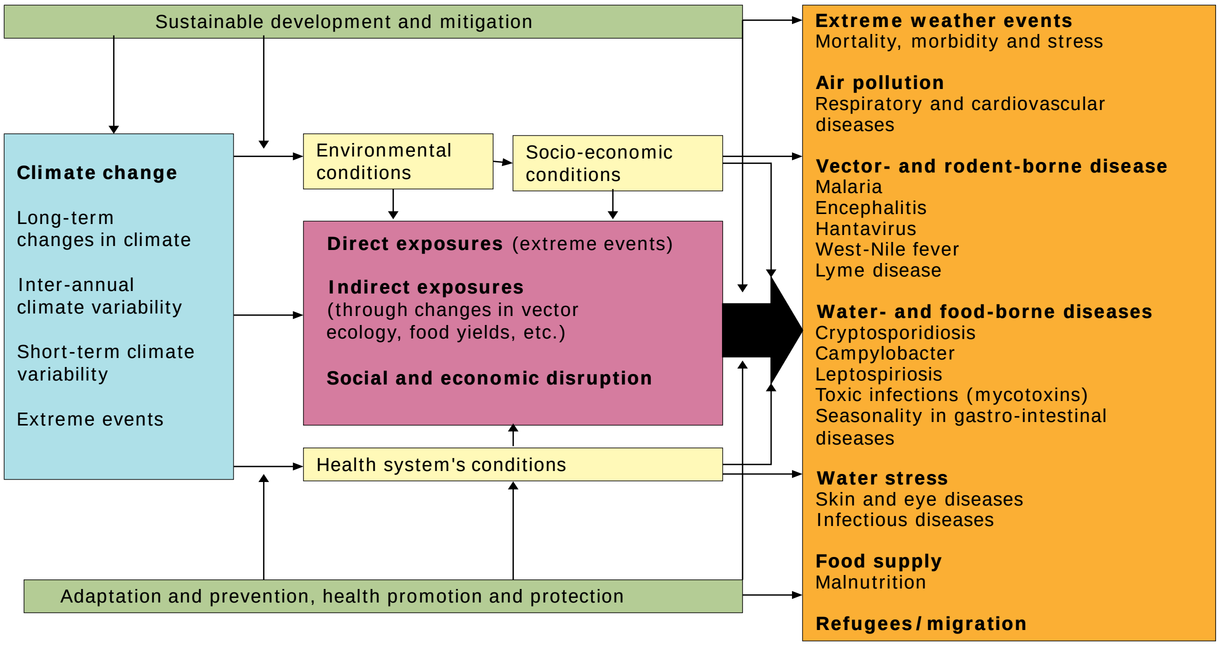
The populations in some European regions, such as the Arctic or the Mediterranean, are particularly vulnerable. The Mediterranean is especially prone to an intensification of heat waves and droughts (Diffenbaugh et al., 2007), which can put pressure on existing ecosystems and life support systems, such as water, food and energy supply. In the Arctic, changes in temperature and precipitation (see Section 2.2), melting of permafrost and decreasing sea ice (see Section 2.3), coastal erosion (see Section 3.2), landscape transformation and biodiversity change (see Section 3.4) can affect the lifestyle and culture of the indigenous people. Climate change is also expected to influence the exposure to some contaminants (mercury, radio nuclides and persistent organic pollutants) and to affect dietary habits. All these changes have implications for human health (Curtis et al., 2005; Confalonieri et al., 2007; Kallenborn et al., 2011).

Key messages: 4.4 Human health

- Climate change is already contributing to the burden of disease and premature deaths in Europe. Its main health effects are related to extreme weather events, changes in the distribution of climate-sensitive diseases, and changes in environmental and social conditions.
- Quantitative projections of future climate-sensitive health risks are difficult due to the complex relationship between climatic and non-climatic factors, climate-sensitive disease and other health outcomes.
- Adverse impacts of future climate change are projected to outweigh beneficial impacts on the global scale. The health costs are also estimated to be substantial in Europe.

([56]) ClimateCost — the Full Costs of Climate Change — FP 7 project (http://www.climatecost.cc); PESETA — Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis (http://peseta.jrc.ec.europa.eu).

Figure 4.5 Impact pathways of climate change on human health



Source: Wolf, 2011, adapted from Confalonieri et al., 2007.

Selection of indicators

This section presents the following indicators on the main climate-sensitive health risks in Europe:

- Floods and health (addressing both coastal and river floods);
- Extreme temperatures and health;
- Air pollution by ozone and health;
- Vector-borne diseases.

The next subsection presents an overview of extreme weather events and health. In addition, the concluding subsection provides information on the links between climate change and water- and food-borne diseases, where the available information is not sufficient to be presented as an indicator.

Data needs and uncertainty

Attribution of health effects to climate change is difficult due to the complexity of interactions, and potentially modifying effects of a range of other factors (such as land use changes, public health preparedness, and socio-economic conditions) (Wardekker et al., 2012). Criteria for defining a climate-sensitive health impact are not always well identified and their detection sometimes relies on complex statistical or modelling studies (e.g. health impacts of heat waves). Furthermore, these criteria as well as the completeness and reliability of observations may differ between regions and/or institutions, and they may change over time. Data availability and quality is crucial in climate change and human health assessments, both for longer term changes in climate-sensitive health outcomes, and for health impacts of extreme events. The monitoring of climate-sensitive health effects is currently fragmentary and heterogeneous. All these factors make it difficult to identify significant trends in climate-sensitive health outcomes over time, and to compare them across regions. In the absence of reliable time series, more complex approaches are often used to assess the past, current or future impacts of climate change on human health.

The links between climate change and health are the subject of intense research in Europe (e.g. the projects cCASHh ([57]), EDEN ([58]), EDENext ([59]), and Climate-TRAP ([60])). Furthermore, the European Centre for Disease Prevention and Control (ECDC) and the World Health Organization (WHO) perform crucial work in this area.

The ECDC has numerous projects investigating the links between climate change and communicable diseases. It has developed the European Environment and Epidemiology (E3) network which will promote geospatial infectious disease modelling in Europe. Additionally, ECDC has multiple ongoing projects assessing the impact of climate change on food-, water-, and vector-borne disease transmission in Europe, and ECDC has also established a pan-European network dedicated to vector surveillance, VBORNET.

The WHO Regional Office for Europe works on climate change and health since 1997. The activities include the assessment of the health effects, the development of measures to protect population health from climate change and to integrate health in climate change related policies. WHO has developed numerous tools and methods, monitors trends over time and advocates evidence based solutions. In the context of the climate environment and health information system sixteen indicators help to monitor trends over time at the national level. WHO guides research and development on data collection, analysis and future scenarios.

Data availability — the case of databases for natural disasters

Currently, worldwide databases for natural disasters, such as EM-DAT/CRED ([61]), the Dartmouth Flood Observatory ([62]) (DFO), or NatCatSERVICE of Munich RE ([63]) are available for Europe-wide studies. The databases are compiled from various sources; the definitions, thresholds, classification criteria, reporting approaches, etc. differ and need to be considered when applying and interpreting the data. In general, larger disasters are captured well in the databases, while they are less accurate for smaller events, which still may have a significant impact (WHO and HPA, Forthcoming). In order to be included in EM-DAT, a disaster needs to meet one of the following criteria: 10 or more people reported killed, a hundred or more people reported affected, declaration of a state of emergency, or call for international assistance. The criteria for defining a flood are 'a significant rise of water level in a stream, lake, reservoir or coastal region' and include general river floods, flash floods and storm surges or coastal flooding (Below et al., 2009). The DFO includes only floods that appear to be 'large', based on a significant damage to structures or agriculture, long reported intervals (decades) since the last similar event, and/or fatalities; it is not specifically defined what constitutes a flood, but it does consider the main cause of the flood. The DFO is likely to capture more flood events than EM-DAT, as any large flood event is recorded as a flood, whereas EM-DAT may classify it as another type of disaster; (tropical) storms are only included in case they also cause flooding.

Multiple counting may occur in the case of events affecting several countries. An important consideration is the increased reporting of events over the past few decades. Therefore, an analysis of the information over time may reveal an increase due mostly to improvements in data collection. Furthermore, different information sources, and use of a range of different assessment methods and rationales, may further increase uncertainty regarding attribution of impacts (i.e. casualties, losses, etc.) associated with each event.

(57) cCASHh — Climate change and adaptation strategies for human health in Europe — the EC FP5 project (http://ec.europa.eu/research/environment/pdf/env_health_projects/climate_change/cl-ccashh.pdf).
(58) EDEN — Emerging Diseases in a changing European eNvironment — the EC FP6 project (http://www.eden-fp6project.net/).
(59) EDENext — Biology and control of vector-borne infections in Europe — the EC FP7 project (http://www.edenext.eu/).
(60) Climate-TRAP – Training, Adaptation, Preparedness of the Health Care System to Climate Change (http://www.climatetrap.eu/).
(61) See http://www.emdat.be/.
(62) See http://floodobservatory.colorado.edu/.
(63) See http://www.munichre.com/en/reinsurance/business/non-life/georisks/natcatservice/default.aspx.

4.4.2 Extreme weather events and health — an overview

Relevance

Extreme weather events, such as heat waves and windstorms (see Section 2.2), floods and droughts (see Section 3.3), and storm surges (see Section 3.2.3) have impacts on human health (Kirch et al., 2005; Confalonieri et al., 2007; EEA, 2011a). However, human vulnerability to extreme weather events is determined by a complex set of factors.

Evidence suggests that globally, climate change has led to changes in climate extremes, including heat waves, record high temperatures and, in many regions, heavy precipitation in the past half century. If vulnerable populations are exposed to such climate extremes, or a series thereof, this can lead to climate-related disasters with substantial health impacts (IPCC, 2012) ([64]). There are regional differences in observed changes; for example, while there is high confidence that heat waves become more severe in southern Europe and the Mediterranean, there is less confidence in the significance of the observed trend in central and northern Europe.

Past trends

According to the EM-DAT international disaster database ([65]), heat waves were the deadliest extreme weather events in 1980–2011 in Europe, particularly in southern and western Europe. Cold events and storms were the deadliest weather extremes in eastern Europe and in northern Europe, respectively. Floods and wet mass movements, including landslides, were linked to the highest death rates in southern and eastern Europe, wildfires in southern Europe, while the deadliest storms were reported in northern and western Europe (Table 4.2). However, the comparability of the data over time is very limited (see above under 'Data needs and uncertainty'). Furthermore, the interpretation of the time series can be dominated by a single extreme event, such as a heat wave of the summer 2003, with over 70 000 excess deaths (June–September 2003) in southern and western Europe. Also in case of flood-related fatalities, the overall number of deaths depends strongly on single events.

The number of reported climate-related disasters in Europe has increased between 1980 and 2011 (Figure 4.6). However, such figures also need to be interpreted with caution. As concluded in a recent

Table 4.2 Number of people killed due to extreme weather events and wildfire by European region (1980–2011)

	Flood and wet mass movement ([a])	Cold event	Heat wave	Storm	Wildfire
Eastern Europe	0.81	2.36	1.15	0.17	0.05
Northern Europe	0.10	0.12	0.34	0.41	0.00
Southern Europe	1.23	0.13	21.00	0.21	0.15
Western Europe	0.27	0.06	18.76	0.37	0.02
Total	**2.41**	**2.68**	**41.24**	**1.16**	**0.22**

Note: ([a]) including landslides.

Numbers are per 10 000 people. Country grouping, as reported to EM-DAT/CRED: eastern Europe: Bulgaria, the Czech Republic, Hungary, Poland, Romania, Slovakia; northern Europe: Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, the United Kingdom; southern Europe and Western Asia: Albania, Bosnia and Herzegovina, Croatia, Cyprus, Greece, Italy, former Yugoslav Republic of Macedonia, Montenegro, Portugal, Serbia, Slovenia, Spain, Turkey; western Europe: Austria, Belgium, France, Germany, Luxembourg, the Netherlands, Switzerland.

Population rates calculated using population data from 2010.

Source: EM-DAT; Eurostat; World Bank.

([64]) Note that the term 'vulnerability' is used in this section following its general use in epidemiology and public health, where it describes the relationship between exposure to a health hazard and the health effect. This use is closer to the term 'sensitivity' in the IPCC Fourth Assessment Report. For further discussion of this term, see Section 1.7.

([65]) See http://www.emdat.be/.

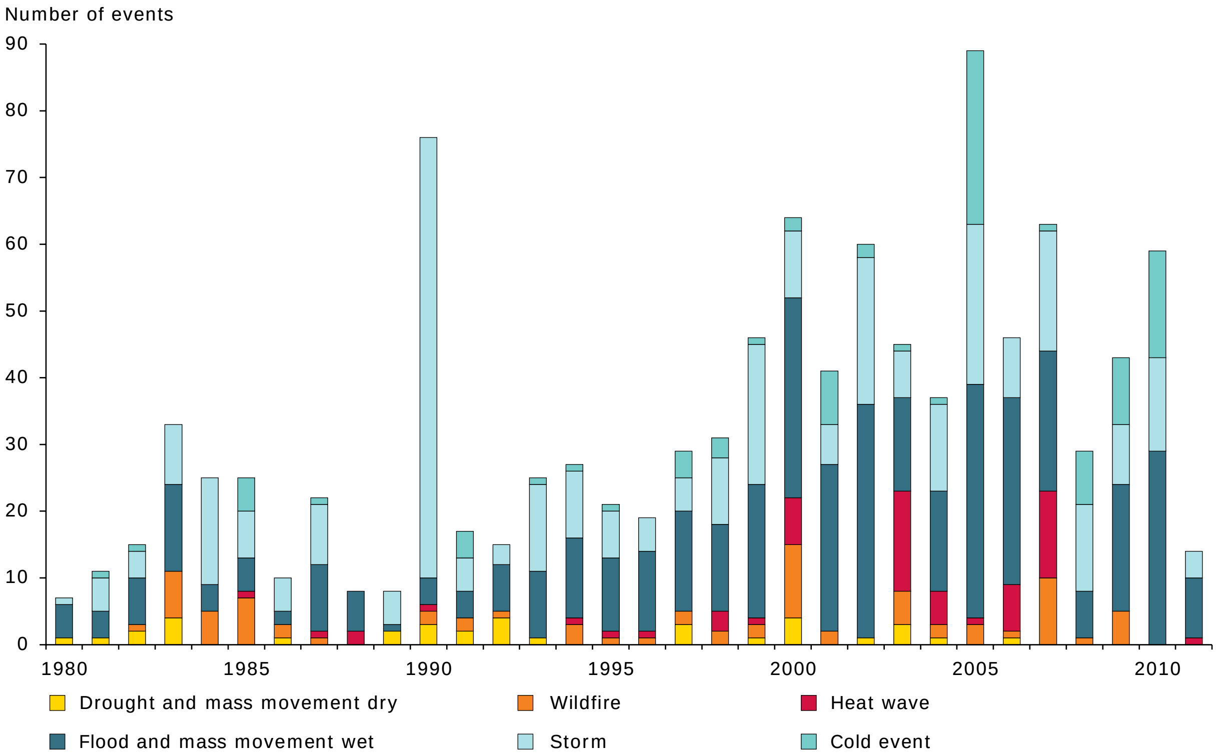
study of weather-related disasters (Visser et al., 2012), trend patterns in disaster burden, in terms of people affected and economic loss, are difficult to explain since several interlinked factors play a role. These include: changes in wealth, changes in population numbers, changes in intensity or frequency of extreme weather events, and changes in vulnerability. Therefore, a direct attribution of changes in disaster burden to one specific factor, such as climate change, should be avoided (Visser et al., 2012).

Projections

Climate change is expected to affect the frequency and severity of extreme weather events (IPCC, 2012). Long-term climate extremes, such as heat waves and droughts, are expected to increase, while the direction of changes is uncertain for short-term meteorological extremes, such as storms (see Section 2.2.6). Model projections show a likely increase for hydrological extremes (i.e. floods). Such an increase is more likely for coastal floods due to projected sea-level rise (see Section 3.2.2) than for river floods (see Section 3.3.3).

While there are no comprehensive projections on health risks of climate change in Europe, some estimates of the projected health impacts related to coastal and river floods, temperature, as well as on air quality and a food-borne disease (salmonellosis), are available through EU research projects (Feyen and Watkiss, 2011; Kovats et al., 2011; Watkiss and Hunt, 2012). They are presented with the respective indicators in the remainder of this section (see also Section 5.5.2).

Figure 4.6 Number of reported extreme weather events and wildfire in EEA member and collaborating countries (1980–2011)



Source: EM-DAT/CRED.

4.4.3 Floods and health

Relevance

Climate change can increase the severity and frequency of extreme weather events, such as heavy precipitation (see Section 2.2.5), storms (see Section 2.2.6), and storm surges (see Section 3.2.3). Floods caused by these events can affect people immediately (e.g. through drowning and injuries), but also a long time after the event (e.g. through the destruction of homes, water shortages, displacement, disruption of essential services and financial loss) and especially through the stress flood victims are exposed to (WHO and HPA, Forthcoming; Ahern et al., 2005; Paranjothy et al., 2011; Stanke et al., 2012).

Past trends

Estimates for the WHO European Region based on a combination of data from EM-DAT and DFO indicate that floods have killed more than 1 000 people and affected 3.4 million others in the period 2000–2009. Deaths from flooding were highest (on a per capita basis) in central and eastern Europe (WHO and HPA, Forthcoming). Map 4.11 shows the number of people affected by flooding in the same period. The largest numbers (on a per capita basis) are found in south-eastern Europe, eastern Europe and central Europe.

Projections

Heavy precipitation events are likely to become more frequent in many regions in Europe (see Section 2.2.5). In the absence of adaptation, river flooding is estimated to affect 250 000 to 400 000 additional people per year in Europe by the 2080s, which corresponds to more than a doubling with respect to the 1961–1990 period. The increase is projected in central Europe and the British Isles (WHO and HPA, Forthcoming).

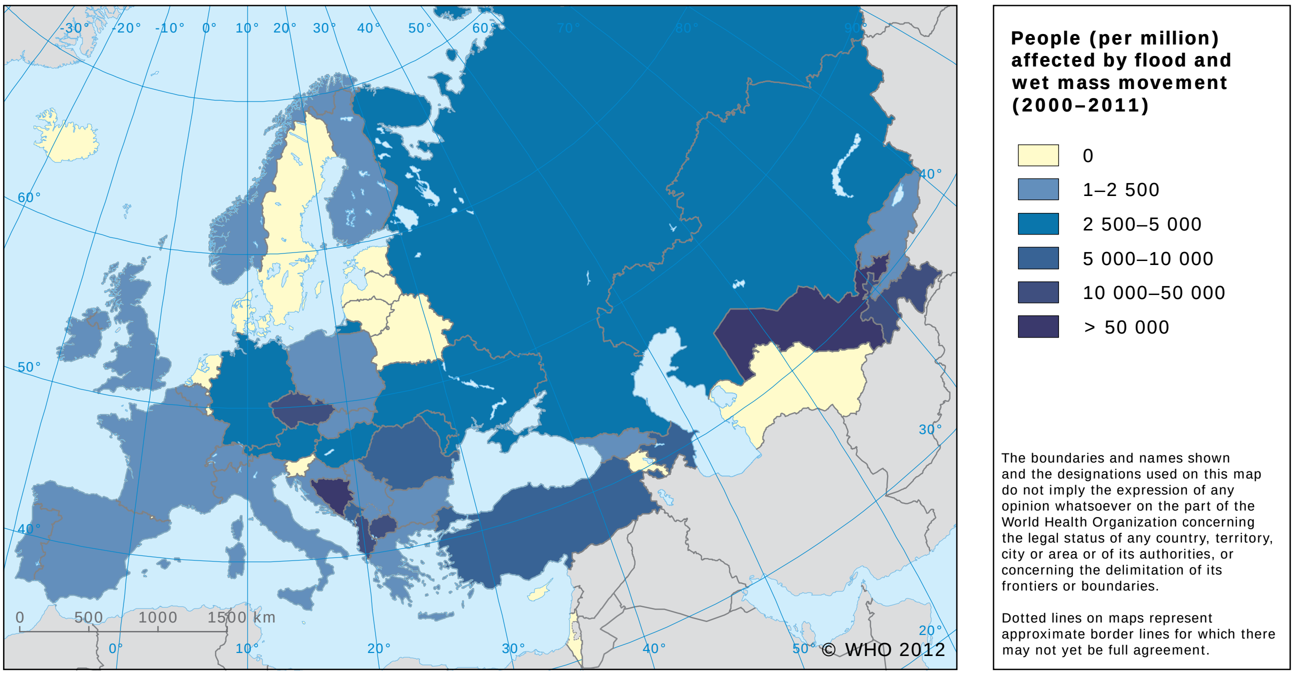
The PESETA project estimated that up to an additional 1.6 million people each year in the northern Mediterranean, and northern and western Europe would experience coastal flooding by 2080 under the SRES A1FI scenario, unless additional adaptation measures were taken. The number of people affected by coastal flooding in the EU ranges between 775 000 to 5.5 million people, depending on the emissions scenario (Ciscar et al., 2011). Under the high sea-level rise scenario (B2), mental health impacts of coastal flooding in the EU could potentially reach five million additional cases of mild depression annually in the period 2071–2100; impacts presumably significantly reduced with adaptation (Watkiss and Hunt, 2012).

According to the SRES A1B scenario, climate and socio-economic change would lead in the EU to 650 deaths per year by the 2080s due to coastal flooding. Two thirds of these deaths would occur in western Europe. These estimates decrease significantly under the E1 mitigation scenario to 185 (2080s) fatalities per year. Coastal adaptation measures can significantly reduce risks to less than 10 deaths per year in 2080 (from 650 without adaptation) (Kovats et al., 2011).

Key messages: 4.4.3 Floods and health

- River and coastal flooding affect millions of people in Europe each year. They affect human health through drowning, heart attacks, injuries, infections, psychosocial consequences, and health effects of chemical hazards as well as disruption of services.
- Observed increases in heavy precipitation and extreme coastal high-water events have led to more river and coastal flooding in many European regions.
- Increases in health risks associated with river and coastal flooding are projected in many regions of Europe due to projected increases in extreme precipitation events and sea level.

Map 4.11 **Number of people affected by flooding per million population in the WHO European Region (annual average 2000–2011)**



Note: 'People affected', as defined in EM-DAT, are people who require immediate assistance during a period of emergency, including displaced or evacuated people.

GIS data source acknowledgement: Countries and Major Rivers, ESRI Data & Maps, © Environmental Systems Research Institute Inc.

EM-DAT/CRED and the Dartmouth Flood Observatory were analysed to determine the flooded countries in the WHO European Region and the impact of these floods (see text for details).

Source: WHO and HPA (forthcoming): Floods: Health effects and prevention in the WHO European Region.

4.4.4 Extreme temperatures and health

Relevance

Temperature affects human well-being and mortality. Both cold spells and heat waves have public health impact in Europe. Heat waves have caused much higher fatalities in Europe in recent decades than any other extreme weather event. For example, in Spain, extreme heat accounted for 1.6 % of all deaths in the warm seasons, and about 40 % of these deaths occurred in periods that would not be classified as heat waves, that is on isolated hot days (Basagaña et al., 2011). The

Key messages: 4.4.4 Extreme temperatures and health

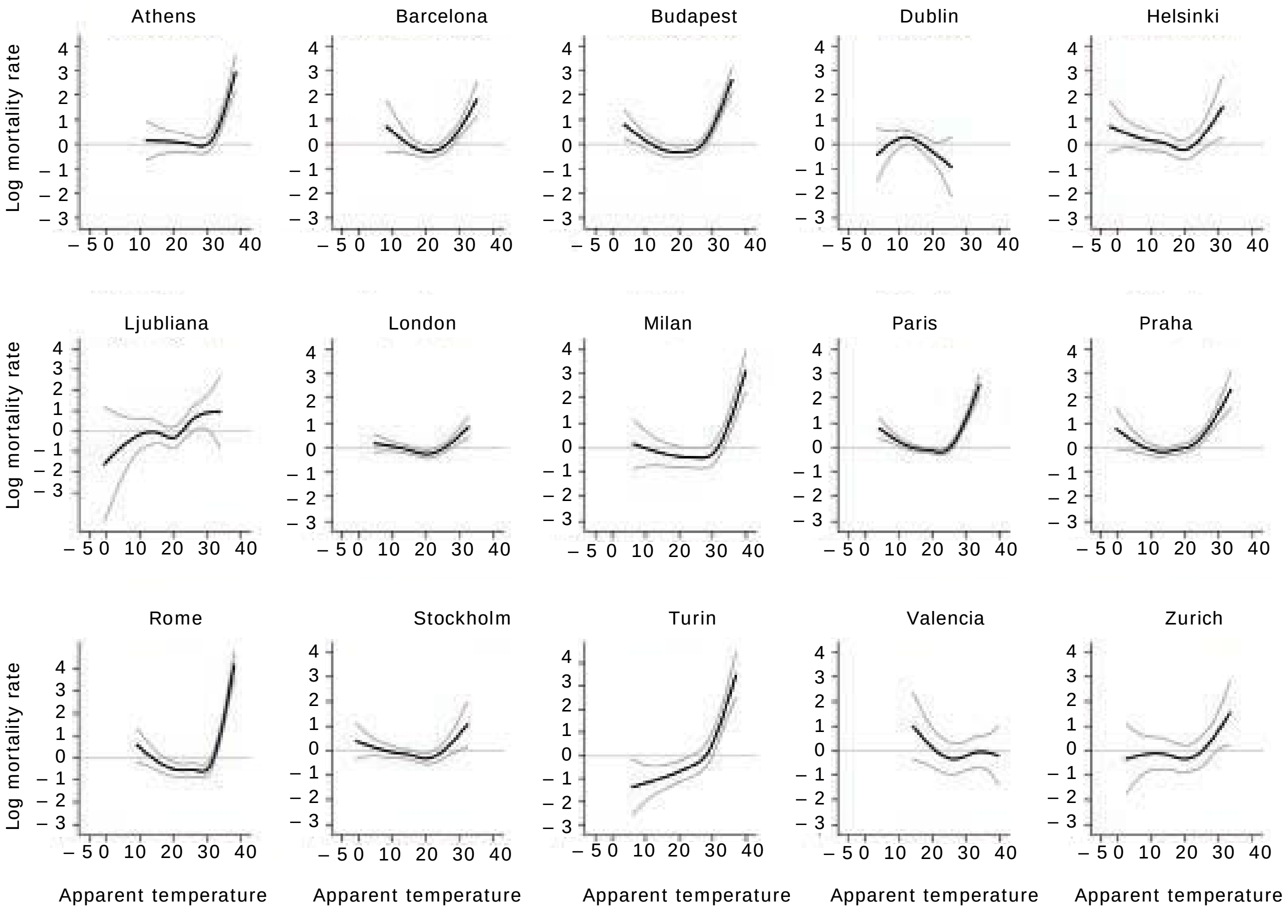
- Mortality and morbidity increase, especially in vulnerable population groups, and general population well-being decreases during extreme cold spells and heat waves, as well as above and below local and seasonal comfort temperatures, with different temperature thresholds in Europe.
- The number of warm days and nights has increased across Europe in recent decades. Heat waves over the last decade have caused tens of thousands of premature deaths in Europe.
- Length, frequency and intensity of heat waves are very likely to increase in the future. This increase can lead to a substantial increase in mortality over the next decades, especially in vulnerable groups, unless adaptation measures are taken.
- Cold-related mortality is projected to decrease in Europe due to climate change as well as better social, economic and housing conditions in many countries.

largest effect was observed among the elderly, but in some cities younger adults were affected as well (D'Ippoliti et al., 2010; Baccini et al., 2011). Heat-related problems are largest in cities; among many interrelated factors, the urban heat island effect plays an important role. Future climate change is very likely to increase frequency, intensity and duration of heat waves. During hot weather, synergistic effects between high temperature and air pollution (PM10 and ozone) were observed. Long warm and dry periods in combination with other factors can also lead to forest fires which have shown to have severe health impacts (Analitis et al., 2012).

Extreme cold can also significantly affect human health. Excess winter mortality in Mediterranean countries is higher than in northern European countries, and deaths often occur several days or weeks after the coldest day of a cold period (Healy, 2003; Analitis et al., 2008).

Besides extreme temperature events, temperatures outside a local comfort temperature range are linked to increased mortality and other adverse health outcomes. Several studies found J-shaped exposure-response relationships with mortality and morbidity, increasing at both ends of the temperature scale (Figure 4.7). Effects of heat occur mostly on the same day and in the following three days whereas cold effects were largest 2–3 weeks after the event (WHO, 2011a; Ye et al., 2011).

Figure 4.7 Temperature-mortality relationship in 15 European cities



Note: Figure shows relationship between daily maximum apparent temperature (Barcelona: mean apparent temperature) and natural mortality (black) and 95% confidence interval (grey).

Source: Baccini et al., 2008. © Lippincott Williams. Reprinted with permission.

Past trends

The summer of 2003 was an outstanding example of increased mortality during periods of extreme temperatures, with an estimated premature mortality of 70 000 people (Robine et al., 2008). During the summers of 2006, 2007 and 2010 temperature records were again broken in different parts of Europe (Barriopedro et al., 2011).

The European Mortality Monitoring Project ([66]) developed coordinated routine mortality monitoring in Europe but is not yet able to provide real-time detection and documentation of heat wave effects on mortality.

Projections

Future climate change is very likely to increase frequency, intensity and duration of heat waves, which leads to a marked increase in heat-attributable deaths under future warming (Baccini et al., 2011). Synergistic effects between high temperature and air pollution (PM_{10} and ozone) were observed during hot weather. Long warm and dry periods in combination with other factors can also lead to forest fires, which can also have severe health impacts (Analitis et al., 2012).

Projections of heat-related mortality use evidence from epidemiological studies combined with future scenarios of climate, population and acclimatisation with regionally specific temperature-mortality relationships (Baccini et al., 2011). The PESETA project estimates that heat-related mortality in Europe in the 2080s will increase by between 60 000 and 165 000 (without adaptation and physiological acclimatisation, compared to the present baseline). Cold-related mortality is projected to decrease by between 60 000 and 250 000, which is about the same magnitude as the increase from heat-related mortality (Ciscar et al., 2011; Huang et al., 2011). Uncertainty in these estimates needs to be carefully addressed (Watkiss and Hunt, 2012). A study covering most of Europe projects a progressive change in the seasonality of maximum monthly mortality from winter to summer, an increase in the frequency of warm extremes and that the number of uncomfortable days will increase. In the absence of adaptation, these changes would lead to a reduction in human lifespan of up to 3–4 months in 2070–2100 (Ballester et al., 2011).

The ClimateCost project estimates an additional 26 000 deaths per year from heat by the 2020s (2011–2040), rising to 127 000 deaths per year by the 2080s (2071–2100) under a medium to high emission (A1B) scenario, assuming no adaptation. While heat-related mortality is projected to increase across Europe, impacts would be highest in southern Europe. Under an E1 scenario, broadly equivalent with stabilising global mean temperature increase at 2 °C above pre-industrial levels, impacts are reduced significantly, with an estimated 69 000 deaths per year by the 2080s. With acclimatisation, the estimated number of heat-related deaths declines substantially to 13 000 per year in the 2020s, and 40 000 per year in the 2080s under the A1B scenario; for the E1 scenario it is down to 18 000 per year in the 2080s (Kovats et al., 2011). Similar to PESETA, these figures are subject to considerable uncertainties.

([66]) EURO-Momo project (http://www.euromomo.eu/).

4.4.5 Air pollution by ozone and health

Relevance

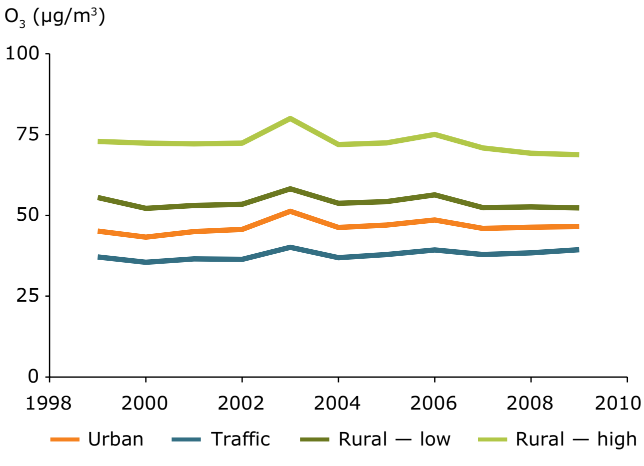
Ozone is a greenhouse gas, but ground level ozone is primarily an air pollutant, which is of high concern in Europe (Confalonieri et al., 2007; Monks et al., 2009; EEA, 2011b). Concentrations of ground-level ozone are determined by both precursor emissions and meteorological conditions, which also influence the transport of ozone and its precursors between continents (UNECE, 2011). Ground-level ozone is highly reactive and therefore harmful to vegetation, materials and human health. Short-term, high-level exposure can cause breathing problems and lung diseases, trigger asthma, and reduce lung function. The estimated effects of excessive exposure to ozone (exceeding the threshold of 70 µg/m^3) include about 20 000 premature deaths, and 14 000 respiratory hospital admissions every year in the EU-25, and up to 108 million person-days with minor activity restrictions, respiratory medication use, cough or lower respiratory symptoms (WHO, 2008a). Evidence of chronic effects (asthma and lung development) of long-term exposure to high ozone levels is still limited (WHO, 2008a; UNECE, 2011). There is a scarce evidence that high ozone levels can further increase mortality during heat waves (Filleul et al., 2006).

Past trends

There is no clear trend in the annual mean concentration of ozone recorded at different types of stations (urban vs. rural) over the period 1999–2009, although there is a slight decreasing tendency since 2006 in rural stations, at various geographical levels, both low-level and high-level (Figure 4.8). Meanwhile, a slight tendency towards increased annual mean concentrations is detected close to traffic. Ozone precursor emissions in Europe have been cut substantially recently whereas average ozone concentrations in Europe have largely stagnated. Meteorological variability and climate change could play a role in this discrepancy, including by increasing emissions of biogenic non-methane volatile organic compounds (NMVOCs) during wildfires, but increasing intercontinental transport of ozone and its precursors in the Northern Hemisphere also needs to be considered (EEA, 2010b; c). Formation of tropospheric ozone from increased concentrations of CH_4 may also contribute to the sustained ozone levels in Europe (EEA, 2012).

The relative contributions of local or regional emission reduction measures, specific meteorological conditions (such as heat waves), hemispheric transport of air pollution and emissions from natural sources (such as wildfires), on overall ozone concentrations is difficult to estimate. A statistical analysis of ozone and temperature measurements in Europe for 1993–2004 shows that in central-western Europe and the Mediterranean

Figure 4.8 Annual mean ozone concentrations (1999–2009) by station type



Source: EEA, 2011b.

Key messages: 4.4.5 Air pollution by ozone and health

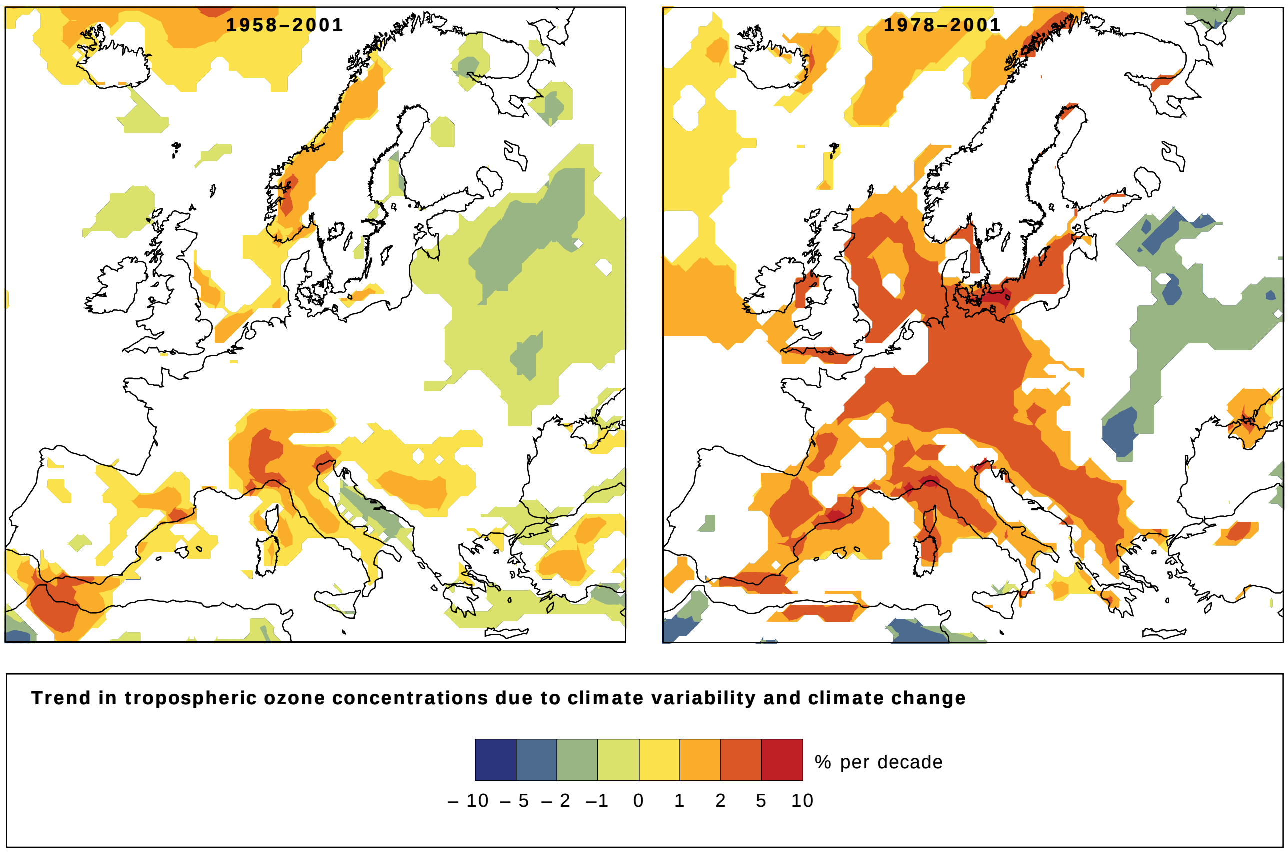
- Ozone is both an important air pollutant and a GHG. Excessive exposure to ground-level ozone is estimated to cause about 20 000 premature deaths per year in Europe.
- Attribution of observed ozone exceedances, or changes therein, to individual causes, such as climate change, is difficult.
- Future climate change is expected to increase ozone concentrations but this effect will most likely be outweighed by reduction in ozone levels due to expected future emission reductions.

area a change in the increase in daily maximum temperatures in 2000–2004 compared with 1993–1996 contributed to extra ozone exceedances. In southern and central Europe, the observed temperature trend was responsible for 8 extra annual exceedance days (above the threshold of 120 µg/m³) on average, which corresponds to 17 % of the total number of exceedances observed in that region (EEA, 2008). A modelling study suggests that observed climate variability and change have contributed to increased ozone concentrations during the period 1979–2001 in large parts of central and southern Europe (Andersson et al., 2007). The reason for this is a combination of changes in temperature, wind patterns, cloud cover and atmospheric stability. Temperature plays a role in various processes which directly affect the formation of ozone, like the emission of biogenic NMVOCs, for example isoprene, and the photo-dissociation of nitrogen dioxide (NO_2).

A study by (Wilson et al., 2012) showed that ozone trends in Europe in the years 1997–1998 were influenced by El Niño and biomass burning events and in the year 2003 by the heat wave in north-west Europe. The study did not conclude on the impact of emission reduction on long-term ozone trends, due to the influence of meteorological variability, changes in background ozone and shift in emission source patterns. Decreased anthropogenic emissions of some ozone precursors (NO_X, CO, and some NMVOCs) in the past two decades have reduced the number of peak ozone concentrations (EEA, 2011b; 2012).

In order to understand historical tropospheric ozone trends, further retrospective sensitivity analysis of precursor emission changes and hindcast modelling of ozone concentrations are needed to quantify the impact and variability of the various factors influencing ozone levels. Map 4.12 shows the estimated trends in tropospheric ozone concentrations over Europe for two time periods derived from such hindcast modelling. There has been a marked increase in ozone concentrations in many regions from 1978 to 2001. However, taking into account a longer perspective starting from 1958, increases are limited to a few European regions. Unfortunately, more recent data is not available.

Map 4.12 Modelled change in tropospheric ozone concentrations over Europe, 1958–2001 and 1978–2001



Source: Andersson et al., 2007, in EEA, 2008.

Projections

Climate change is expected to affect future ozone concentrations due to changes in meteorological conditions, as well as due to increased emissions of specific ozone precursors (e.g. increased isoprene from vegetation under higher temperatures) and/or emissions from wildfires that can increase under periods of extensive drought. Most of the links between individual climate factors and ozone formation are well understood (Table 4.3) (Jacob and Winner, 2009; Monks et al., 2009). Nevertheless, quantification of future levels of ground-level ozone remains uncertain due to the complex interaction of these processes. Available studies indicate that projected climate change affects different regions in Europe differently, by increasing average summer ozone concentrations in southern Europe and decreasing them over northern Europe and the Alps (Andersson and Engardt, 2010; Langner et al., 2012). Preliminary results indicate that in a long time perspective (2050 and beyond), envisaged emission reduction measures of ozone precursors have a much larger effect on concentrations of ground-level ozone than climate change (Langner et al., 2011). Climate change in combination with the emission reductions will influence the future levels of ground-level ozone.

Table 4.3 Selection of meteorological parameters that might increase under future climate change and their impact on ozone levels

Increase in...	Results in....	Impact on ozone levels ...
Temperature	Faster photochemistry	Increases (high NO_x) Decreases (low NO_x)
	Increased biogenic emissions (VOC, NO)	Increase
Atmospheric humidity	Increased ozone destruction	Increases (high NO_x) Decreases (low NO_x)
Drought events	Decreased atmospheric humidity and higher temperatures	Increases
	Plant stress and reduced stomata opening	Increases
	Increased frequency of wild fires	Increases
Blocked weather patterns	More frequent episodes of stagnant air	Increases
	Increase in summertime/dry season heat waves	Increases

Note: Level of understanding of the process is marked with colours: green (good understanding), orange (moderate understanding) and red (poor understanding).

Source: Royal Society, 2008.

4.4.6 Vector-borne diseases

Relevance

Climate change can lead to significant shifts in the geographic and seasonal distribution ranges of vector-borne diseases in Europe (Semenza and Menne, 2009).

Climate can affect vector-borne diseases by shortening the life-cycles of vectors and the incubation periods of vector-borne pathogens, thereby potentially leading to larger vector populations and higher transmission risks. Over the longer term, seasonal changes could affect both vectors and host animals, as well as human behaviours and land-use patterns, thereby further influencing the geographical distribution, seasonal activity and overall prevalence of vector-borne diseases in Europe (Lindgren et al., 2012). Furthermore, climatic suitability is essential for the arrival, establishment and spread of 'exotic' diseases that are not currently established in continental Europe. In addition to climate, the spread of communicable diseases depends on a range of interconnected ecological, economic and social factors, such as land-use patterns and fragmentation; biological diversity; the capacity of public health systems; travel, trade and migration; and human behaviours affecting individual risk factors (EEA, 2010a; Suk and Semenza, 2011).

Past trends

Vector-borne diseases are an emerging public health issue in Europe. Lyme borreliosis is the most common vector-borne disease in the EU, with a reported incidence of approximately 85 000 cases per year. The mean number of reported cases of tick-borne encephalitis (TBE) in Europe has been almost 2 900 per year during the period 2000–2010 (ECDC, 2011). However, these numbers need to be considered with care due to difficulties in diagnosis and case definition. Thus, the overall burden of these tick-borne diseases in Europe remains unclear.

Mosquito-borne diseases have not been a substantial concern within Europe until recently. However, locally transmitted outbreaks of Chikungunya, Dengue and even malaria have occurred in recent years. Periodical outbreaks have been reported in Greece and possibly neighbouring countries for leishmaniasis, a disease transmitted by sandflies which naturally occur in southern Europe.

Tick-borne diseases

TBE and Lyme borreliosis are the two most important tick-borne diseases in Europe, transmitted primarily by *I. ricinus*. A key determinant is the abundance of ticks, which is sensitive to climatic variables, notably temperature. Climate change may shift the distribution range of *I. ricinus* towards higher latitudes and altitudes, as milder winter temperatures, longer vegetation seasons and earlier onsets of summer appear and warmer temperatures occur (Jaenson and Lindgren, 2011). There have already been reports on the northerly migration of the tick species in Sweden (Lindgren et al., 2000), and to higher altitudes in the Czech Republic (Daniel et al., 2003). Range shifts have also been observed in Germany and Norway (Semenza and Menne, 2009).

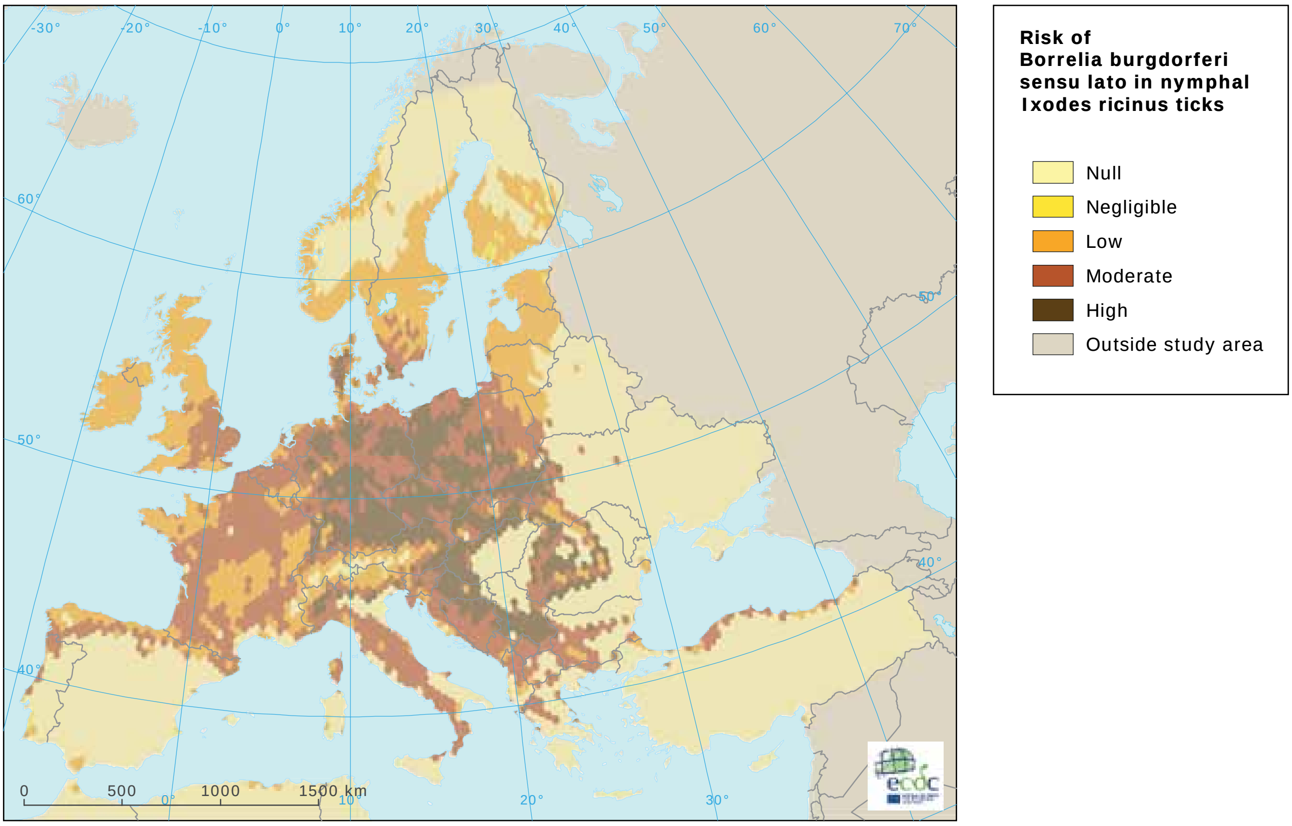
Map 4.13 shows the risk of the Lyme disease pathogen (*Borrelia burgdorferi*) in Europe. High risk is associated with mild winters, high summer temperatures, low seasonal amplitude of temperatures and high scores on vegetation indices (Estrada-Pena et al., 2011).

There are considerable differences between the distribution of ticks and the observed incidence of TBE (Süss et al., 2006). There has been a marked

Key messages: 4.4.6 Vector-borne diseases

- The transmission cycles of vector-borne diseases are sensitive to climatic factors but also to land use, vector control, human behaviour and public health capacities.
- Climate change is regarded as the main factor behind the observed northward and upward move of the tick species *Ixodes ricinus* in parts of Europe.
- Climate change is projected to lead to further northward and upward shifts in the distribution of *I. ricinus*. It is also expected to affect the habitat suitability for a wide range of disease vectors, including *Aedes albopictus* and *phlebotomine* species of sandflies, in both directions.

Map 4.13 European distribution of *Borrelia burgdorferi* in questing *I. ricinus* ticks



Note: The risks described in this figure are relative to each other according to a standard distribution scale. Risk is defined as the probability of finding nymphal ticks positive for *Borrelia burgdorferi*. For each prevalence quartile, associated climate traits were used to produce a qualitative evaluation of risk according to Office International des Epizooties (OIE) standards at five levels (high, moderate, low, negligible, and null), which directly correlate with the probability of finding nymphal ticks with prevalence in the four quartiles.

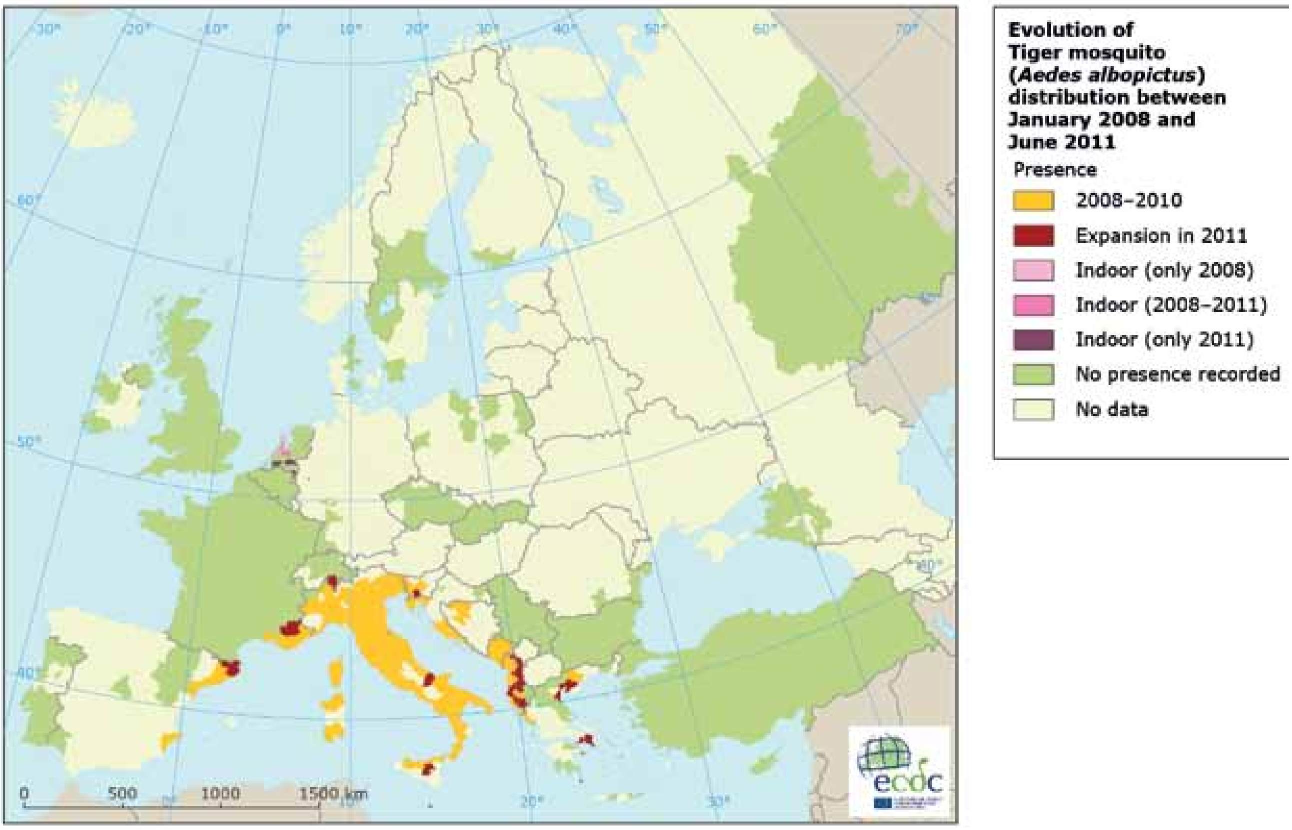
Source: Adapted from Estrada-Pena et al., 2011. © American Society for Microbiology.

upsurge of TBE in recent years but it is not currently possible to assess the relative importance of climatic changes and of other factors influencing disease incidence, including vaccination coverage, tourism patterns, public awareness, distribution of rodent host populations and socio-economic conditions (Randolph, 2008). There is limited evidence that two other tick-borne diseases may be sensitive to climate change. Some models have suggested that the Mediterranean basin has become suitable for an expansion of Crimean-Congo haemorrhagic fever (Maltezou and Papa, 2010), but demographic factors and land-use change may be more important drivers. Rickettsia has also expanded in recent years, but the reasons for this are not yet well understood (Gouriet et al., 2006).

Mosquito-borne diseases

Mosquito habitats are influenced by temperature, humidity and precipitation levels. The Asian tiger mosquito (*Aedes albopictus*) is an important vector in Europe transmitting viral diseases, including Chikungunya and Dengue. Since its establishment in Italy in 1990, *A. albopictus* has substantially extended its range, aided by trade and travel; it is present in several EU countries and in some countries neighbouring the EU (Map 4.14). Even larger parts of Europe are climatically suitable for *A. albopictus* (Map 4.15, left).

Map 4.14 Change in distribution of *Aedes albopictus* in Europe between 2008 and 2011



Note: Areas marked as '2011' indicate that the tiger mosquito was detected in 2011 for the first time. They include areas of known geographical expansion of *A. albopictus* in France, northern Italy and Spain where vector surveillance has been in place since 2008 but also areas in Albania, Greece, and central and southern Italy, where the first detection of the vector in 2011 could be the result of increased vector surveillance rather than actual geographical expansion. '2008–2010' refers to all areas where the vector has been present before 2011. Indoor presence corresponds to the presence recorded in greenhouses.

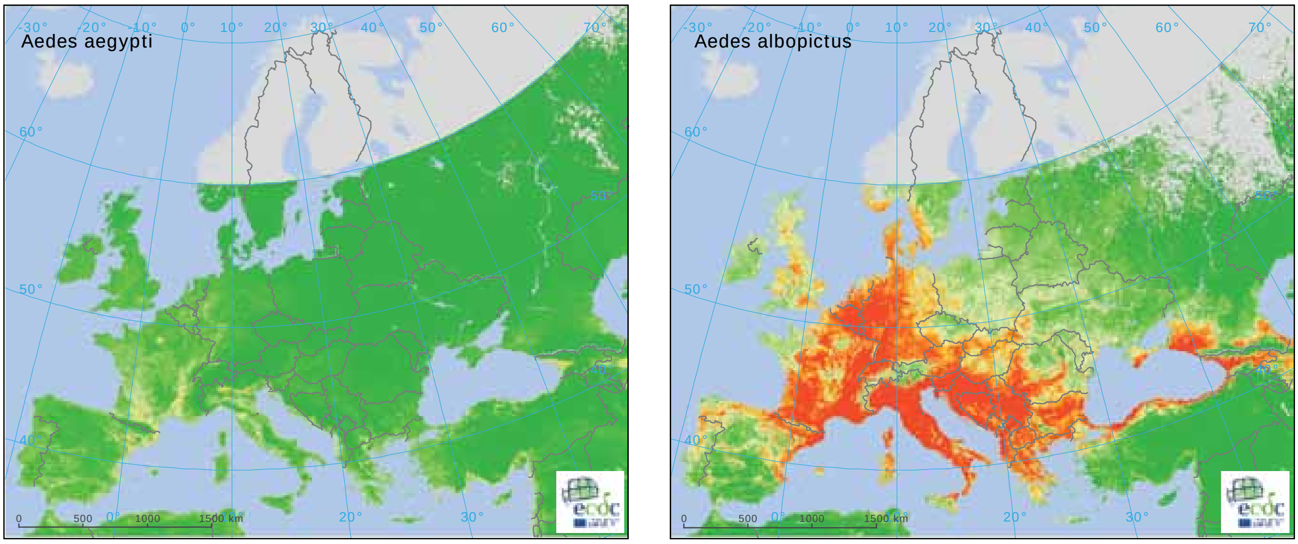
Source: See http://ecdc.europa.eu/en/activities/diseaseprogrammes/emerging_and_vector_borne_diseases/Pages/VBORNET.aspx. © European Centre for Disease Prevention and Control, 2012.

Several disease outbreaks transmitted by the mosquito *A. albopictus* were recently reported in Europe: Chikungunya in Italy (Rezza et al., 2007) and in France (Grandadam, 2011), as well as local transmissions of Dengue in France (La Ruche et al., 2010) and Croatia in 2010 (Gjenero-Margan et al., 2011). In all cases the virus has been imported to Europe by travellers. Some parts of Europe are currently climatically suitable to *A. aegypti*, a primary vector for Dengue (Map 4.15, right).

Malaria was largely eradicated in Europe in the second half of the 20th century (Semenza and Menne, 2009). However, the malaria vectors (*Anopheles mosquitos*) are still present in much of Europe, and a few cases of local transmission occur each year (Florescu et al., 2011). The risk of malaria re-establishment in a particular region depends on its **receptivity**, which refers to climatic and ecological factors favouring malaria transmission and to vector abundance, and on **vulnerability** to infection, which refers to either proximity to malarial areas or influx of infected people and/or infective mosquitoes (WHO, 2007).

Human cases of West Nile Virus (WNV) are relatively rare in Europe, and roughly 80 % of the cases are asymptomatic. The virus primarily infects birds and is transmitted to humans through mosquitoes (*Culex* sp.). WNV outbreaks in Europe have been associated with high temperature, rainfall and humidity (Paz and Albersheim, 2008; Semenza and Menne, 2009; Paz, 2012). Other factors influencing the WNV risk include the populations of migrating birds and reservoir hosts, and early detection and diagnosis.

Map 4.15 Climatic suitability for the mosquitos *Aedes albopictus* and *Aedes aegypti* in Europe



Climatic suitability for Aedes aegypti and Aedes albopictus (Asian tiger mosquito) in Europe

Suitability (%)

0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–100 | No prediction

Note: Climatic suitability for the mosquitos *Aedes albopictus* (left) and *Aedes aegypti* (right) in Europe. Darker to lighter green indicates conditions not suitable for the vector whereas yellow to orange colours indicate conditions that are increasingly suitable for the vector. Grey indicates that no prediction is possible.

Source: ECDC, 2012. © European Centre for Disease Prevention and Control, 2012.

Sandfly-borne diseases

Leishmaniasis is the most common disease transmitted by sandflies in Europe. Transmission of the two parasites responsible for this disease that are endemic in the EU (*Leishmania infantum* and *L. tropica*) is heavily influenced by temperature. *L. tropica* occurs sporadically in Greece and neighbouring countries, while *L. infantum* is endemic in the Mediterranean region of the EU. Sandfly vectors currently have wider distribution ranges than the leishmaniasis pathogens. The evidence of an impact of climate change on the distribution of sandfly in Europe is scarce (Ready, 2010). Climate change was suggested as one possible reason for the observed northward expansion of sandfly vectors in Italy (Maroli et al., 2008).

Projections

Tick-borne diseases

An expansion of the distribution range of ticks to higher altitudes and latitudes is projected under future warming (Jaenson and Lindgren, 2011) under the condition that their natural hosts (deer) would also shift their distribution. TBE is projected to shift up to higher altitudes and latitudes, potentially increasing the risk in some parts of northern and central Europe, unless targeted vaccination programmes and TBE surveillance are introduced. TBE risk is generally projected to decrease in southern Europe. Warmer winters may facilitate the expansion of Lyme borreliosis to higher latitudes and altitudes, particularly in northern Europe, but it would decrease in parts of Europe projected to experience increased droughts (Semenza and Menne, 2009).

Mosquito- borne diseases

Various studies have found that warm seasonal and annual temperature and sufficient rainfall provide favourable climatic conditions for *A. albopictus* in Europe (Medlock et al., 2006; Roiz et al., 2011). The climatic suitability for *A. albopictus* is projected to increase in central and western Europe and to decrease in southern Europe (Fischer, Thomas, et al., 2011). The risk of Chikungunya may also increase, particularly in those regions in Europe where the seasonal activity of *A. albopictus* matches the seasonality of endemic Chikungunya infections abroad (Charrel et al., 2008), thereby potentially increasing the importation risk.

Climate-related increase in the *A. albopictus* density or active season could lead to a small increase in risk of Dengue in Europe. The risk could also increase should temperature increase facilitate the re-establishment of *A. aegypti*, the primary Dengue vector. Further modelling studies are required to assess whether climate change would increase or decrease the climatic suitability for *A. aegypti* in continental Europe.

Some climate-related change in malaria **receptivity** in Europe is suggested, but probably not enough to re-establish malaria. The largest threat in Europe relates to population **vulnerability**, which is influenced by sporadic introductions of the parasite through global travel and trade.

Climate change is not generally expected to strongly impact on WNV in Europe (Gale et al., 2009; Gould and Higgs, 2009). However, it could influence the virus transmission through affecting the geographic distribution of vectors and pathogens, and changed migratory patterns of bird populations, as well as through changes in the life-cycle of bird-associated pathogens.

Sandfly diseases

Future climate change could impact on the distribution of leishmaniasis by affecting the abundance of vector species and parasite development. Recent modelling indicates that the central European climate will become increasingly suitable for *Phelobotomus* spp. sandflies, thereby increasing the risk of leishmaniasis, but such an expansion would be somewhat constrained by the limited migration ability of sandflies (Fischer, Moeller, et al., 2011). The risk of disease transmission may decrease in some areas in southern Europe where climate conditions become too hot and dry for vector survival.

4.4.7 Water- and food-borne diseases

Relevance

Climate change could affect food- and water-borne diseases in Europe through higher air and water temperatures, through increases in heavy rainfall events and through extreme events, such as flooding, which can lead to contamination of drinking, recreational or irrigation water, and to disruption of water supply and sanitation systems (WHO, 2011b). Potential impacts will be modulated by the quality of food safety measures, the capacity and quality of water treatment systems, human behaviour, and a range of other conditions.

Elevated air temperatures could negatively affect the quality of food during transport, storage and handling. Higher water temperatures increase the growth rate of certain pathogens, such as *Vibrio* species that can cause food-borne outbreaks (seafood). On rare occasions, they may lead to severe necrotic ulcers, septicemia and death in susceptible persons with wounds that are bathing in

Key messages: 4.4.7 Water- and food-borne diseases

- It is not possible to assess whether past climate change has already affected water- and food-borne diseases in Europe.
- Climate change will likely increase the risk of food- and water-borne diseases in many parts of Europe.
- Increased temperatures could increase the risk of salmonellosis.
- Where precipitation or extreme flooding is projected to increase in Europe, the risk of campylobacteriosis and cryptosporidiosis could increase.
- Climate change can impact food safety hazards throughout the food chain.

contaminated waters (Lindgren et al., 2012). Floods and increased water flows can lead to contamination of drinking, recreational or irrigation water and thus increase the risk of water-borne diseases, such as cryptosporidiosis.

It is not currently possible to attribute past trends in these diseases, or individual outbreaks, to climate change due to data gaps for selected pathogens and climatic determinants. The current knowledge on the relationship between climatic factors and the risk associated with several climate-sensitive food- and water-borne diseases (caused by bacteria, viruses and parasites) in Europe is presented below.

Campylobacter

Incidence of campylobacteriosis has been linked to mean temperatures, though not consistently (Fleury et al., 2006; Bi et al., 2008). High ambient temperatures and relatively low humidity have been linked with increased incidence (Patrick et al., 2004; Lake et al., 2009). Assessment of this relationship is difficult, as *Campylobacter* does not replicate outside its animal host and the seasonal incidence peak does not occur during the hottest time of the year. Rain in early spring can trigger campylobacteriosis outbreaks (WHO, 2008b). Outbreaks tend to occur more often in rural areas, where households are supplied by private water sources, more susceptible to contamination during extreme weather events (Pebody et al., 1997; Hearnden et al., 2003). With the projected increase in heavy rainfall events in northern Europe, the risk of surface and groundwater contamination is expected to rise. Climate change might increase the use of rainwater during times of drought in certain locations. If the harvesting of rainwater increases, *Campylobacter* in untreated roof run-off water might contribute to an increased risk of both animal and human disease (Palmer et al., 1983; Savill et al., 2001).

Salmonella

A raise in weekly temperature is followed by an increase in salmonellosis in different settings (Naumova et al., 2006; Zhang et al., 2007; Nichols et al., 2009). Ambient seasonal temperatures are suspected drivers of reported salmonellosis cases, but an influence of temperature might be attenuated by public health interventions (Lake et al., 2009). Seasonal detection frequencies for *Salmonella* sp. in water environments were related to monthly maximum precipitation in summer and fall following faecal contamination events (Craig et al., 2003; Martinez-Urtaza et al., 2004). Floods caused by heavy rainfall events may disrupt water treatment and sewage systems and contribute to increased exposure to *Salmonella* sp. and other pathogens. Salmonellosis continues to decline in Europe over the last decade, in part due to control measures. Thus, health promotion and food safety policies should be able to mitigate adverse impacts on public health.

Available projections indicate that by the 2020s, under the A2 scenario, the average annual number of temperature-related cases of salmonellosis in Europe may increase by almost 20 000 as a result of climate change, in addition to increases expected from population changes. By the 2071–2100 period, climate change could result in up to 50 % more temperature-related cases than would be expected on the basis of population change alone. However, these estimates need to be interpreted with caution, due to high uncertainty (Watkiss and Hunt, 2012).

Cryptosporium

Heavy rainfall has been associated with the contamination of water supplies and outbreaks of cryptosporidiosis (Aksoy et al., 2007; Hoek et al., 2008), as the concentration of *Cryptosporidium* oocysts in river water increases significantly during rainfall events. Dry weather conditions preceding a heavy rain event has also been associated with drinking water outbreaks (Nichols et al., 2009). Thus, heavy precipitation can result in the persistence of oocysts in the water distribution system and the infiltration of drinking water reservoirs from springs and lakes. A rise in precipitation is predicted to lead to an increase in cryptosporidiosis, although the strength of the relationship varies by climate category (Jagai et al., 2009)

Norovirus

Food-borne norovirus outbreaks have been linked to climate and weather events; for example, heavy rainfall and floods may lead to wastewater overflow which can contaminate shellfish farming sites. Flood water has been associated with a norovirus outbreak in Austria (Schmid et al., 2005). The magnitude of rainfall has also been related to viral contamination of the marine environment and with peaks in diarrhoea incidence (Miossec et al., 2000). The predicted increase of heavy rainfall events under climate change scenarios could lead to an increase in norovirus infections because floods are known to be linked to norovirus outbreaks.

Vibrio (non-cholera)

Vibrio sp. propagates with rising water temperatures and exploits prolonged periods of permissive environmental conditions (Pedersen et al., 1997). In the Baltic Sea, notified *V. vulnificus* infections occur during hot summer months and augment with water temperatures above 20 °C (Hemmer et al., 2007). There is evidence of a link between elevated summer (water) temperatures, extended summer seasons and non-cholera *Vibrio* sp. infections, but the disease increase is projected to be modest due to low current incidence rates. The recent analysis of the long-term sea surface temperature data revealed an unprecedented rate of the Baltic Sea warming (0.063–0.078 °C per year from 1982 to 2010), and found strong links between the temporal and spatial peaks in sea surface temperatures and the number and distribution of *Vibrio* infections in the Baltic Sea region (Baker-Austin et al., 2012).

4.5 Energy

4.5.1 Overview

Relevance

Energy plays a fundamental role in supporting all aspects of modern life. This sector is responsible for the majority of anthropogenic GHG emissions (EEA, 2012). At the same time, both energy supply and energy demand are sensitive to changes in climate, in particular in temperature.

The increasing frequency of extreme weather events, including heat waves, droughts and potentially storms, poses additional challenges for energy systems (Rademaekers et al., 2011). In particular, thermal power plant efficiency and output can be adversely affected by a rise in temperature or a decrease in availability of cooling water. Storms and extreme wind gusts could also pose a challenge for the energy infrastructure, such as transmission and distribution networks, as well as for renewable generators. Increased flooding could affect power stations and substations. Changed precipitation patterns or variability could add greater uncertainty for investing in hydropower facilities and alter output, but may also result in local benefits from increased hydropower output from facilities in some countries. Hydropower production could also be impacted by increased silting of sediment into reservoirs due to increased erosion and sediment displacement as a consequence of climate change. Renewable energy supply may also be impacted by climate change, in particular by impacts on the production of bioenergy but also on wind turbines and solar cells.

Indicator selection

This section uses one indicator, heating degree days (HDD), to present information on climate impacts on energy demand. An additional subsection presents information on changes in electricity demand and electricity production, which does not qualify to be presented as an indicator due to limited data availability. Some limited information on the costs of projected impacts on the energy sector is provided in Section 5.5.2.

Key messages: 4.5 Energy

- The number of heating degree days has decreased by an average of 16 per year since 1980. This helps reduce the demand for heating, particularly in northern and north-western Europe.
- Climate change will affect future energy and electricity demand. Climate change is not expected to change total energy demand in Europe substantially across Europe, but there may be significant seasonal effects, with large regional differences.
- Climate change is projected to strongly increase energy demand for cooling in southern Europe, which may further exacerbate peaks in electricity supply in the summer.
- Further increases in temperature and droughts may limit the availability of cooling water for thermal power generation in summer when the abundance of cooling water is near its lowest.
- Both renewable and conventional electricity energy generators may be impacted by changing temperatures, rainfall patterns and possible increases in storm severity and frequency. Most impacts will be negative, although some localised positive impacts may occur.

Data quality and data needs

Data for calculation of HDD have been collected by Eurostat for decades; this indicator can therefore be considered as very reliable. The same data used could also be used for the calculation of cooling degree days. Such an indicator is currently not available even though it would be highly policy-relevant and could be calculated with little additional effort. It should be noted that the indicator HDD is a purely physical metric, which does not consider differences in technical, social and economic factors (housing quality, behaviour, prices, etc.) between regions and their development over time.

Information on past and projected impacts of climate change on electricity demand and electricity generator output is very fragmented. The signal of long-term climate change may be difficult to detect due to concurrent changes in technical, social, behavioural and economic aspects, whereas the effects of extreme events are generally easier to detect.

4.5.2 Heating degree days

Relevance

A 'Heating Degree Day' (HDD) is a proxy for the energy demand needed to heat a home or a business; it is derived from measurements of outside air temperature. The heating requirements for a given structure at a specific location are considered to be to some degree proportional to the number of HDD at that location. However, they also depend on a large number of other factors, notably in relation to income levels, building design, energy systems and behavioural aspects. HDD are defined relative to a base temperature ([67]), the outside temperature below which a building is assumed to need heating.

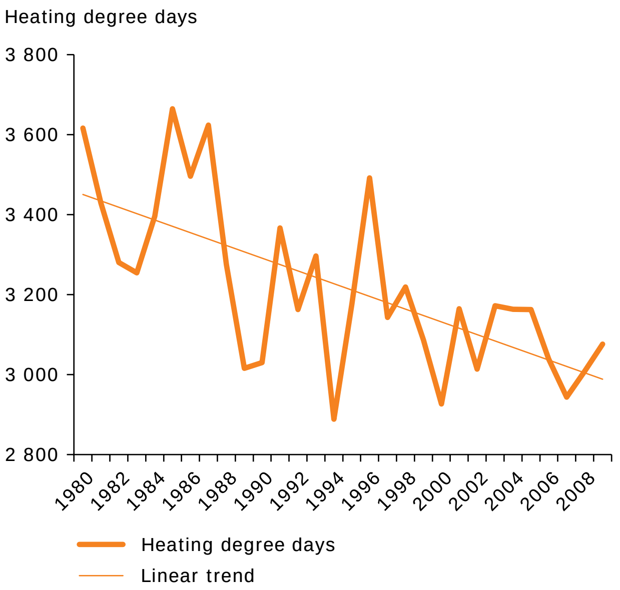
Space heating is responsible for a large component of European energy use, so a decrease in the use of space heating has the potential to lead to a significant decrease in overall energy use. There are many contributory factors to heating demand, such as the energy performance of the building envelope, the type of heating system available, occupant behaviour and energy prices. However, the external temperature is the only component which is directly affected by climate change. The number of HDD is therefore a proxy for the energy demand for space heating, and hence an indicator for possible changes in overall energy use directly related to climate change.

An increase in cooling demand would off-set in part or completely the gains from a reduced energy demand for space heating and the effects resulting from a reduction in heating demand. While heating is delivered to end users in different ways (individual boilers fuelled by oil, gas, and coal, and electricity and district heating), cooling is delivered currently almost exclusively through electricity. As a result, a given increase in cooling demand is generally associated with higher costs, a higher increase in primary energy demand and larger impacts on the peak capacity of supply networks than the same decrease in heating demand.

Past trends

The number of HDD has decreased by 13 % over the last 3 decades, yet with substantial interannual variation (Figure 4.9). Map 4.16 shows that the decrease in HDD has not been homogeneous across

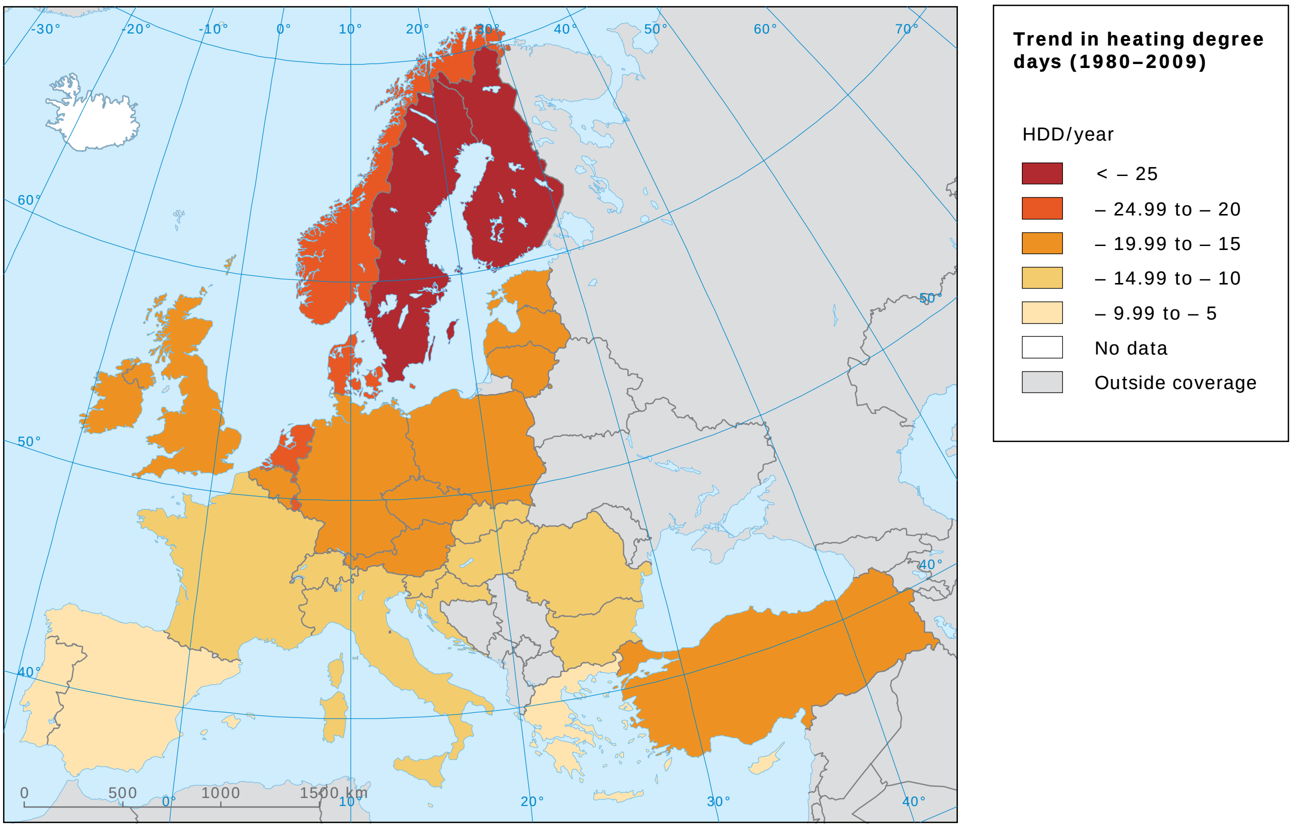
Figure 4.9 Trend in heating degree days in the EU-27 (1980–2009)



Source: Eurostat, 2012.

([67]) Eurostat calculates HDD as (18 °C — Tm) x d if Tm is lower than or equal to 15 °C (heating threshold) and zero if Tm is greater than 15 °C, where Tm is the mean (Tmin + Tmax/2) outdoor temperature over a given period of d days.

Map 4.16 Trend in heating degree days in the EU-27 (1980–2009)



Source: Eurostat, 2012.

Europe. The absolute decrease has been largest in the cool regions in northern Europe where heating demand is highest.

Projections

Temperatures in Europe are projected to continue to increase. Hence, the trend of decreasing numbers of HDD is very likely to continue, and most likely to accelerate. For example, the heat demand for space heating in 2050 was projected to decrease by 25 % in the United Kingdom (Flörke et al., 2011), and by 9 % in the EU ([68]).

4.5.3 Electricity demand and production

A number of studies have modelled future electricity demand in a changing climate. Approximately 30 % of Europe's domestic space heating requirement is provided by electricity, but with substantial variation across countries (Mideksa and Kallbekken, 2010). Cooling is almost exclusively provided by electricity. Therefore, changes in heating demand, and even more so in cooling demand, will directly influence electricity demand.

No systematic analysis is available on the relationship between past climate and electricity demand. A number of studies have looked at projected trends for different European countries, and the results are summarised in Table 4.4. The variation in projected demand for electricity is usually a result of the selection of climate change scenario. It is worth noting that an increased electricity demand peak in the summer would coincide with increased difficulty in obtaining sufficient cooling water for thermal power generation during very hot conditions (Förster and Lilliestam, 2009).

([68]) Pre-publication of results from the ClimateCost project (http://www.climatecost.cc).

Table 4.4 Overview of studies on future electricity demand due to climate change

Study	Region	Date of projection	Annual change in electricity demand	Peak demand
(Pilli-Sihvola et al., 2010)	Germany, Spain, France, the Netherlands and Finland	2015–2050	Decreases in northern countries, increase in Spain; overall neutral	+ 2 % to + 4 %, Spain
(Mirasgedis et al., 2007)	Greece	2070–2100	+ 3 % to + 6 %	+ 13 %, June
(Eskeland and Mideksa, 2010)	Europe	2100	Small, but disguises large regional variations	+ 20 %, Turkey
(Mima et al., 2012)	Europe	2010–2100	Increase of 12 % by 2050 rising to 24 % by 2100 (EU-27) due to electricity for cooling demand above future baseline (A1B scenario), reduced to 8 % across period for E1 mitigation scenario. Strong regional variations, with greater increases in southern Europe	

Fossil-powered and nuclear electricity generators are sensitive to a reduced availability and increased temperature of cooling water, and to increased air temperature, which reduces their efficiency (World Bank, 2011, p. 33). Nuclear plants are particularly susceptible in this regard (Linnerud et al., 2011; Rübbelke and Vögele, 2011).

The literature on change in output from electricity generators due to climate change is rather sparse. Considerable reductions in river flow during the 2004–2005 drought across the Iberian Peninsula, resulted in a 40 % drop in hydroelectric power production, which had to be replaced by electricity from thermoelectric power plants (García-Herrera et al., 2007). Similarly in 2005, Portugal had to compensate for low hydro-electrical production by using fossil fuel worth EUR 182 million, with an additional expense of EUR 28 million to purchase CO_2 emissions licenses. The total cost was finally estimated at EUR 883 million, equivalent to 0.6 % of GDP (Demuth, 2009).

A recent study estimated changes in the capacity of thermoelectric power plants in Europe due to changes in temperature and river flow based on a multi-model GCM ensemble (Vliet et al., 2012). This study projects decreases in the capacity of power plants due to climate change by 6–19 % in the 2040s, compared to the 1980s control period depending on cooling system type and climate scenario. Increases are projected for most of Scandinavia and decreases for the rest of Europe. A study examining the impacts of climate change on hydropower and nuclear electricity output identified Austria, France and Switzerland as particularly vulnerable countries (Rübbelke and Vögele, 2011, p. 14).

The conclusions from the stress test applied to European nuclear power plants in the aftermath of the Fukushima accident, with respect to the adequacy of preparedness of these plants in the event of natural hazards (earthquakes, flooding) and extreme weather events were that further improvements can be made, particularly in the case of preparedness for extreme weather events (EC, 2011; ENSREG, 2012). The International Atomic Energy Agency (IAEA) has developed guidelines that represent good practice to increase robustness against natural hazards and extreme events that are expected to be implemented in a number of European countries as a result of the stress test (IAEA, 2011). Renewable electricity generators are most susceptible to changes in precipitation which affect the output of hydropower plants, and potentially to extreme storm gusts which might damage wind turbines. The performance of solar photovoltaic modules is also reduced in hot weather.

The ClimWatAdapt project assessed changes in seasonal water availability as a proxy for risks to hydropower potential, with the largest reductions shown in many regions of southern Europe. However, the study could not quantify the risks to electricity production because it did not include information on dams, reservoirs and hydropower stations (Flörke et al., 2011). A study by the Directorate-General for Energy (DG ENER) assessed adaptation costs for nuclear power stations and other energy infrastructure based on stakeholder consultation (Rademaekers et al., 2011).

The United Kingdom has performed a national-level climate change risk assessment of the energy sector (see Box 4.2). In addition, several localised studies assessed potential climate change impacts on individual power stations or water catchments.

Box 4.2 Case study — UK Climate Change Risk Assessment for the energy sector

In January 2012 the United Kingdom published its climate change risk assessment (CCRA), which included in-depth analysis of the risks to 11 sectors, one of which was energy. The CCRA considered different 'tiers' of risk; Tier 1 identifies a broad range of potential impacts, and Tier 2 provides a more detailed analysis, including quantification and monetisation.

The topics considered as Tier 2 include:

- flooding of energy infrastructure;
- flooding of power stations;
- demand for cooling;
- heat-related damage/disruption;
- water abstraction.

These topics were considered as a high priority because they are considered relatively urgent, with the potential for large-scale impact, and with a high likelihood of being affected by rising temperatures and other climatic variables.

Outputs from the analysis include:

- an increase in power stations 'at risk' of flooding, from 19 today to 26 in the 2020s, to 38 in the 2080s;
- an increase in building cooling-demand needs and electricity demand of about 4 % annually;
- a possible risk to power generation from reduced future availability of abstracted water;
- a possible effect of increasing temperature (and other indirect factors) could potentially reduce overall thermal power generation efficiency.

4.6 Transport services and infrastructure

4.6.1 Overview

Land-based transport infrastructure and operation are sensitive to changes in climate, including snow and rainfall patterns, coastal and inland flooding, wind storms and heat waves. In the far north, semi-permanent frost structures may become unusable for larger portions of the year. Water-based transport is particularly sensitive to river droughts and changes in ice cover of oceans and inland waters. Some impacts of climate change may be positive, such as a decrease in the ice cover of oceans and rivers, but most of them will be negative (Koetse and Rietveld, 2009). In the Arctic, climate change is opening up new transport lanes and enables the exploitation of both natural and mineral resources (see Section 2.3.6 on Arctic sea ice). While this can be of benefit for the regional and global economy, it will also have repercussions on the Arctic's fragile environment if not managed with the utmost care (EC, 2012).

Table 4.5 provides an overview of potential impacts of climate change on transport infrastructure.

Key messages: 4.6 Transport services and infrastructure

- Data on past climate-related impacts on transport is restricted to individual extreme events, and attribution to climate change is generally not possible.
- Information on the future risks of climate change for transport in Europe has improved recently due to several EU research projects focusing on climate change, extreme weather events and inland water transport.
- Climate change is projected to have both beneficial and adverse impacts on transport, depending on the region and the transport mode.
- Available projections suggest that rail transport will face the highest percentage increase in costs from extreme weather events. The British Islands, central Europe/France, eastern Europe and Scandinavia are projected to be most adversely impacted.

Table 4.5 Overview of climate change impacts on transport infrastructure

Factor	Effect	Impact on infrastructure/services
1. Temperature	**Change of distribution patterns, higher average and maximum temperature**	
1.1 High temperatures and heat waves	Overheating	Infrastructure equipment, lifetime reduction, reliability of the electronic and the electric components (i.e. rail rolling stock equipment); slope instabilities due to the thawing of permafrost in alpine regions
1.2 Sudden temperature changes	Tension, overheating	Rail track buckling, slope fires, signalling problems
1.3 Intense sunlight		
1.4 Freezing and thawing cycles	Soil erosion	Damage to embankments, earthwork
2. Precipitation	**Change of distribution patterns, more extreme events**	
2.1 Intense rainfall	Soil erosion, landslides, flooding	Damage to embankments, earthwork Road traffic safety: risk of collisions as a result of bad weather conditions Risk of weather-related delays in all modes of services
2.2 Extended rain periods	Slower drainage, soil erosion	Rail infrastructure assets, operation
2.3 Flooding: coastal, surface water, fluvial	Landslides	Drainage systems, tunnels, increased scour of bridges Risk of weather-related delays in all modes of services
2.4 Drought	Desiccation	Earthworks desiccation Road traffic safety: risk of collisions as a result of dust on road and consequent decrease of wheel grid Increased abrasion of mechanical components Potential change of water levels on navigable rivers (very low levels during summer and high levels in rain periods)
2.5 Snow and ice	Heavy snowfall, avalanches	Restrictions/disruption of train operations Road traffic safety: risk of collisions as a result of bad weather conditions Risk of weather-related delays in all modes of services
3. Wind	**Change of distribution patterns, more extreme events**	
3.1 Storm/gale (inland)	Higher wind forces	Damage to rail installations, catenary All modes potential traffic disruptions and safety concern
	Uprooting of trees	Restrictions/disruption of train operation Road traffic safety
3.2 Coastal storms and sea-level rise	Coastal flooding	Embankments, earthwork, operation
4. Lightning strikes and thunderstorms	**Overvoltage**	**Catenary, traffic control and communications systems**
5. Vegetation	**Faster plant growth, new plants**	**Vegetation management**

Source: Adapted from Nolte et al., 2011 to incorporate main impacts on all modes of transport.

Data on past climate-related impacts on transport are restricted to individual extreme events, and attribution to climate change is generally not possible. Some countries in Europe have assessed potential climate impacts on their transport infrastructure and/or adaptation options (e.g. the United Kingdom (UKCIP, 2011; Thornes et al., 2012), Spain (Crespo Garcia, 2011), Germany (Deutsche Bundesregierung, 2008) and Switzerland (BAFU, 2012). The level of detail in the analysis and the consideration of the potential risks and impacts on the different modes and on the transport sector as a whole differ considerably. The UK CCRA for the transport sector highlights extreme weather events as the main challenge for the maintenance and operation of existing infrastructure.

The literature on potential economic impacts of climate change on transport infrastructure is still scarce but rapidly evolving. Most sector-specific studies on potential climate impacts and adaptation options focus on river transport (see Section 4.6.2) and on rail infrastructure (Nolte et al., 2011). Climate impacts on road transport can be both beneficial and adverse. Reduced snow and ice cover would improve traffic conditions, but increasing severity of storms would worsen them (see also Section 4.6.3). The remainder of this section presents results from three research projects addressing climate change impacts on transport that were funded under the Seventh Framework Programme for Research (FP7) of the European Commission.

4.6.2 Inland water transport

The FP7 project ECCONET ([69]) assesses the impact of climate change on inland waterway transport (IWT) as well as possible adaptation measures. The project uses the Rhine–Main–Danube corridor as a case study with special emphasis on low water situations, which are most problematic for IWT. Over a period of 20 years, the average annual welfare loss due to low water levels on the Rhine was calculated at EUR 28 million; the 2003 extreme low-water year was associated with a welfare loss of EUR 91 million (Jonkeren et al., 2007). Other climate-related changes, such as high water levels, changed ice formation or a change in visibility due to fog, are assessed only briefly in ECCONET.

Results based on projections from different climate models show no significant effects on low flow conditions for the Rhine canal and the Rhine-Main-Danube canal until 2050. The upper Danube would experience a moderate increase in low flow conditions. The trend towards drier summers and wetter winters will gain in importance towards the end of the 21st century. Disposition for ice formation on both the Rhine and Danube will most likely decrease over the whole 21st century (Nilson et al., 2012).

Simulations with the NODUS transport model (Jonkeren et al., 2011) suggest that projected climate change until 2050 is unlikely to impact the Rhine hydrology strong enough to induce any significant shift in modal shares. The study estimates that a 'dry' year leads to approximately a 6–7 % increase in total transport cost compared to a 'wet' year, but these variations are already present under the current climate conditions and will not be influenced heavily by climate change until the 2050s. Low water levels could also trigger further impacts due to interruptions of coal supply to power stations (Rothstein and Halbig, 2010).

4.6.3 Impacts of changes in weather extremes

Two FP7 projects assessed the impacts of climate change and extreme weather conditions on transport systems: WEATHER ([70]) and EWENT ([71]). The WEATHER project aimed at identifying risks, economic impacts, and suitable crises management and transport adaptation strategies for all modes of transport across Europe. The EWENT project looked more deeply into long-term weather scenarios and the sensitivities of transport modes by following a standard risk assessment process. Note that the definition of extremes strongly varies between approaches. In both projects it had to be acknowledged that there is a lag of reliable statistical data for a sound vulnerability assessment of transport modes in the European region.

The WEATHER project considered the following extreme events: hot and cold spells, floods, landslides, wild fires and storms. Data were gathered through studies of various weather phenomena on transport in North America, Australia, Europe and New Zealand, a review of over 1 000 damage reports for 6 countries, and an assessment of available transport operator data for some European transport networks. The combined results have been extrapolated to eight European climate zones using meteorological indicators as well as infrastructure coverage and transport performance indicators. The standard cost values were considered specifically for public transport services, time losses and safety impacts for transport users. In addition, the assessment of indirect costs imposed by transport disruptions on other economic sectors was estimated.

For the assessment period 1998 to 2010, the total costs borne by the transport sector (damages, repair and maintenance costs of infrastructures, vehicle damages, increased system operation costs, etc.) across all weather phenomena were estimated at EUR 2.5 billion per year. The indirect costs of transport disruptions on other sectors were estimated at EUR 1 billion per year. Rail is the most affected transport mode in relation to passenger and tonne kilometres, with hot

([69]) See http://www.ecconet.eu.
([70]) See http://www.weather-project.eu.
([71]) See http://ewent.vtt.fi.

spots in eastern Europe and Scandinavia largely caused by hydrological phenomena and their consequences. The effects on roads are more evenly distributed across Europe with somewhat higher costs in mountain areas and Scandinavia. The high vulnerability of road and rail infrastructure in mountain areas can be explained by the usually expensive infrastructures, while the high vulnerability of rail is due to the more complex reaction mechanisms in emergency cases. Projections for the period 2040–2050 (based on predictions of extremes taken from the EWENT project) suggest that rail will face the highest cost increase, with particular emphasis on the British Islands, central Europe and Scandinavia, mostly due to increases in hydrological extremes.

The EWENT project assessed average annual costs due to weather extremes for the current (1998–2010) and a future (2041–2070) time period. Costs comprise accident costs, time costs, infrastructure damage and maintenance, and effects on freight and logistics. EWENT estimates costs from extreme weather events in the baseline period of more than EUR 15 billion, which is dominated by the costs of road accidents. This estimate is more than four times above the estimates of direct and indirect costs from the WEATHER project. The main reasons for this difference are a wider definition of extreme events in EWENT, inclusion of externalities (accidents), and the explicit consideration of non-motorised travel and logistics among other aspects, which were omitted by the WEATHER project.

According to results from EWENT, different regions in Europe will respond to future changes in different ways. In Northern Europe, cold spells will become less frequent but the amount of snow (especially for the thresholds of deeper snow coverage) will increase. Continental climate in Eastern Europe will continue to warm up and this results in less cold spells and snow. Similar developments will be observed in Central Europe and the Alpine region. In the maritime region the main threat is the potential increase in strong winds. This will also be observed in the Mediterranean region, where also the heat waves are becoming more prolonged by 2050 (Leviäkangas et al., 2011; Vajda et al., 2011). Road transport is projected to experience beneficial and adverse impacts, with somewhat complex regional patterns. Rail transport experiences mostly negative impacts, with the exception of the Iberian Peninsula; the most severe impacts are projected for the British Isles and France. Aviation is projected to experience negative impacts throughout Europe. Negative impacts across all transport modes are projected for Scandinavia, the British Isles, France, and Eastern Europe. These projections are largely consistent with those of the WEATHER project discussed above.

EWENT also assessed changes in the overall costs of extreme events on the transport sector. These costs are projected to decrease substantially in the future but this decrease is driven primarily by reduced costs of road accidents due to improved vehicle safety technologies. Follow-on costs on freight and logistics are expected to increase substantially but this increase is primarily driven by the projected increase in freight volumes. In summary, the costs of weather extremes on the transport sector are expected to be influenced more strongly by changes in technology and transport demand than by changes in weather extremes.

The overall risks of extreme weather were assessed in EWENT for EU-27 Member States. A risk indicator based on probabilistic weather hazards and resilience and vulnerability of each Member State revealed that countries with poor quality infrastructures, dense traffic volumes and population, and low income levels are usually most at risk and will face the severest consequences (Molarius et al., 2012).

4.7 Tourism

4.7.1 Overview

The tourism sector accounts for approximately 5 % of the total workforce in Europe. In total, the European tourism industry generates more than 5 % of EU GDP, and this figure has been steadily rising (ECORYS, 2009). The Mediterranean region is the world's most popular holiday destination. It attracts some 120 million visitors from northern Europe each year, the largest international flow of tourists on the globe, and while there they spend more than EUR 100 billion each year (Amelung and Moreno, 2009). International tourism is estimated to contribute about 10 % of GDP and employment in countries around the Mediterranean Sea (Magnan et al., 2012). In popular tourist regions in Greece, Spain, France, Italy and Portugal both the share of GDP and employment is far above these values.

In Europe tourism shows a strong seasonality, with a peak in the summer season (July–September) and generally lower levels of activity in the winter season (October–March). Climate both in tourism source and destination regions is an important resource for many types of summer and winter tourism, and it is a key factor for the provenance of tourists and their destination. There are large regional differences within Europe and among seasons as to attractiveness for tourism. At present, the predominant tourist flows in summer are from north to south, in particular to the coastal zone.

The knowledge base on climate change and tourism in Europe is continuously being expanded, for example through research projects or European Territorial Cooperation projects, such as AdaptAlp ('Adaptation in the Alpine Arc'), ClimAlpTour ('Climate Change and its impact on tourism in the Alpine Space'), CLISP ('Climate Change Adaptation by Spatial Planning in the Alpine Space'), BaltAdapt ('Adaptation in the Baltic Sea region'), ACCESS ('Arctic Climate Change, Economy and Society') and ESPON Climate (see Section 5.3). These projects strengthen the information available to stakeholders, for example by analysing case studies and developing tools supporting policy and decision-making. More information about these projects is available on the European Climate Adaptation Platform ([72]).

There are obviously different types of tourism activities depending, amongst others, on the location, season and personal preferences. This section distinguishes between 'general (summer) tourism' (based largely on the Tourism Climatic Index (TCI)) and 'winter sport tourism' (based largely on Greiving et al., 2011; Davoudi et al., 2012). None of the information is presented as an EEA indicator.

4.7.2 General tourism

An important foundation for many recent studies on the relationship between climate and tourism was the development of the TCI. This index is a composite measure for systematically assessing the climatic elements that are most relevant to the quality of the tourism experience for the 'average' summer tourist. It uses a weighted aggregate of several climate variables (i.e. maximum and mean daily temperature, humidity, precipitation, sunshine

Key messages: 4.7 Tourism

- Climatic suitability for general tourism activities is currently best in southern Europe. The regions most favourable for general tourism are projected to shift northwards as a result of climate change. The touristic attractiveness in northern and central Europe would increase in most seasons. Suitability of southern Europe for tourism would decline markedly during the key summer months but improves in other seasons.
- The widespread reductions in snow cover projected over the 21st century will negatively affect the winter sports industry in many regions. Regions close to the low elevation limit for winter sport are most sensitive to the projected warming.
- The projected climatic changes are expected to shift the major flows of tourism in Europe and can have substantial consequences for regions where tourism is an important economic sector. The magnitude of the economic impacts is strongly determined by non-climatic factors, such as the ability of tourists to adjust the timing of their holidays.

([72]) Climate-ADAPT (http://climate-adapt.eea.europa.eu).

and wind) to assess human comfort for general outdoor activities. The TCI has been partly validated for the Mediterranean countries. Tourism activities calling for specific climate conditions are not specifically covered by the 'standard' TCI.

Changes in the TCI are used in several new studies that investigate climate change effects on tourism (Amelung and Moreno, 2009, 2011; Ciscar et al., 2009). Map 4.17 compares the TCI for baseline and projected future climate conditions in Europe in all seasons. According to these maps, climate resources in the reference period are generally best in southern Europe (left column). Over this century, climate change is projected to shift the latitudinal band of favourable climate northward, thereby improving climate resources in northern and central Europe in most seasons (central column). Southern Europe's tourism suitability drops strikingly in the summer holiday months; this drop is partially compensated for by improvements in other seasons (right column). Further detailed analysis of the change in the number of acceptable, good and excellent days per month for eight European regions is available in the original study (Perch-Nielsen et al., 2010).

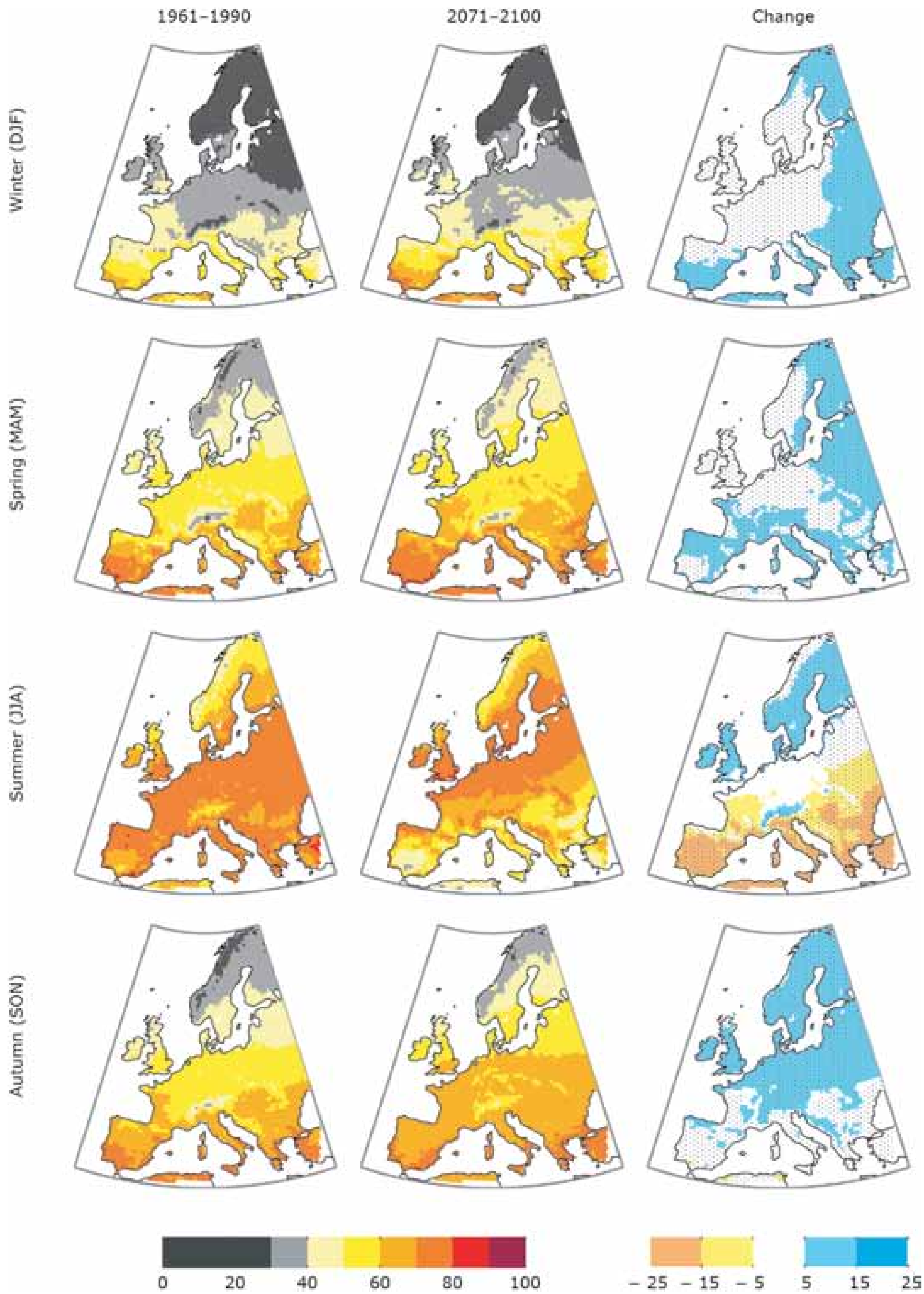
The projected decline in the suitability of the Mediterranean for tourism during the key summer months could trigger shifts in the major flows of tourism within the EU and have important socio-economic consequences for regions where tourism is a key contributor to the economy. The economic effects of climate change on tourism depend very much on the question whether holiday seasons in Europe remain fixed or would possibly shift. With a more flexible timing of travelling, climate change could benefit the tourist industry in the Mediterranean by evening out demand, reducing the summer peak while increasing occupancy in the spring and autumn, which become climatically more suitable. Without such adjustments, however, the Mediterranean tourist industry is projected to be strongly negatively affected by climate change.

The CIRCE project ('Climate Change and Impact Research: the Mediterranean Environment') addressed to some extent the vulnerability of coastal tourism in the south of Europe (Magnan et al., 2012). The findings suggest that projected climate change would decrease tourism flows from north to south of Europe and increase flows within the north of Europe. Another study used a survey to elicit the climatic preferences for summer tourism of 10 beach and urban destinations to the Mediterranean of potential travellers from northern Europe (Rutty and Scott, 2010). The study suggests that only in the medium (2046–2065) and long term (2080–2099) would destinations gradually become 'unacceptably hot' during the peak summer months for this target group. It also indicates that in the long term there is the potential for a much longer warm weather tourism season as the selected destinations would no longer be considered as 'unacceptably cool' during the Mediterranean's current shoulder season of spring and autumn.

It is important to note that several factors, which are difficult to model, might alter these general findings. The combination of adverse circumstances could play a crucial role in shifting future touristic destinations and seasonality patterns. A plausible example could be summer heat waves in the Mediterranean exacerbated by water supply problems due to maximum demand coinciding with minimum resources availability. Changes in urban tourism patterns might also have a knock-on effect on summer and beach tourism. There might also be a shift towards a greater level of domestic tourism in regions with increasing attractiveness. Finally, the European tourism industry is also highly sensitive to the economic situation in Europe and globally.

Water supply problems in tourist resorts are becoming increasingly common in Europe. For example, the Aegean islands are subject to more than 15 million overnight stays per year and on some islands the summer population is 30 times greater than the winter population. Demand for water has risen markedly and is now met through water importation from the mainland by tanker, and desalination (Gikas and Tchobanoglous, 2009). These problems would be exacerbated in a future climate with hotter and longer summers.

Map 4.17 Projected changes in the tourism climatic index for all seasons



Note: Tourism climatic index (TCI) for four seasons in the present period (1961–1990, left), under future climate change (2071–2100, middle), and change between present and future period (right). Future climate conditions are based on the SRES A2 scenario and derived from the ensemble mean of five regional climate models that participated in the PRUDENCE project.

Source: Perch-Nielsen et al., 2010. Reprinted with permission.

4.7.3 Winter sport tourism

The winter sports industry across Europe attracts millions of tourists each year, generating nearly EUR 50 billion in annual turnover. The main winter sport destination in Europe is the Alps where 69 % of Alpine ski areas in Germany, 87 % in Austria, 93 % in Italy and 97 % in France and Switzerland can be considered as naturally snow-reliable under the present climate (Agrawala, 2007).

Warm winters have already affected Alpine winter tourism. For example, in the record warm winter 2006/2007, some low-altitude ski areas in Austria were not able to offer a continuous skiing season from December to April despite being equipped with artificial snow-making (Steiger, 2011).

The widespread reductions in snow cover projected over the 21st century (see Section 2.3.2) will affect snow reliability and consequently the length of the ski season. Substantial reductions of naturally snow-reliable ski areas have been projected for the Alps, for the Black Forest region in Germany and for Sweden (Agrawala, 2007; Moen and Fredman, 2007; Endler and Matzarakis, 2011). Low-lying ski areas are most sensitive to climate change. Studies have estimated that an increase of mean temperatures of 1 °C in low-lying regions in the Alps will reduce the skiing season by up to 6 weeks (Hantel et al., 2000; Beniston et al., 2007).

Artificial snow-making is still the main adaptation option, covering 38 % of the total skiing area in the European Alps and showing an increase by 48 % since 2004 (Agrawala, 2007; Rixen et al., 2011). However, there are both environmental and economic constraints to an expansion of artificial snow-making.

5 Vulnerability to climate change

5.1 Introduction

The vulnerability of natural and human systems in Europe to climate change and other stressors results from a series of factors. It is widely recognised that climate change is an additional stressor to socio-economic and demographic developments that strongly determine the level of exposure of European population and infrastructure.

This chapter presents information on the vulnerability of populations and regions to climate change, considering where available other relevant developments, such as demographic and socio-economic changes, technological innovation, and consumption and settlement patterns. The information stems from various EU projects (ClimWatAdapt, PESETA-I, ESPON Climate, ClimateCost). In addition, this chapter presents information on economic losses from observed weather and climate events (Munich RE NatCatSERVICE and EM-DAT disaster databases).

The information presented here is relevant for informing European adaptation policy. However, it is not suitable to be presented as an EEA indicator due to limited availability of observed data, uncertainty about the continuity of information provision, or information being presented in relative (unitless) units only.

Note that the term vulnerability is used in rather different ways by various scientific disciplines, communities of practitioners, and decision-makers involved in climate change science and policy (see Section 1.7 for a more detailed discussion). Section 5.2 (based on ClimWatAdapt) and Section 5.3 (based on ESPON Climate) apply the 'outcome interpretation' of vulnerability as defined in the IPCC AR4. In contrast, use of the term vulnerability in Section 5.4 (on cities and urban areas) is more closely related to that of the disaster risk community.

5.2 River flooding, water scarcity and droughts

Section 3.3 addressed climate change impacts on inland waters in connection with, amongst others, hydrological changes and river flow (water availability), and the past and projected occurrence of river floods and water scarcity and droughts. This section briefly presents the projected socio-economic consequences of river floods and water scarcity and droughts, on the basis of the results of the ClimWatAdapt project and other studies.

The economic losses due to past floods in Europe have increased over the last decades (Barredo, 2009) mainly as a consequence of socio-economic factors such as increased population and wealth

Key messages: 5.2 River flooding, water scarcity and droughts

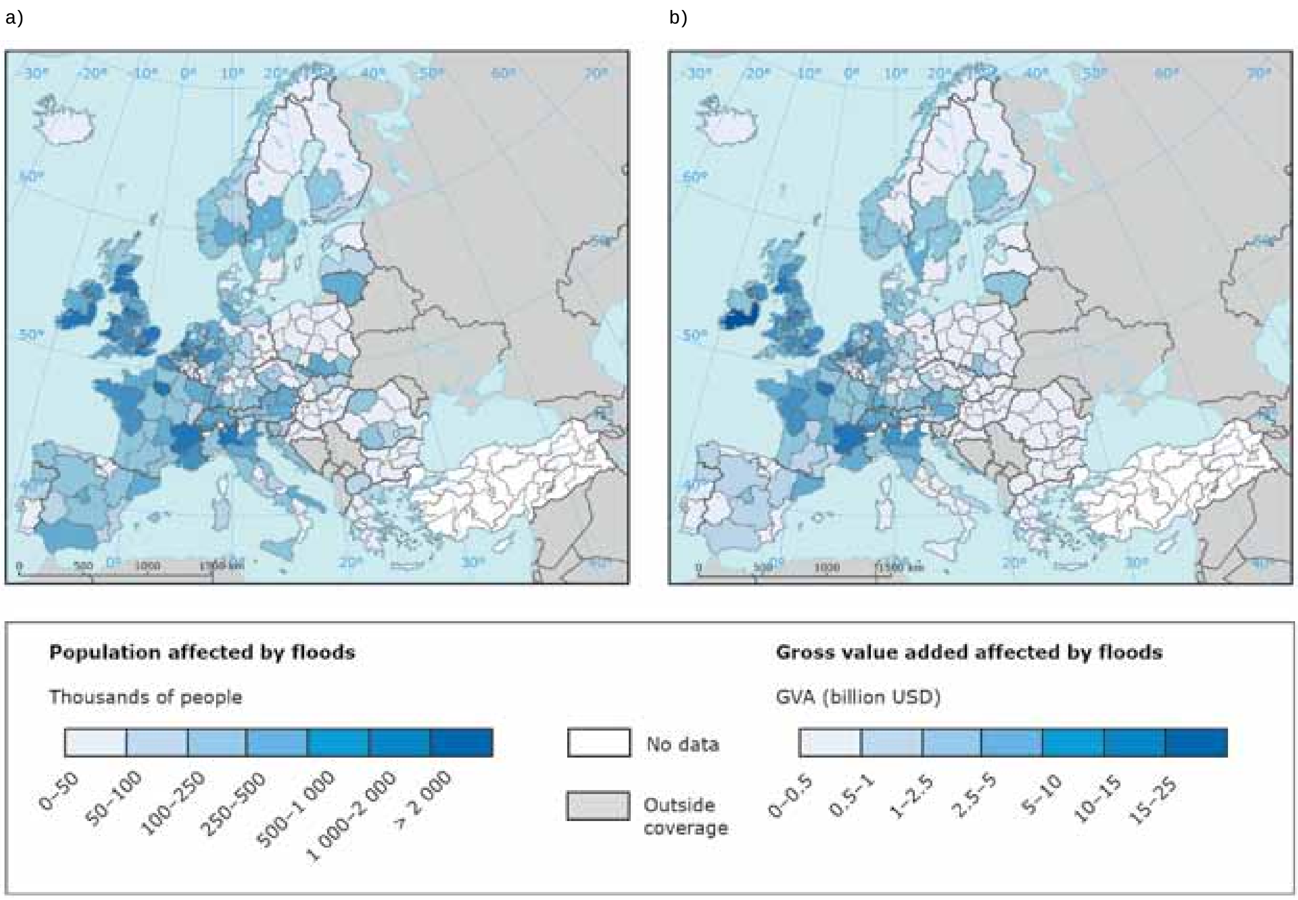
- In large parts of Europe annual economic losses due to floods are projected to significantly increase in the future. Water stress is projected to worsen in the absence of sustainable approaches to the management of Europe's water resources.
- Future socio-economic developments, such as changes in land use and demography, will play a central role in determining Europe's vulnerability to floods, droughts and water scarcity, with climate change being an additional factor.
- Decreasing water availability is projected to exacerbate water stress, especially in southern Europe. Increasing irrigation efficiency can reduce irrigation water withdrawals to some degree but will not be sufficient to compensate for climate-induced increases in water stress.
- Environmental flows, which are important for the healthy maintenance of aquatic ecosystems, are threatened by climate change impacts and socio-economic developments.

in flood-prone areas as well as climate change. However, it is difficult to detangle the specific effect of climate change on these economic losses from floods (Feyen et al., 2011). So the observations provide no conclusive and general proof on how climate change affects flood risks. Also, the effect of flood protection measures is not unambiguous. For example, dikes are taken as a safety guarantee by populations living in flood-prone areas. Thus, there may be incentives to build in these flood-prone areas and thus damage potential may have grown more than if no or fewer measures would have been taken. Thus, damages when such an area was flooded may have been higher than in the case of less or no flood protection (Kundzewicz et al., 2010).

Map 5.1 shows the affected population and gross value added (GVA) affected by floods for the 2050s for the 'Economy First' scenario, taking into account both climate change and socio-economic changes.

Economy First is a scenario where a globalised and liberalised economy pushes the use of all available energy sources and an intensification of agriculture where profitable. The adoption of new technologies and water-saving consciousness are low and thus, water use increases. Only water ecosystems providing ecological goods and services for economies are preserved and improved. For this Economy First scenario, for many parts of Europe the GVA affected by floods for the 2050s is larger than for the baseline scenario. Differences in the affected population are estimated to be small. The analysis also shows an uneven pattern of vulnerability across Europe. Note that the maps show the absolute number of affected people or GVA in a region rather than the percentage of population or GVA. It should also be noted that there are large differences in changes in projected flood frequency and intensity between different climate models.

Map 5.1 Estimated number of people and gross value affected by 100-year flood events in the 'Economy First' scenario for the 2050s



Note: Number of people (a) and amount of manufacturing gross value added (GVA), (b) affected by 100-year flood events in the 'Economy First' scenario for the 2050s. Calculations based on median ensemble results from LISFLOOD linked to population projections from SCENES scenarios.

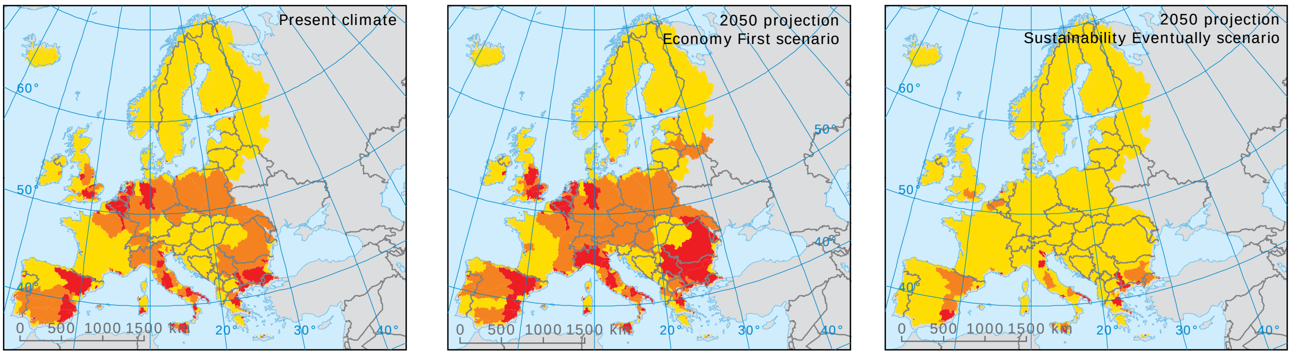
Source: Flörke, Wimmer, Cornelius, et al., 2011.

The ClimWatAdapt project also prepared projections for low flow and water stress. Map 5.2 shows annual water stress, which is calculated as the ratio of water abstraction to availability for two scenarios. Due to various uncertainties care should be taken in interpreting these projections. Details on the assumptions and models are available in their final report (Flörke, Wimmer, Laaser, et al., 2011). In the Economy First scenario water stress shows a large increase for the 2050s across much of Europe compared to the current situation. The implementation of a sustainable approach to the management of Europe's water resources is investigated in a 'Sustainability First' scenario. This scenario sketches the transition from a globalising, market-oriented Europe to environmental sustainability, where local initiatives are leading. A considerable reduction in annual water stress is projected across much of Europe, compared to both the Economy First scenario and the present day situation (Flörke, Wimmer, Laaser, et al., 2011).

Drought risks will increase throughout large areas of the EU (see also Section 2.2.5), whereby southern Europe is the most vulnerable region in Europe. Increasing irrigation efficiency can reduce irrigation water withdrawals to some degree but technological changes will not be sufficient to save southern Europe from water stress. Besides agriculture, electricity production is vulnerable to climate change effects on river low flows and water temperature for their cooling water (see Section 4.5.3). However, the energy sector has a high potential to reduce water withdrawals through technological improvements.

Environmental flows, which are important for the healthy maintenance of aquatic ecosystems, are threatened by climate change impacts and socio-economic developments. Although a Good Ecological Status is required by the Water Framework Directive (WFD), river basin management plans currently do not consider climate change impacts sufficiently and further coordination between river basin management plans and drought management plans is preferable. Mandatory water abstraction schemes are needed during low-flow periods to protect ecosystems. Many river basins are expected to be in the severe water stress class in 2050. Competition for scarce water resources could be an ongoing source of tension between different users and in the case of transboundary river basins between nations as well.

Map 5.2 Annual water stress for present conditions and projections for two scenarios



Annual water stress for present conditions and projections for two scenarios

Low | Mild | Severe | Outside coverage

Note: Left: present climate; middle: projection for 2050 based on Economy First scenario, median of general circulation models — regional climate models (GCM-RCM) combinations;
right: projection for 2050 based on Sustainability Eventually scenario, median of GCM-RCM combinations.

Yellow: low water stress (withdrawals-to-availability ratio: 0–0.2); orange: mild water stress (withdrawals-to-availability ratio: 0.2–0.4), red: severe water stress (withdrawals-to-availability ratio: > 0.4).

Source: Flörke, Wimmer, Laaser, et al., 2011.

5.3 Integrated assessment of vulnerability to climate change

5.3.1 The ESPON Climate project

The ESPON Climate project, whose results are presented below, developed a methodology which provides common metrics for assessing impacts and vulnerability to climate changes in an integrated manner. Its results are broadly consistent with the information presented in earlier chapters of this report.

The ESPON Climate project ([73]) is a good example for policy-oriented research that takes up the challenge of climate change's multi-dimensional nature. The project conducted an integrated and pan-European climate change vulnerability assessment with a prime focus on the territorial dimension. In contrast to more specialised sectoral studies, this integrated and territorial approach ensured that findings would be comparable between sectors and between regions. The project thus enables policymakers to understand both the diversity and accumulation of climate change impacts and to develop territorially differentiated adaptation strategies at the European, national and regional levels.

Methodologically the project compared projections of the CCLM climate model (A1B scenario) for the time periods 1961–1990 and 2071–2100 ([74]). Eight climate change variables ([75]) were thus calculated and supplemented by two variables on 'triggered' changes in river flooding and coastal storm surge flooding. These exposure indicators were then related to 22 sensitivity indicators ([76]). The resulting individual impact indicators were afterwards aggregated to determine the physical, cultural, social, economic and environmental impacts of climate change (always at the NUTS3 level). The aggregate impact was calculated using different weights for these impact dimensions, based on a Delphi survey among the ESPON Monitoring Committee, which represented the European Commission, 27 European countries and 4 Partner States. Similarly, 15 indicators on the economic, technological, educational and institutional adaptive capacity were aggregated. Finally, adaptive capacity and impacts were combined in order to determine the climate change vulnerability of each region. Seven case studies at the trans-national, regional and local levels cross-checked and deepened the findings of the pan-European assessment and explored the diversity of response approaches to climate change.

Obviously also the ESPON Climate project has limitations: For example, it is based on only one climate forcing scenario (A1B) and one climate model (CCLM) as the multi-model data sets of ENSEMBLES were not available yet when the respective ESPON analyses were performed. Furthermore, while the project was able to integrate some long-term demographic trends, the big challenge remains to develop long-term projections for all areas of economic, physical, environmental and cultural sensitivity that would thus match the climate models' projections. Therefore, the project's

Key messages: 5.3 Integrated assessment of vulnerability to climate change

- The most vulnerable types of European regions include: 1) Coastal regions with high population, in particular those with high dependency on summer tourism, 2) mountain regions with high dependence on winter and summer tourism, 3) agglomerations with high population density, where the problem of urban heat might become most relevant, and 4) regions exposed to river flooding.
- Most regions for which climate change impacts are expected to be the most severe (mainly in the south) are also the ones exhibiting low adaptive capacity.
- The integrated assessment of European regions' vulnerability to climate change suggests that it will probably deepen the existing socio-economic imbalances within Europe and eventually play out against further territorial cohesion.

([73]) 'ESPON Climate — Climate Change and Territorial Effects on Regions and Local Economies'. Conducted 2009–2011. Funded by ESPON Programme 2013. Coordinated by Institute of Spatial Planning (IRPUD), TU Dortmund University.
([74]) For details on the methodology and findings of ESPON Climate, see (Greiving et al., 2011).
([75]) Exposure indicators used by ESPON Climate related to change in annual mean temperature, frost days, summer days, winter precipitation, summer precipitation, heavy rainfall days, snow cover days and evaporation.
([76]) Sensitivity indicators used by ESPON Climate related to roads, railways, airports, harbours, thermal power stations, refineries, settlements, coastal population, population in river valleys, heat sensitive population in urban heat islands, Natura 2000 protected areas, occurrence of forest fires, soil organic carbon, soil erosion, museums, cultural World Heritage Sites, energy supply and demand, agriculture and forestry employment and GDP, tourism comfort index and tourist accommodations.

results have to be seen as a vulnerability scenario, which shows what Europe's future in the wake of climate change *may* look like (based on current knowledge and assumptions), and not as a clear-cut forecast.

ESPON Climate is one of several recent EU-funded research projects that employ an integrated methodology to assessing climate change impacts, adaptation and vulnerability, for example like ClimSAVE, RESPONSES and MEDIATION. However, these other projects are still ongoing and are scheduled to deliver their final results by the end of 2012 and 2013, respectively. There are only a few other studies at the European level that attempted a cross-sectoral, integrated vulnerability assessment like the one presented in this chapter. As part of its Regions 2020 report, the European Commission commissioned a background paper on the challenges of climate change for Europe's regions (Römisch, 2009). This vulnerability assessment was integrated into the Regions 2020 background report on climate change (EC, 2008). The Regions 2020 vulnerability index differs from the ESPON Climate vulnerability assessment, for example it used NUTS2 level, two climate change and five sensitivity indicators, no adaptive capacity indicators, different weighting methods and an A2 climate scenario. Consequently the results are less robust and fine-grained, but nevertheless show similar overall spatial patterns in that regions in the south and south-east of Europe are the most vulnerable regions.

A more extensive follow-up study to the Regions 2020 report was performed in 2011for the European Commission (Aversano-Dearborn et al., 2011). This study analysed key challenges facing Europe in regard to globalisation, demographic change, secure, sustainable and competitive energy, social polarisation and, lastly, climate change. In regard to climate change, aggregate vulnerability indicators were developed (building on 12 impact and 10 adaptive capacity indicators) for agriculture and forestry, natural and semi-natural ecosystems, natural hazards and coastal threats, health and heat waves, water dependency and summer tourism. These were subsequently combined in a cluster analysis. However, despite its ambitious integrated approach, the study's results cannot be compared with those from ESPON Climate, because (Aversano-Dearborn et al., 2011) used only indicators on past and current climate, that is, no climate projections.

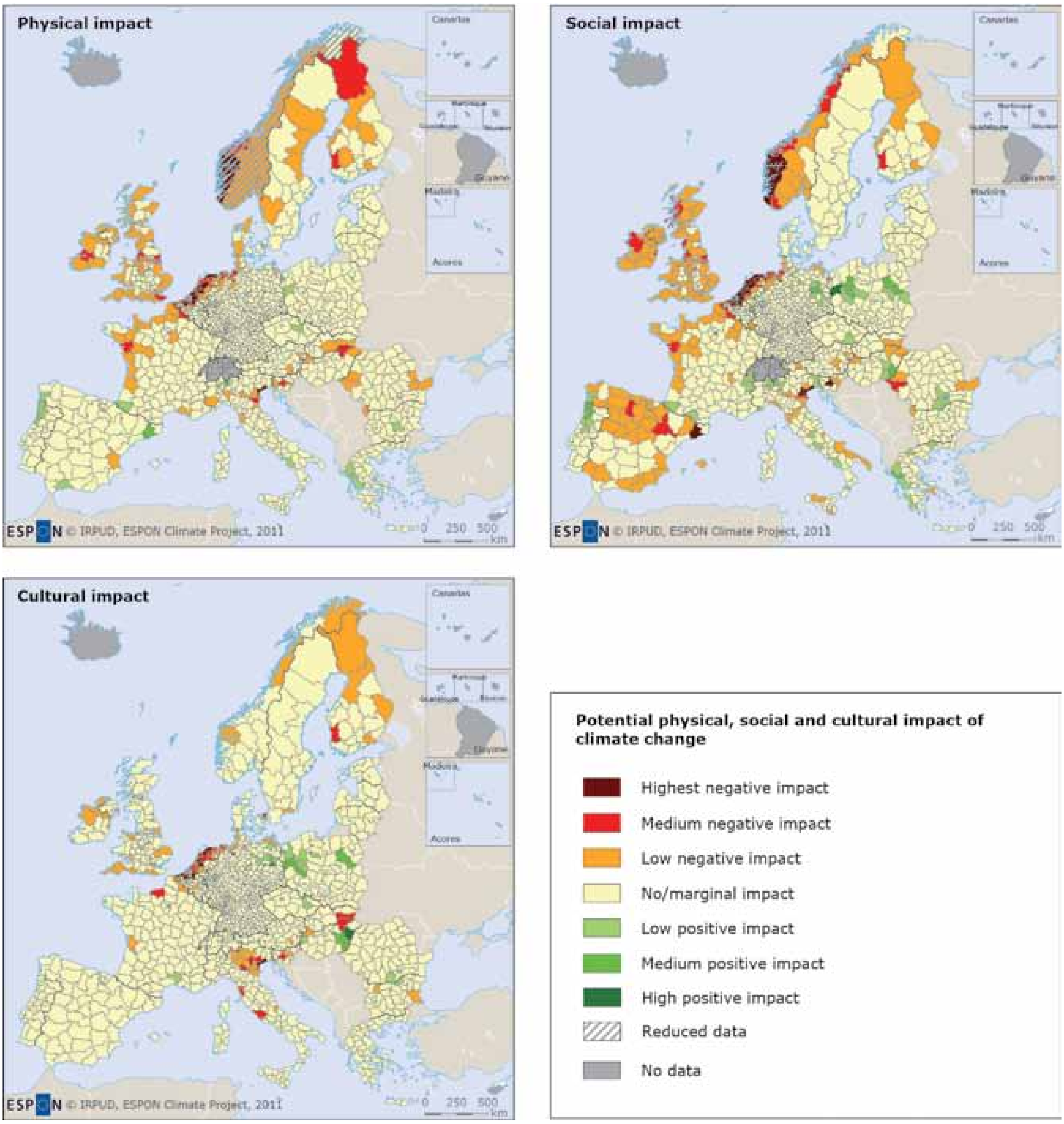
5.3.2 Key findings

The project's findings regarding impacts of climate change may be grouped into impacts primarily caused by extreme events (flooding and heat) and those caused by changes of average climate conditions. The former group consists of potential physical, cultural and social impacts (displayed in Map 5.3) whereas the latter consists of economic and environmental sub-systems that are sensitive even to creeping climatic changes (see Map 5.4). When interpreting the maps below, it is important to note that they show a combination of absolute impacts (per NUTS3 region) and relative impacts (per person or unit area). For example, regions shown with the highest social impacts have high social impacts per person *and* a large population.

Potential **physical impacts** relate to physical structures such as settlements, roads, railways, airports, harbours, thermal power plants and refineries. These structures are especially sensitive to flood events. Consequently, the adjustment of coastal storm surge heights with the projected sea-level rise accounts for most of the high impacts in north-western European regions bordering the Atlantic Ocean (sometimes exacerbated by fluvial and pluvial flooding). Projected increases in river flood heights are responsible for regional 'hot spots' in Italy, Hungary and Slovenia. However, large parts of Europe may not expect significant impacts on their infrastructure resulting from climate change. In fact, physical structures in some central and southern European regions may even experience less climate-related impacts due to decreasing precipitation in these regions.

The potential **social impacts** of climate change relate to Europe's population, which is also mainly sensitive to extreme events that are driven by climate change: coastal storm surges exacerbated by sea-level rise, increases in river flood heights, increasing flash floods, but also increasing heat events. Sensitivity to these changes is a matter of location, age group distribution, but also the density and size of urban areas that create urban heat island (UHI) effects. Hence, the social impact patterns again largely resemble those of physical impacts, because population centres are also concentrations of buildings and infrastructures. The highest impacts are primarily flood-related and are projected for urban agglomerations on the Belgian, Dutch and Norwegian coasts as well as the city

Map 5.3 Potential physical, social and cultural impact of climate change



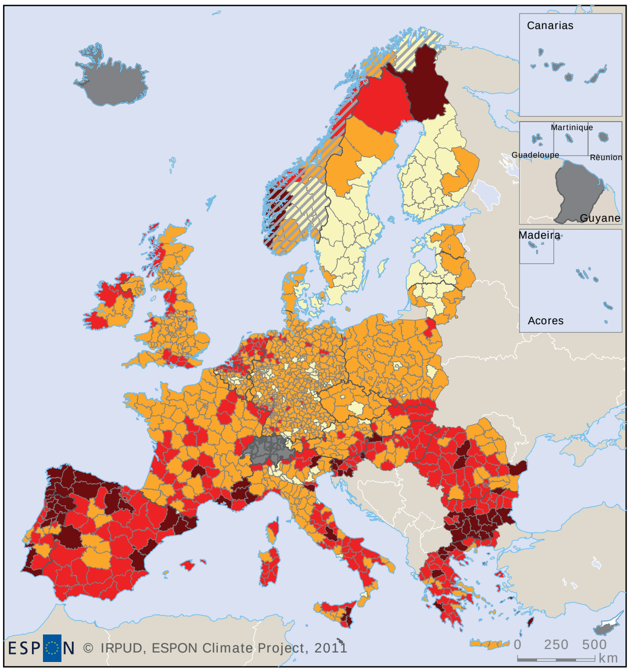
Note: Normalised potential impacts aggregated from individual impact indicators on roads, rail, airports, harbours, settlements, power stations and refineries (physical), population in coastal areas, river valleys, urban heat islands and flash flood-prone population (social), and museums as well as cultural World Heritage Sites in coastal areas and river valleys (cultural).

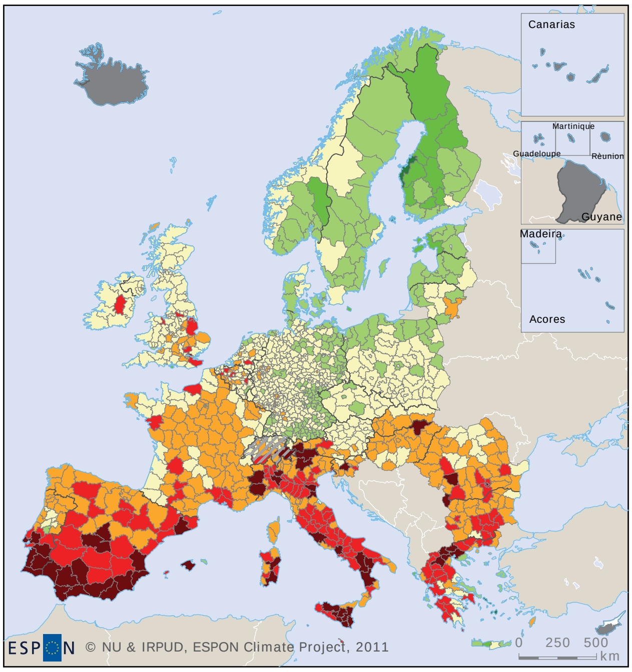
Source: ESPON Climate, 2011.

regions around Barcelona, Venice and Ljubljana. In addition, southern Europe would be more affected because of the more compact urban form of its cities and greater increases in hot summer days. In contrast, the population of most non-coastal areas of Europe is potentially not or only marginally affected by climate change and some regions are even projected to have positive impacts due to declining flood hazards, for example in Poland and Portugal.

The potential **cultural impacts** of climate change focused on tangible cultural assets, because intangibles like norms and attitudes were considered part of the adaptive capacity of a region. More precisely, ESPON Climate analysed what impact the projected climatic changes may have on the 350 UNESCO World Heritage Sites and approximately 20 000 museums in Europe. Not surprisingly the impact patterns for these cultural

Map 5.4 Potential environmental and economic impact of climate change





Potential environmental impact of climate change

- Highest negative impact
- Medium negative impact
- Low negative impact
- No/marginal impact
- No data
- Reduced data

Potential economic impact of climate change

- Highest negative impact
- Medium negative impact
- Low negative impact
- No/marginal impact
- Low positive impact
- Medium positive impact
- High positive impact
- No data
- Reduced data

Note: Normalised potential impacts aggregated from individual impact indicators on protected natural areas, forest fire-prone forests, soil organic carbon and soil erosion (environmental), and agriculture and forestry, energy production and consumption as well as summer and winter tourism (economic).

Source: ESPON Climate, 2011.

assets resemble those for infrastructures and settlements: The high impacts in Belgium, northern France, Italy, Hungary, the Netherlands, Slovenia, Slovakia, and in parts of Denmark and Finland are a consequence of the projected increase of flood hazards and the density of cultural sites in these regions. On the other hand, cultural assets in some central European regions, especially in Poland, would benefit from decreasing flood hazards.

The potential **economic impacts** of climate change were analysed in regard to especially climate-sensitive economic sectors, namely agriculture and forestry, energy production and consumption as well as summer and winter tourism. Overall, the economic impacts of climate change show a clear south-north gradient: many central European regions and almost all Scandinavian regions are projected to have positive impacts, while almost all southern European regions would experience negative impacts. This is largely due to the economic dependency of large parts of southern Europe on (summer) tourism and agriculture. Both sectors are projected to be negatively impacted by increasing temperatures and decreases in precipitation, whereas the environmental conditions for agriculture in north-eastern Europe tend to improve. In addition, energy demands would rise in the south for cooling purposes and decrease in the north due to less heating. Finally, the Alps as a premier tourist-dependent region can be identified as an impact 'hotspot', which mainly results from the projected decrease in snow cover days.

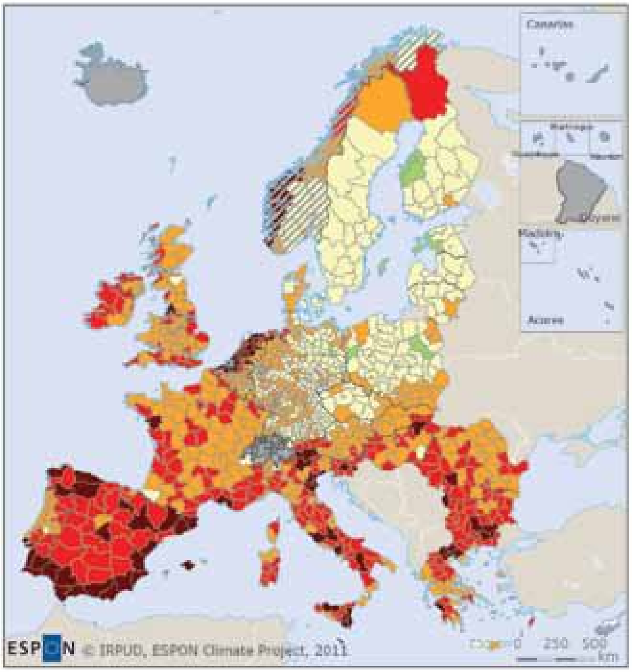
The potential **environmental impacts** analysed relate to protected natural areas, soil organic carbon content, and the propensity of soil erosion and forest fires. The overall findings show that for these environmental variables negative impacts are projected for almost all European regions. But the highest negative environmental impacts are expected in the north and south of Europe. In southern European regions the drier and hotter climate is projected to increase the likelihood of forest fires and to also degrade soil conditions in mountainous and coastal areas. The severe environmental impacts in northern Scandinavia are mainly due to very large protected areas where any climatic change (in this case warmer and wetter climate) is considered as negatively affecting the specific ecosystems under protection.

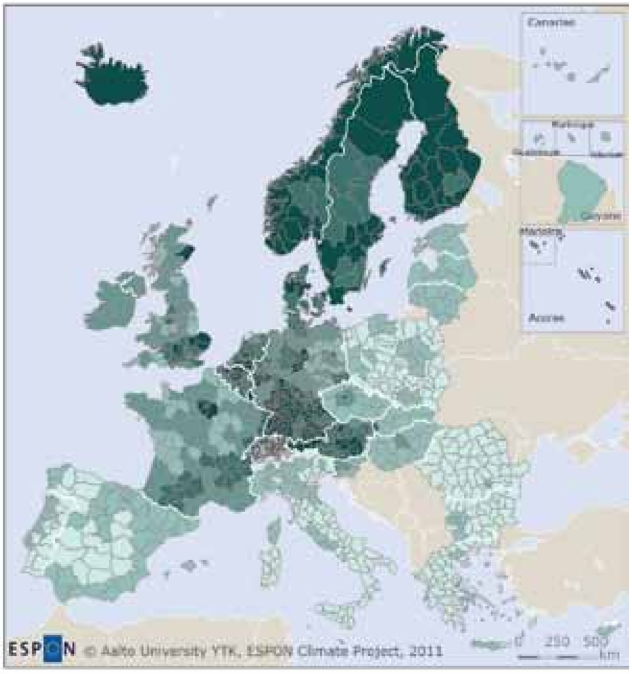
A defining feature of ESPON Climate was the aggregation of sectoral impacts to aggregate impacts, and the combination of aggregate impacts with adaptive capacity to the potential vulnerability (see Map 5.5). The aggregate **potential impacts** of climate change exhibit the following general patterns: coastal regions are projected to be negatively affected because their high concentrations of physical, economic, social and cultural assets would face increasing flood hazards. Southern European regions are expected to be negatively impacted because their hotter and drier climates severely worsen conditions for their populations, economies and natural environments. Highly negative impacts are therefore projected for southern Europe's agglomerations and tourist resorts along the coasts. But inland mountain regions that are dependent on agriculture, forestry and winter and/or summer tourism would also be highly affected. In contrast, many central, eastern and northern European regions would face virtually no negative impacts or would even experience positive impacts of climate change — mainly due to marginal climatic changes or projected decreases in river and flash floods.

The **adaptive capacity** was defined by indicators on knowledge and awareness, economic resources as well as technological, infrastructural and institutional capacity to adapt to climate change. Mapping the overall adaptive capacity yields an almost inverted pattern compared to the impact map: Most regions for which climate change impacts are expected to be the most severe (mainly in the south) are in fact the least capable of adapting to these impacts.

Finally, combining aggregate impacts and adaptive capacity results in the **potential vulnerability** to climate change. The vulnerability map seems to mirror the territorial pattern of potential impacts, but with an even more pronounced south-north gradient. This is due to the high adaptive capacity in western European and Scandinavian regions, which partly compensates for the potential impacts projected for these regions. On the other hand, in south-east Europe and in the Mediterranean region, where medium to high negative impacts are expected, the ability to adapt to climate change is generally lower thus resulting in even higher levels of vulnerability. The overall most vulnerable types of regions are: 1) Coastal regions with high population and high dependency on summer tourism, 2) mountain regions with high dependence on winter and summer tourism, and 3) agglomerations with high population density, where the problem of urban heat might become most relevant.

Map 5.5 Potential aggregate impact, adaptive capacity and vulnerability



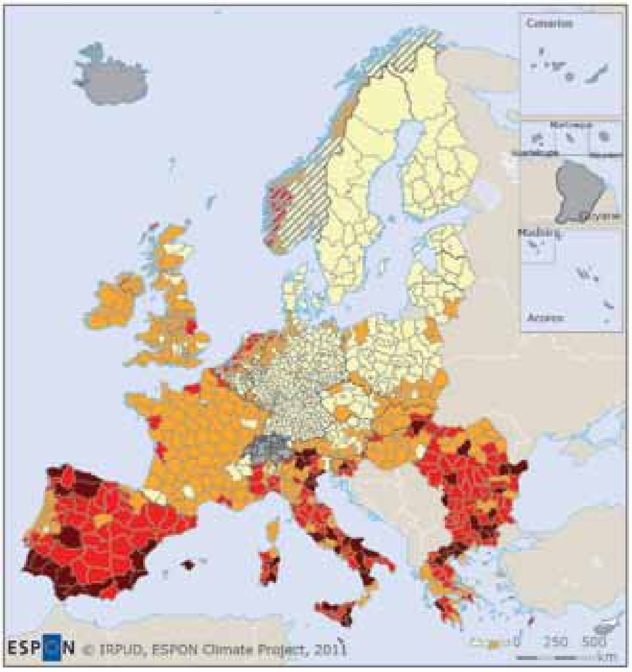


Aggregate potential impact of climate change

- Highest negative impact
- Medium negative impact
- Low negative impact
- No/marginal impact
- Low positive impact
- No data
- Reduced data

Overall capacity to adapt to climate change

- Highest capacity
- High capacity
- Medium capacity
- Low capacity
- Lowest capacity
- No data



Potential vulnerability to climate change

- Highest vulnerability
- Medium vulnerability
- Low vulnerability
- No/marginal vulnerability
- No data
- Reduced data

Note: Overall impacts derived from 26 impact indicators, overall adaptive capacity from 15 individual indicators, and overall vulnerability from a combination of overall impacts and adaptive capacity.

Source: ESPON Climate, 2011.

5.3.3 Policy implications

The ESPON Climate project constitutes the most comprehensive pan-European climate change vulnerability assessment to date. The project provides not only regionally specific results but also aggregated, cross-sectoral findings that lend themselves to high-level European policymaking.

For example, ESPON Climate demonstrated that Europe's climate change vulnerability runs counter to territorial cohesion. The assessment indicated that climate change will probably deepen the existing socio-economic imbalances between the core of Europe and its southern and south-eastern parts because many economically lagging regions are also the most vulnerable to climate change. Most likely these imbalances will even increase in the future: the current economic and financial crises in Greece, Spain, Italy and Portugal are reducing both individual and collective adaptive capacities. And in eastern Europe severe demographic changes like massive out-migration and ageing are projected to continue, which would further increase regional climate change sensitivity and decrease adaptive capacity levels (e.g. an older regional population is more sensitive to heat and less able to adapt to climate change).

ESPON Climate's methodologies and results could possibly become part of an evolving policy support tool that would enable policymakers at European, national and regional levels to 1) identify regional 'hot spots' with projected high impacts and weak capacity and devise appropriate adaptation mechanisms, 2) develop a more strategic and climate change-responsive approach to territorial cohesion, 3) identify especially vulnerable (sub)sectors and mainstream climate change adaptation into the respective sectoral policies, 4) develop territorially differentiated adaptation strategies that take into account the regional variations in regard to climate change exposure, sensitivity, impact and adaptive capacity, and 5) coordinate and integrate sectoral policies with a view to preventing potential negative climate change impacts and capitalising on positive development opportunities.

5.4 Vulnerability of cities and urban areas

5.4.1 Introduction

Cities are the places where most people in Europe will experience climate change impacts first; they accommodate around three quarters of the population, a share which is expected to increase further (EEA, 2006a, 2010b; PLUREL, 2011; UN, 2012). Urban areas are distinct from the surrounding rural regions. Their specific composition of people and activities as well as their urban design alters climate change impacts, for example exacerbates heat waves due to the UHI effect, generating urban floods due to a high share of impervious surfaces and water scarcity due to the concentration of people and socio-economic activities (EEA, 2012). Cities are key for Europe's economy; innovation and major economic assets concentrate here (EC, 2009). The high and overall growing size of the urban population, economic assets of cities, and the complexity of city systems to provide and manage energy, water, waste, food and other services make these cities highly vulnerable to both current climate variability and climate change.

With regards to data quality and data needs, the proportion of green and blue urban areas, population density, soil sealing and the share of elderly population were selected for assessing vulnerabilities of cities to heat waves, flooding and water scarcity. They should be considered as a first approximation. Many more factors determine vulnerability like morphology, sewage infrastructure, other sensitive groups or adaptive action taken, like green roofs and walls or respective building design.

Key messages: 5.4 Vulnerability of cities and urban areas

- Over the past, increasing urban land take and urbanisation have in many places increased the vulnerability of European cities to different climate impacts like heat waves, flooding or water scarcity. The impacts of extreme events like flooding at the river Elbe (2002) or in Copenhagen (2011) demonstrate this increased vulnerability.
- In the future, ongoing urban land take, growth and concentration of population in cities, and an ageing population contribute to further increasing the vulnerability of cities to climate change. It is, however, currently uncertain to which extent an intelligent urban design and urban management of individual cities can buffer these negative effects.

The availability of comparable urban data at city level is limited. Main sources are the Urban Audit database (Eurostat), the Urban Atlas and the soil sealing layer (EEA). Data describe the current state. Past trends or future projections comparable across Europe are not available. We reflect therefore on overall European trends (e.g. population dynamics) or highlight potential risks in the form of 'what if the current development continues…?'

A more extended assessment of urban vulnerabilities can be found in (EEA, 2012).

5.4.2 Past trends

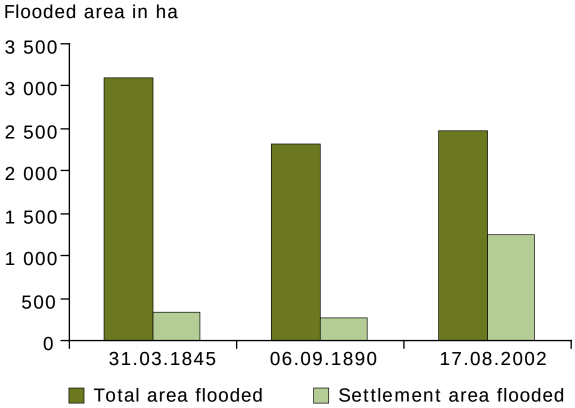
The past climatic trends described in Chapter 2 are relevant for cities as well as the overall trends of climate impacts on systems and sectors (Chapters 3 and 4), but the latter could have been altered in cities due to cities' composition, management and urban design.

Flood risk

Ongoing urban land take has increased the area of impervious surfaces and buildings in Europe (EEA, 2010c). It has limited the areas for natural drainage, water retention, production of fresh air and fixation of CO_2 in and around cities and thus often increased the effects of heat waves, floods or water scarcity. This has already in the past led to higher vulnerabilities to climate impacts. An example is provided in Figure 5.1, which compares three major flood events of the river Elbe in Dresden in 1845, 1890 and 2002. Although the total flooded area in 2002 was only slightly bigger than in 1890 and smaller than in 1845, the flooded builtup area had increased dramatically.

High soil sealing of urban areas restricts direct drainage of water into the ground. This is also a main factor for the development of a particular urban phenomenon — urban drainage floods. The low drainage into the soil leads to a high run-off of water into the sewage system and can deplete its capacity. Excess water travels down roads and other paths of least resistance and floods low-lying areas as described for the urban flood 2011 in Copenhagen (Box 5.1).

Figure 5.1 Flooded area in Dresden (Germany) during different flood events



Source: Schumacher, 2005.

Box 5.1 The cloudburst in Copenhagen on 2 July 2011

After a substantially hot period Copenhagen was hit by a huge thunderstorm on 2 July 2011. During the afternoon clouds and thunder had been building up over the southern part of Sweden. During a 2-hour period over 150 mm of rain fell in the city centre. This constituted the biggest single rainfall in Copenhagen since measurements began in the mid-1800s.

The city's sewers were unable to handle all of the water and as a result many streets were flooded and sewers overflowed into houses, basements and onto streets thereby flooding the city. The consequences were quite drastic as emergency services had to close roads and attend to people trapped in their cars. The emergency services were within minutes of having to evacuate the city's two biggest hospitals because of flooding and power cuts. Insurance damages alone were estimated at EUR 650–700 million. Damage to municipal infrastructure not covered by insurance, such as roads, amounted to EUR 65 million.

Source: Lykke Leonardsen, city of Copenhagen, 2011 (personal communication); EEA, 2012.

Box 5.2 Water scarcity in Ankara

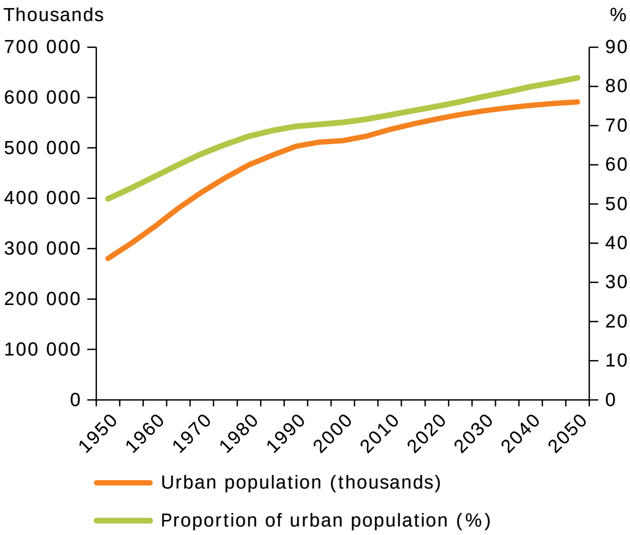
From 2006 until 2008, Ankara suffered from severe droughts. In August 2007 the water supply had to be cut off because the capacity of 8 major water reservoirs dropped to 5 % of normal levels. The situation was aggravated by the bursting of two main pipelines. From April 2007 to March 2008 an emergency plan came into action and the municipality constructed a system of pipelines from the Kizilirmak dam.

Drought is not unusual in Turkey caused by the large variation in rainfall over the years. During the previous 80 years the situation in Ankara regarding water demand has changed dramatically. The population increased from 75 000 in 1927 to 3.2 million in 2000 and is expected to grow further to 7.7 million in 2025. This will put an enormous strain on the city's water supply that is already insufficient to meet current demands. Moreover, due to an increase in prosperity, water consumption per person has increased and is expected to increase further from 169 litres per day in 1995 to 203 litres in 2025.

While Ankara's population is expected to increase further, precipitation and river flows are expected to decrease due to climate change. Hence, the frequency and intensity of drought periods will likely increase in the coming decades.

Source: GWI, 2007; Ceylan, 2009; Tigrek and Kibaroglu, 2011; EEA, 2012.

Figure 5.2 European urban population trends



Source: UN, 2012.

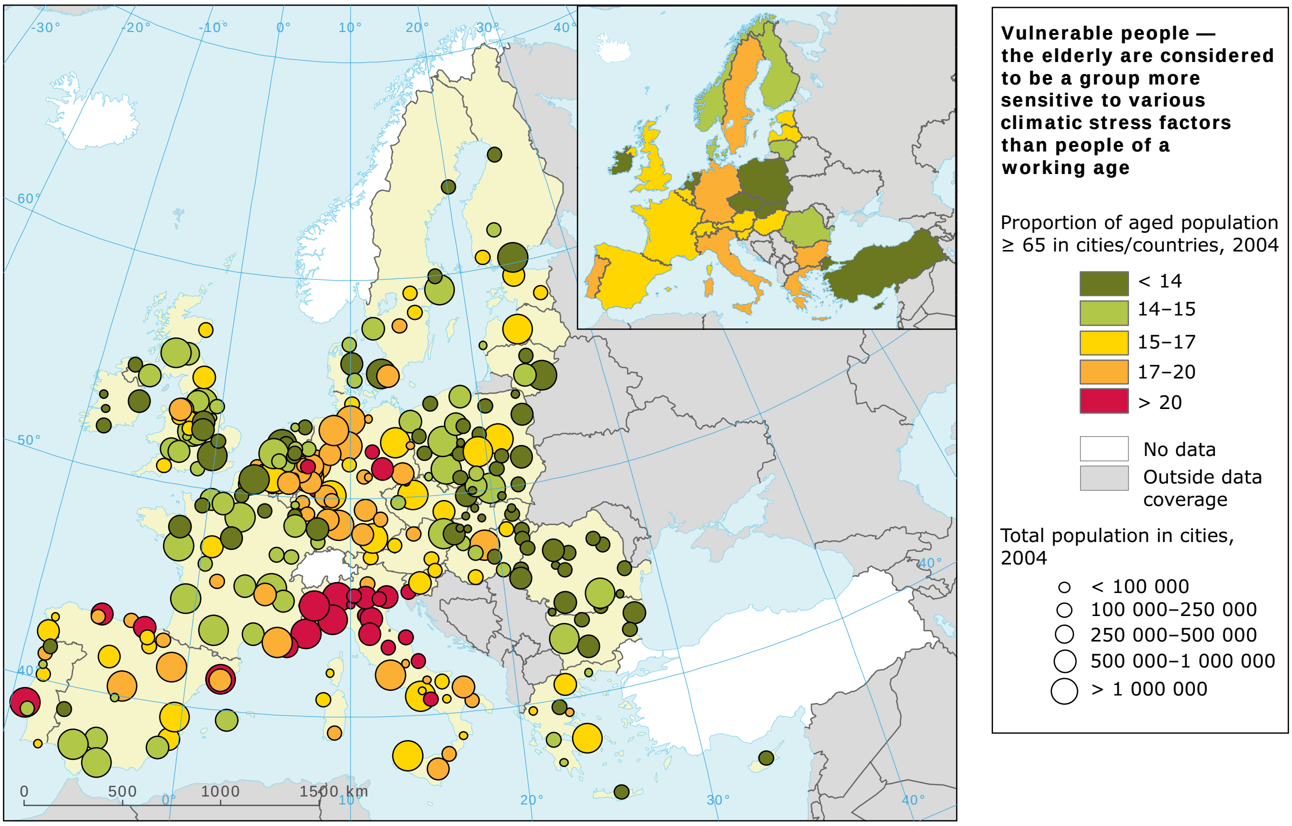
Water scarcity

The increase in the share and number of urban population in Europe (Figure 5.2) led to bigger cities and higher population concentrations in urban areas. Their water demand goes beyond the supply of the cities' areas; they rely on the surrounding region. From a local perspective, many cities are in a water scarcity situation already and in some areas water scarcity has increased — see the example of Ankara (Box 5.2).

Vulnerable populations

The vulnerability to climate change depends not only on the climate exposures but also on the presence of sensitive groups. Low income groups might not have the resources to move to better adapted apartments or sites or to take action. The disabled and sick, young children and the elderly are particularly vulnerable to various environmental health hazards. Ethnic minorities and less educated people might not be able to access or absorb relevant adaptation knowledge. The elderly (> 65 years) are considered to be a group more sensitive to various climatic stress factors such as heat waves but also flooding and water scarcity. This group constitutes currently about 17.1 % of the total population of Europe (Eurostat, 2008). Map 5.6 shows that the proportion of elderly people in cities is higher in countries in the area stretching from Italy to Germany and in northern Spain. In Belgium and Germany this proportion usually follows the country average. Cities in northern Italy, meanwhile, tend to have values above the country average. For

Map 5.6 Elderly population in cities



Note: Data for Bulgaria, the Czech Republic, Ireland, France, Cyprus, Latvia and Finland are from 2001.

Source: Eurostat, 2004; EEA, 2012.

other countries such as Bulgaria, southern Spain, France, Romania and the United Kingdom, the share of elderly people in most cities is lower than in rural areas.

Projections

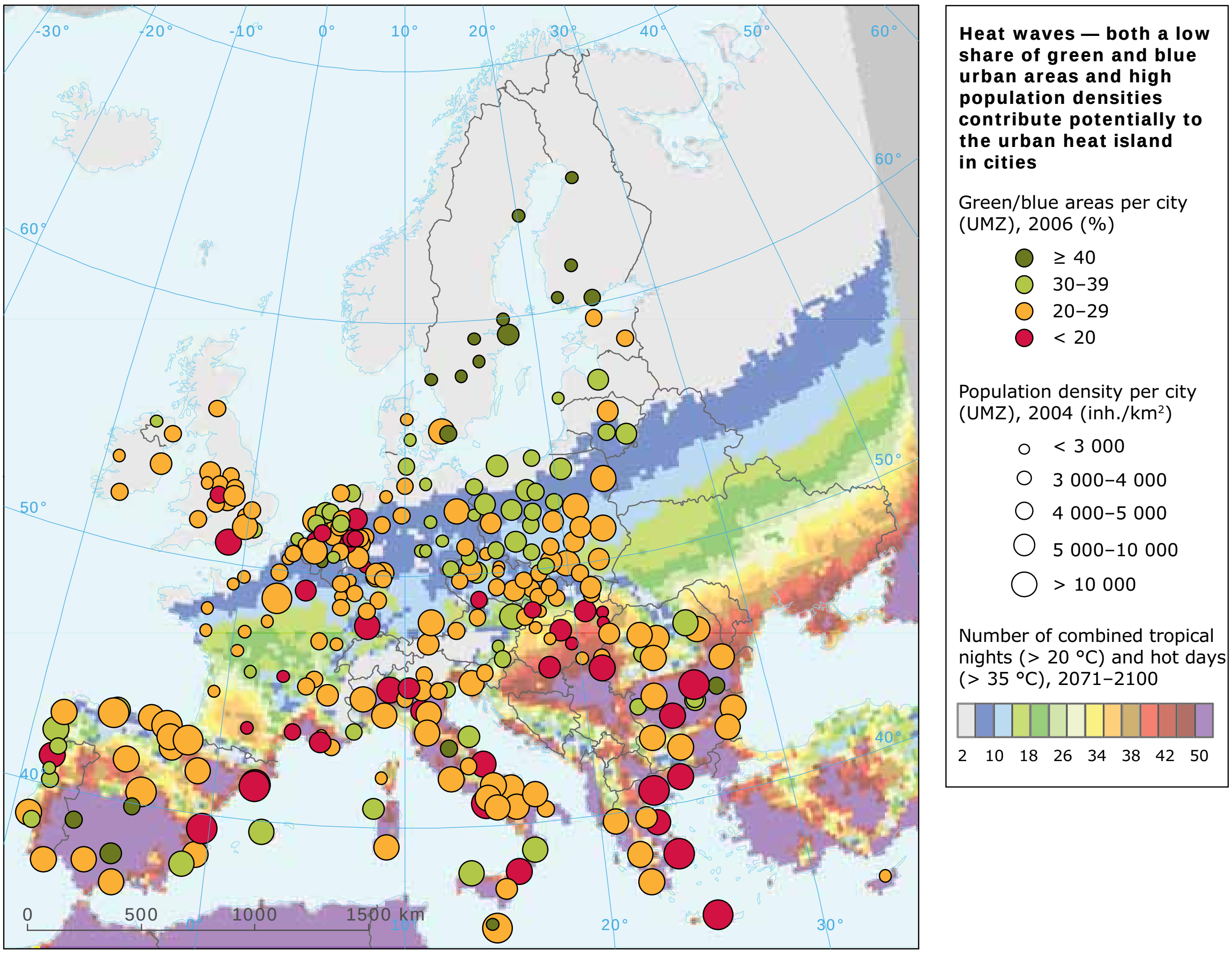
Heat waves and the urban heat island potential

The health impacts of extreme heat are discussed in Section 4.4. The scenarios for the increase in heat wave days (described in Section 2.2.3) do not, however, take into account the UHI effect and underestimate the temperature in cities. In Map 5.7, population density and the share of green and blue areas in major European cities provide an indication for the UHI: the lack of green and blue areas contributes to higher temperatures as well as population density, which is associated with building density, low share of green/blue areas and anthropogenic heat (EEA, 2012).

Map 5.7 shows these values on a background map describing the modelled number of heat wave days in the period 2071–2100. The map indicates a large number of cities with large UHI potential in the north-west due to low shares of green and blue urban areas and in particular south-eastern Europe where, in addition, population densities are higher. In the western part of the Mediterranean area, the UHI potential seems to be quite variable, with a mix of cities with both strong and weak UHI potential. Comparing expected heat exposure changes with the UHI potential reveals that a large share of cities in eastern and southern Europe will experience relatively strong increases in heat load in the future. If the heat wave intensity also expands more to the north-west as shown in other projections, cities in the Benelux countries and the United Kingdom would also be more affected (EEA, 2012).

The share of green and blue urban areas and the population density in Map 5.7 describe the current situation. The ongoing urbanisation in many parts

Map 5.7 Factors determining vulnerability to heat waves



Note: The background map presents the projection for the period 2071–2100. Values for the earlier periods are presented in (EEA, 2012). City data for Bulgaria and Ireland are from 2001; the concept of city is defined uniquely by the urban land-use areas within its administrative boundary.

Source: Eurostat, 2004; EEA, 2006b, 2012; Fischer and Schär, 2010.

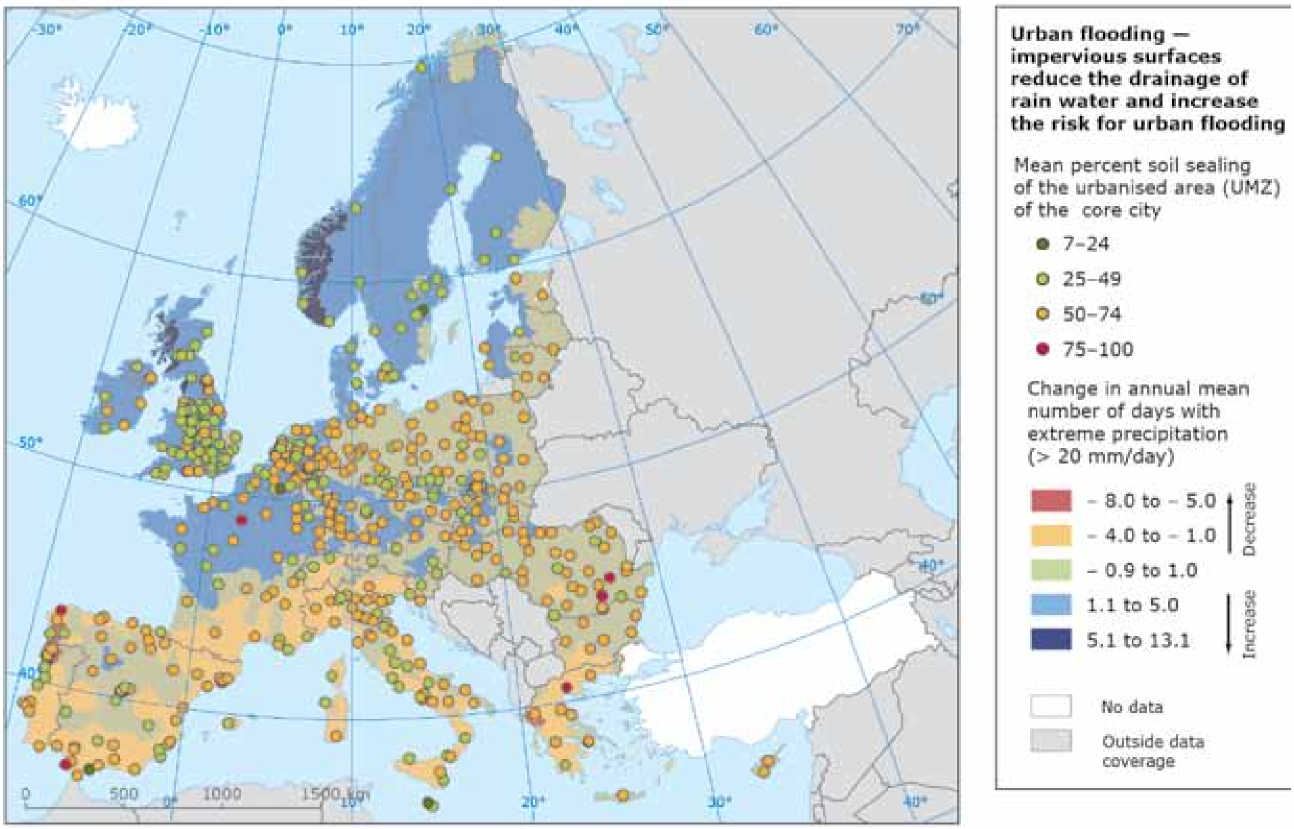
of Europe in the form of urban land take and densification (EEA, 2006a, 2010c; UN, 2012) might aggravate the UHI. On the other hand, an increase of green infrastructure including parks, trees, green walls and roofs, as well as low-density urban developments and shrinking cities in some regions can decrease the effect. These trends are however uncertain.

Flooding

The high share of build-up areas and thus low natural drainage capacities increase the impacts of all types of flooding on cities. Urban drainage floods are, however, an additional phenomenon generated in cities during extreme precipitation events.

Section 2.2.5 describes the projected increase in extreme precipitation. Map 5.8 indicates that cities of high and low soil sealing degree can be found in all regions and do not cluster in a particular region, with the exception of rather low sealing degrees in Norwegian and Swedish cities. It shows that cities with a high soil sealing and an increasing number of intensive rainfall events particularly concentrate in north-western and northern Europe. They face a higher risk of urban drainage flooding. Nevertheless, cities in areas with a decreasing number of such events but high soil sealing also still face a flooding risk, just less often (EEA, 2012).

Map 5.8 Factors determining vulnerability to urban flooding



Note: Average percent soil sealing per city and change in annual mean number of days with extreme precipitation (> 20 mm/day) between the CCLM scenarios run (2071–2100) and the reference run (1961–1990) for IPCC scenario A1B. The city is defined by its morphological form (Urban Morphological Zone) inside the core city boundaries derived from Urban Audi (Eurostat).

Source: Soil sealing: EEA, 2009; Precipitation: Lautenschlager et al., 2008; EEA, 2012.

Water scarcity

Climate change is expected to increase droughts and water scarcity in Europe (Section 3.3.4). A major part of the increase of water stress is expected in areas of already high urbanisation and population density, western Europe and the coasts. These are the areas where even more population growth is expected, mostly in and around cities. Cities will most probably adapt to water scarcity getting water from regions further abroad by wide water networks for transporting water. However, this will increase their dependency on far away resources and in most cases increase the price for water and heat the competition for water with other users like agriculture, energy generation and tourism (EEA, 2012).

Social sensitivity

The ongoing urbanisation (Figure 5.2) will increase the number of people affected by specific urban climate change impacts. Also, the share of sensitive population groups will change. The share of elderly in Europe is expected to rise from about 17.1 % to 30 % by the year 2060. The share of people aged 80 years or older (4.4 % in 2008) will nearly triple by 2060 (Eurostat, 2008). This demographic trend will naturally bring increased heat-related mortality rates even without climate change if no adaptation measures are taken. However, demographic development in cities does not necessarily follow overall European or regional trends. There are at present no European-wide demographic projections available at the city level.

5.5 Damage costs

The first part of this section presents observed trends in weather and climate-related events and the economic losses associated with them. While these events have been influenced by global climate change, it is not generally possible to attribute specific events or observed trends to global climate change. The second part presents results of the ClimateCost project, which estimates economic costs of climate change in Europe for different emissions scenarios.

5.5.1 Damages from weather and climate-related events

Relevance

Economic losses from weather- and climate-related disasters have increased, but with large spatial and interannual variability. Global weather- and climate-related disaster losses reported over the last few decades reflect mainly monetised direct damages to assets, and are unequally distributed. Loss estimates are lower-bound estimates because many impacts, such as loss of human lives, cultural heritage and ecosystems services, are difficult to value and monetise, and thus they are poorly reflected in estimates of losses. Economic, including insured, disaster losses associated with weather, climate and geophysical events are higher in developed countries. Fatality rates and economic losses expressed as a proportion of GDP are higher in developing countries (IPCC, 2012).

Europe is experiencing an increasing number of hydro-meteorological, geophysical and technological disasters that are caused by a combination of changes in its physical, technological and human/social systems. The potential for a hazard to cause a disaster mainly depends on how vulnerable an exposed community is to such hazards. Actions and measures, if well implemented, can reduce the human health and economic impact of a hazardous event. In recent years, policies for disaster risk reduction and management have shifted to a comprehensive, integrated risk approach. The full disaster cycle — prevention, preparedness, response and recovery — should be taken into consideration (EEA, 2011). Adaptation to climate change and disaster risk management provide a range of complementary approaches for managing the risks of climate extremes and disasters (IPCC, 2012).

Uncertainties and data gaps

Information for Europe can be extracted from two global disaster databases, namely the EM-DAT database maintained by CRED ([77]) (see also Section 4.4) that places a particular focus on human fatalities and displaced and affected people, and the NatCatSERVICE database (NatCatSERVICE, 2012) maintained by Munich RE that provides data on insured and overall losses. The 'disaster thresholds' for an event to be included in these global databases are as follows:

- EM-DAT: 10 or more people killed and/or 100 or more people affected and/or declaration of a state of emergency and/or call for international assistance;

Key messages: 5.5.1 Damages from weather and climate-related events

- Hydro-meteorological events (storms, floods, and landslides) account for 64 % of the reported damages due to natural disasters in Europe since 1980; climatological events (extreme temperatures; droughts and forest fires) account for another 20 %.
- Overall damages from extreme weather events have increased from EUR 9 billion in the 1980s to more than EUR 13 billion in the 2000s (inflation-corrected).
- The observed damage increase is primarily due to increases in population, economic wealth and human activities in hazard-prone areas and to better reporting.
- It is currently difficult to determine accurately the proportion of damage costs that are attributable to climate change. The contribution of climate change to the damage costs from natural disasters is expected to increase due to the projected changes in the intensity and frequency of extreme weather events.

([77]) See http://www.emdat.be.

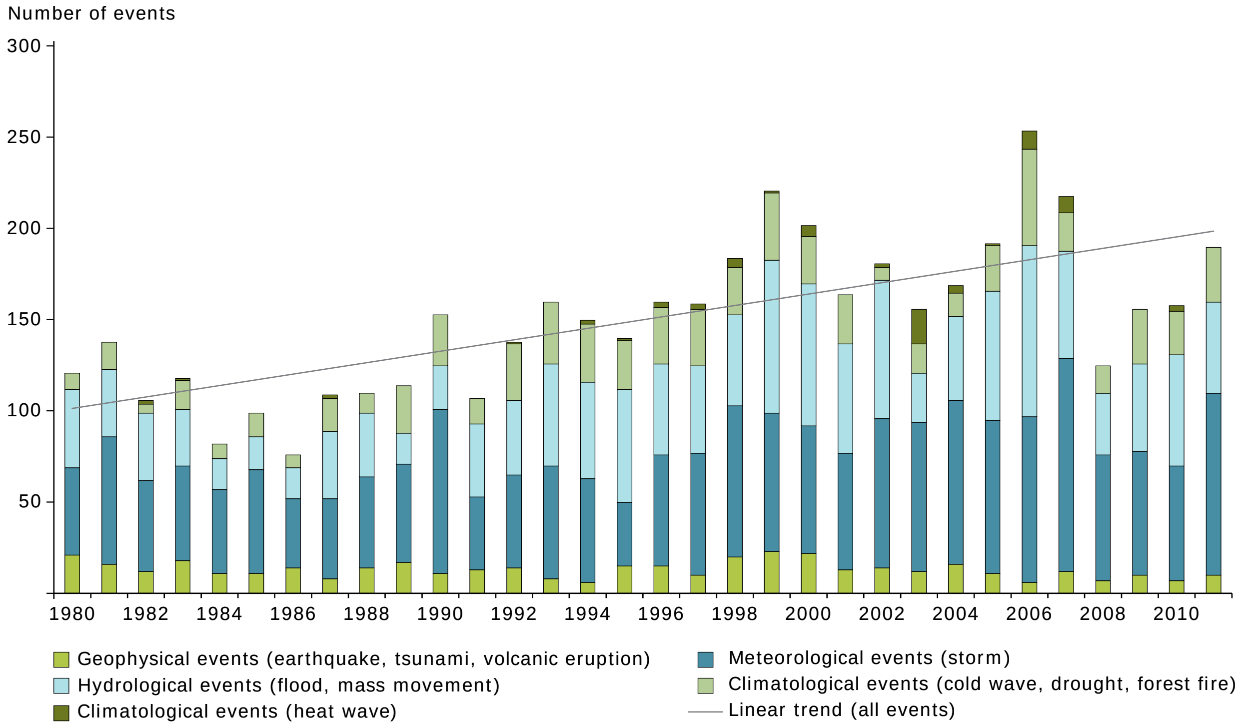
- NatCatSERVICE: Small-scale property damage and/or one fatality. Additionally, Munich RE uses different classes to classify the events.

Over recent years these global databases have been harmonised, although some differences remain. During the past decades both databases have improved their reporting which means that caution is needed in formulating conclusions about trends. In addition, both databases are less suitable for analysing the impacts of smaller events or for analyses at the sub-national level. However, despite these considerations both databases serve as a good starting point for getting an overview of the impact and damage costs of disasters in Europe.

Past trends

According to the (NatCatSERVICE, 2012) of Munich RE, the number of reported natural disasters in EEA member countries shows an upward trend since 1980 (see Figure 5.3). Whereas the number and impacts of weather and climate-related events increased considerably between 1980 and 2011, the number of geophysical hazards remained more stable. Hydro-meteorological events (storms, floods, and landslides) account for about 75 % of natural disasters that have occurred in Europe since 1980 and around 64 % of the reported damage costs; climatological events (extreme temperatures; droughts and forest fires) account for another 16 % of the disasters and 20 % of the damage costs (NatCatSERVICE, 2012).

Figure 5.3 Natural disasters in EEA member countries (1980–2011)



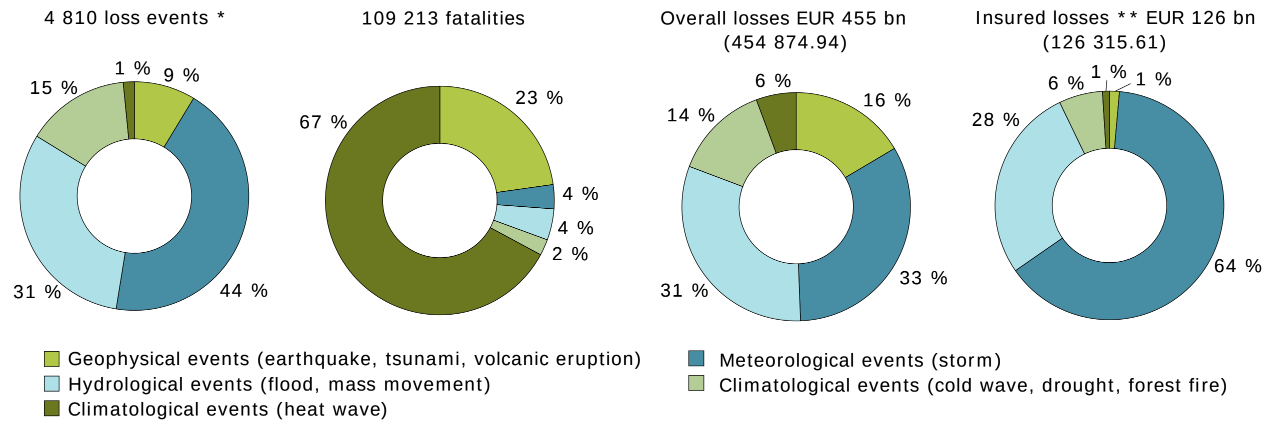
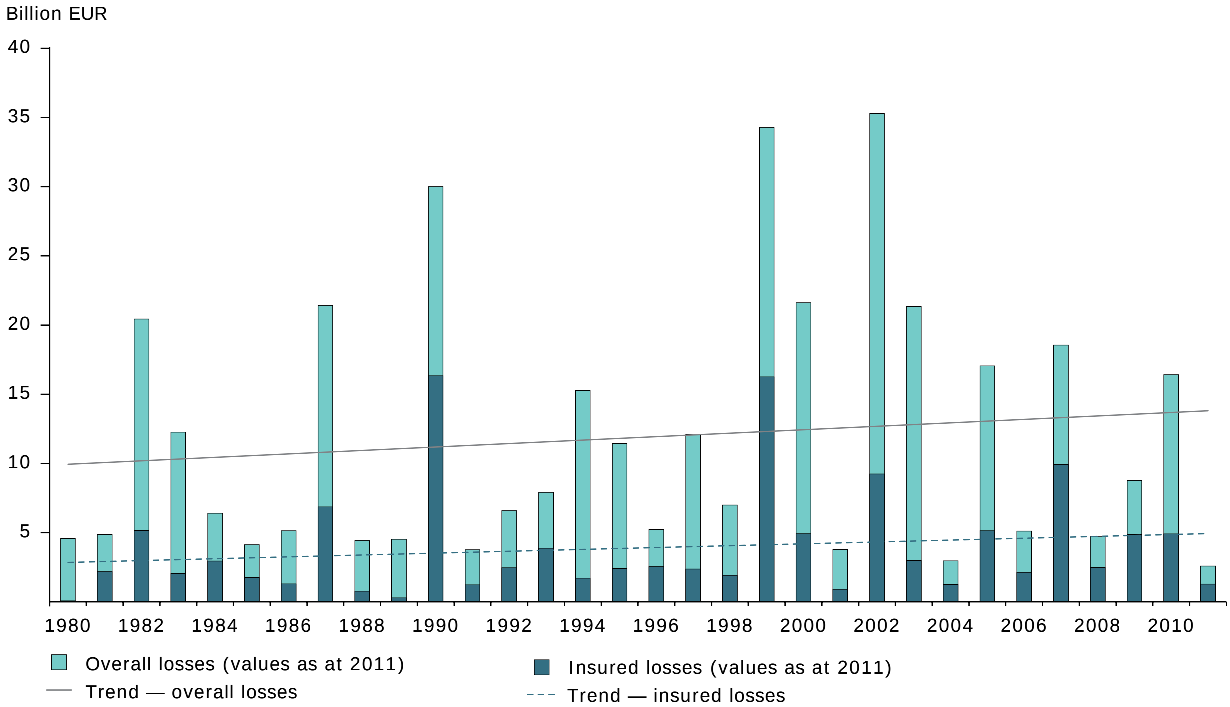


Figure 5.3 Natural disasters in EEA member countries (1980–2011) (cont.)



Note: Events can occur in several countries; events are counted country-wise.

Source: NatCatSERVICE, 2012.

Between 1980 and 2011, the economic toll of natural disasters in the whole of Europe approached EUR 445 billion in 2011 values ([78]). About half of all losses can be attributed to a few large events such as storms like Lothar in 1999, Kyrill in 2007 and Xynthia in 2010, and the floods of central Europe in 2002 and in the United Kingdom in 2007. Damage costs from extreme weather events in EEA member countries have increased from EUR 9 billion in the 1980s to more than EUR 13 billion in the 2000s (values adjusted to 2011 inflation). Similar trends were presented in a recent report for Organisation for Economic Co-operation and Development (OECD) countries (Visser et al., 2012).

One important question is to what extent the observed increase in overall losses during recent decades is attributable to changing climatic conditions rather than other factors. According to (IPCC, 2012), increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters. Long-term trends in economic disaster losses adjusted for wealth and population increases have not been attributed to climate change, but a role for climate change has not been excluded.

Available studies for Europe, such as (Barredo, 2009; 2010), on river floods and storms, suggest that increased losses are primarily due to socio-economic changes and increasing exposed elements due to changes in population and economic wealth, and activities in hazard-prone areas. Upward trends in losses can also be explained to a certain extent by better reporting. The study mentioned above (Visser et al., 2012) presents similar conclusions. By normalisation of disaster trends, meaning correcting

([78]) This corresponds to events that have been entered into the Munich RE database for the whole of Europe, i.e. events that led to property losses and/or fatalities. The following Munich RE definitions apply to natural disasters: 1) a small-scale loss event is defined as a 1–9 fatalities event with a small-scale property damage; 2) a moderate loss event is defined as 10+ fatalities event with a moderate property and structural damage; 3) a severe catastrophe is defined as a 20+ fatalities event with overall losses in excess of USD 50 million; 4) a major catastrophe is defined as a 100+ fatalities event with overall losses in excess of USD 200 million; 5) a devastating catastrophe is defined as a 500+ fatalities event with overall losses in excess of USD 600 million; and 6) a great natural catastrophe or great disaster is defined at leading to thousands of fatalities with the economy being severely affected and extreme insured losses; interregional or international assistance is necessary, hundreds of thousands are made homeless (UN definition).

for changes in wealth and/or population, trend patterns for economic losses and people affected appear stable for OECD countries.

Projections

Although it is currently difficult to determine accurately the proportion of losses that are attributable to climate change (EEA, 2008; 2010c), in view of current and projected climate change impacts and risks its contribution to losses is expected to increase.

Several studies have analysed the costs of projected climate change impacts in Europe for various sectors. However, these studies do not provide specific estimates for projected damage costs for weather and climate-related disasters, since reliable projections for weather and climate-related extreme events are not available (see also Section 2.2).

The following section provides an overview of the main information on costs of projected climate change impacts across a range of sectors in Europe.

5.5.2 Projected costs of climate change

Introduction

The effects of climate change, as outlined in the previous chapters and sections, will lead to wide ranging impacts on the natural and man-made environment. They will also lead to economic costs, often known as the 'costs of inaction', which are increasingly used to inform the policy debate on climate change in Europe. A number of different methods and models are being used to advance estimates of the costs of inaction. As an input to the global debate, and for the estimation of the social cost of carbon (the marginal economic costs of a tonne of GHG emitted), the primary approach has been to use global economic integrated assessment models. At the regional to national level, the emerging focus has been on scenario-based impact assessment.

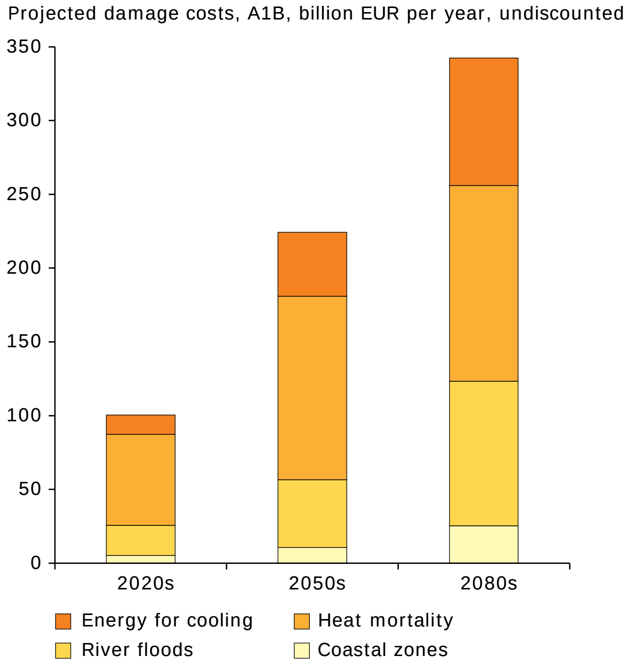
At the European scale, a number of studies have advanced these assessments as part of consistent sectoral assessments, notably in the PESETA project (Ciscar et al., 2009, 2011) and the EU FP7-funded ClimateCost Project (Watkiss, 2011), though there are many additional studies in individual sectors. A large number of studies and estimates are also emerging at Member State level (not reported here).

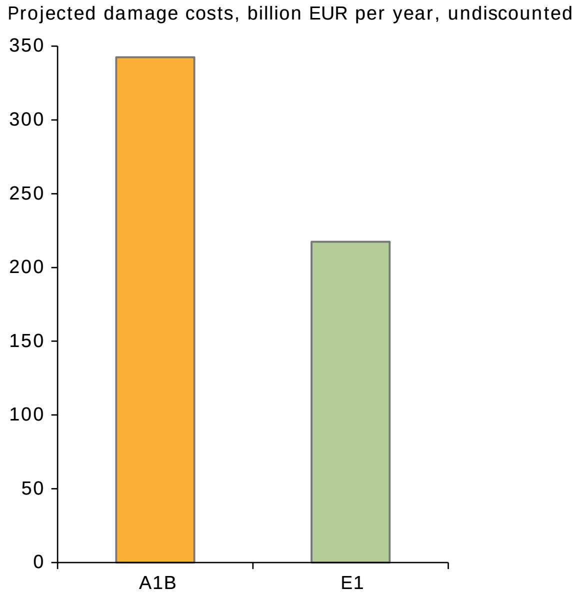
In reporting and comparing these numbers, a large number of caveats are needed, reflecting variations in practice among studies. It is important to consider whether results are reported for the impact of climate change and socio-economic change together, the effects of climate change alone above future socio-economic change, or the effects of future climate change on current socio-economic conditions. There are also major issues with the reporting and adjustment of economic values in different time periods, and whether future values are presented as discounted or present values. Note that in the information that follows, values are generally reported as current prices in all future time periods to facilitate direct comparison, over time, and among sectors.

Key messages: 5.5.2 Projected costs of climate change

- Projections suggest large increases in costs from coastal and river flooding, heat waves and energy demand (for cooling) due to the combined effects of climate change and socio-economic developments in Europe.
- There are strong geographical differences in projected costs, with pronounced damage costs in southern Europe due to increases in energy demand and heat waves, in western Europe due to coastal flooding and heat waves, in northern Europe due to coastal and river floods, and in eastern Europe due to river floods.
- Significant cost reductions can be achieved if mitigation policy would constrain climate change consistent with the EU's 2 °C objective, compared to a business-as-usual emissions scenario.
- Cost estimates have a medium to good coverage at European level for coastal and river flooding, water supply, energy demand, agriculture and human health, but cost estimates are not available or very incomplete for infrastructure, built environment, tourism, transport and forestry. Economic costs for impacts on biodiversity and ecosystems services are difficult to prepare due to the challenge of proper valuation.
- Information on the total costs of the impacts of global climate change on the European economy is lacking.

Figure 5.4 Projections of economic costs from climate change and socio-economic developments for four major categories





Note: Left: damage costs for the A1B scenario for energy for cooling, heat-related mortality (weighted average of Value of a Statistical Life (VSL) and Value of a Life Year Lost (VOLY)), river floods and coastal zones. Time horizon: 2010–2040, 2040–2070 and 2070–2100.
Right: A1B and E1 scenarios, 2070–2100.

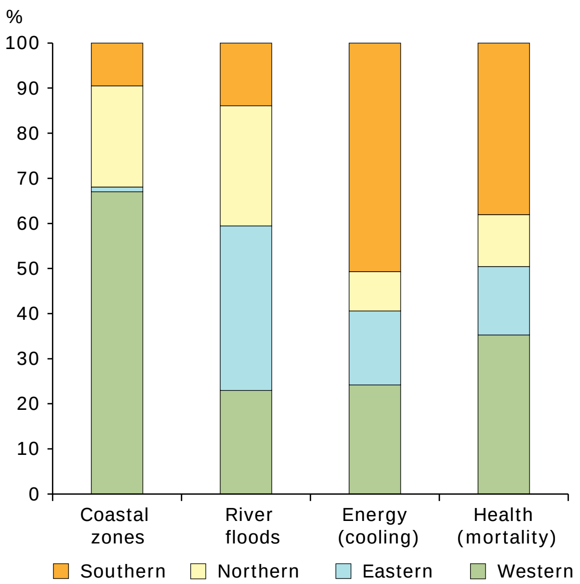
Source: Watkiss, 2011.

Summary of results

The results of the ClimateCost project reveal potentially large costs of inaction in Europe (see Figure 5.4). They also show the strong geographical differences across regions (see Figure 5.5). Importantly, they show the significant reductions in costs of inaction that can be achieved by mitigation policy consistent with the EU's 2 °C target, including avoiding some of the potential lower-probability, high-consequence events (see Figure 5.4).

There are also some headline aggregated results which report large economic costs for Europe. As an example, the PAGE09 Integrated Assessment Model (IAM) (Hope, 2011; Watkiss, 2011) reports total damage costs equivalent to almost 4 % of GDP for Europe by 2100 under an A1B scenario, with a risk of extremely large costs at the tails of the distribution (in excess of 10 % of GDP equivalent). Under the E1 scenario (equivalent to the 2 °C target) these fall to under 1 % of GDP equivalent and, more importantly, remove the tail of extreme values. It is stressed, however, that some other IAMs report much lower values.

Figure 5.5 Projected distribution of economic costs from climate change and socio-economic developments by impact type and European region



Note: EU-27 only; A1B scenario, 2070–2100, combined effects of climate change and socio-economic change.

Source: Watkiss, 2011.

Of course, all of the estimates above are partial. Even within the sectors covered, the analysis considers a subset of the possible effects of climate change. There are also important sectors for which estimates are not reported above (e.g. water, business, etc.) and some others where valuation remains challenging, notably biodiversity and ecosystems services (including terrestrial, aquatic and marine systems, including the effects of ocean acidification).

The analysis also excludes the cross-sectoral, wider economic and international (non-European) effects. There has been some assessment of wider macro-economic effects in Europe (Ciscar et al., 2011) using computable general equilibrium models, but the coverage of cross-sectoral effects remains at an early stage, and there is very little quantitative evidence on how impacts internationally will impact within Europe. All of these additional categories need to be considered in weighing up the overall economic estimates of climate change to Europe.

An indicative summary table showing the coverage of damage cost estimates is shown in Table 5.1.

Table 5.1 Coverage of European-wide damage cost studies by sector

Sector	Coverage	Damage cost estimates
Coastal zones	High coverage (infrastructure/erosion) for Europe, regions, several Member States as well as cities/local examples. Less on valuation of coastal ecosystems.	✓✓✓✓
Water	Medium. European-wide studies of flood risks, as well as national, river basin or sub-national studies on water supply. Some coverage of droughts and wider demand-supply balance.	✓✓✓
Energy	Medium. Cooling/heating demand for Europe, as well as some Member States. Number of studies on hydro-generation, and some analysis of thermal plant.	✓✓✓
Agriculture	Medium. Large number of studies on crop productivity, with consideration of values, including as part of international studies looking at trade effects. Much less analysis outside main crops, e.g. on horticulture, livestock and wider multi-functionality of agriculture.	✓✓✓
Health	Medium. Several European studies on heat-related mortality, and a number of other effects (food-borne disease, some flood risk aspects). Less coverage of economics of other health risks.	✓✓✓
Infrastructure/ built environment	Medium. Largely covered through flood and energy analysis above. Some indicative estimates for storm damage, some national studies of subsidence.	✓✓
Tourism	Medium — Low. Some European analysis (summer tourism) and winter tourism (Alps).	✓✓
Transport	Medium — Low. Recent European analysis, and number of national and individual sector case studies.	✓✓
Forestry	Low — Medium. A number of studies, within Europe and linked as part of global assessments, mostly focused on timber value, though some carbon storage values emerging.	✓✓
Biodiversity/ ecosystems services	Low – limited number of quantitative studies, though some examples through to valuation (e.g. carbon sequestration).	✓
Business and industry	Very low — no quantitative studies found.	–
Indirect and cross-sectoral	Low — some examples (e.g. flooding) but limited, and little coverage of full range of effects and compounding factors.	✓
Macro-economic effects	Low — a number of studies have fed sectoral impact assessment values into computable general equilibrium (CGE) models.	✓
International (effects into EU)	Very little quantitative literature. Potentially includes issues with imports/exports, supply chains, international price effects, and socially contingent effects such as from migration or conflict (and impacts on Europe or on development funding).	–
Tipping elements	Low — though a number of studies on economic costs of major sea-level rise in Europe and at Member State level.	✓

Note: See main text for discussion and caveats.

Key: ✓✓✓✓ Good coverage at European, national and local levels.

✓✓✓ Reasonable coverage, with a selection of European and national studies.

✓✓ Emerging coverage, with a selection of European and some national studies.

✓ Low coverage with some initial European or selected national or case studies.

– Lack of published studies, literature mostly focused on qualitative analysis.

Source: EEA, 2010a.

Finally, it is also important to account for additional policy co-benefits. Mitigation policy has a beneficial effect in reducing GHG emissions, but also reduces emissions of air pollutants which lead to air quality benefits, which importantly are both local and immediate. The GAINS and ALPHA models were used to estimate the health and environmental benefits of achieving the EU's 2050 low-carbon path (Holland et al., 2011). The large benefits in terms of increased life expectancy and lower pollution-related impacts were estimated at EUR 48 billion to EUR 99 billion per year in 2050 for the EU-27 (current prices, undiscounted), and generated very significant economic benefits per tonne of CO2 reduced. Additional economic benefits would also arise from enhanced energy security and the reduction in energy imports

Even if emissions of GHGs stop today, changes in the climate will continue for many decades and there is a need to develop adequate adaptive responses (adaptation). To allow a fully informed policy debate on adaptation, there is a need to consider the economic aspects of adaptation, that is, the costs and benefits. There is an emerging literature on such estimates, and alongside European estimates many countries are developing economic assessments as part of their climate change and adaptation policy development. Information on the costs of adaptation is included in the dedicated EEA report 'Adaptation in Europe'.

The remainder of this section presents information on costs in the main sectors investigated in the ClimateCost project.

Coastal floods

The most studied sector to date is the coastal sector, which has long reported European damage costs from models such as DIVA (Vafeidis et al., 2008; Hinkel and Klein, 2009) with more detailed studies for some Member States (notably the Netherlands and the United Kingdom, e.g. Evans et al., 2004; Deltacommissie, 2008). Previously reported estimates from PESETA (Richards and Nicholls, 2009; Bosello et al., 2011) have been updated by (Hinkel et al., 2010) and more recently as part of the ClimateCost project (Brown et al., 2011). The latter analysis considered a medium-high emissions A1B scenario and a mitigation scenario the ENSEMBLES E1 scenario (Lowe et al., 2009; van der Linden and Mitchell, 2009). The mitigation scenario leads to long-term stabilisation at 450 ppm, which has a high chance of limiting global warming to less than 2 °C, relative to pre-industrial levels, consistent with the EU target. It also considered an extreme sea-level rise consistent with the more recent literature since the AR4, considering a rise of more than 1.2 m of sea-level rise (SLR) by 2100 (see for example Rahmstorf, 2007). Assuming that defences are not upgraded from the standards modelled in the 1995 baseline, the costs in Europe are estimated at around EUR 11 billion/year (for the mid estimate of temperature-sea level response) for the 2050s (annual average costs for the period 2040–2070), rising to EUR 25 billion/year by the 2080s (annual average costs for the period 2070–2100) for the A1B scenario (combined effects of climate and socio-economic change, based on current prices, with no discounting). It is highlighted there is a wide range around these values due to the uncertainty in projected temperature and sea-level rise response. Under the E1 (mitigation) scenario, costs in later time periods fall significantly. The consideration of a more extreme sea-level scenario (over 1.2 m by 2100) increases the estimated annual damage costs for the EU to EUR 156 billion/year (undiscounted) by the 2080s — six times higher than that for the A1B scenario. This is an important finding as it highlights the need for both mitigation as well as adaptation as the chances of these extreme scenarios are significantly reduced with mitigation. There are also major differences among Member States in the costs projected. At the overall European level these coastal damage costs are a relatively low percentage of GDP, but there are higher relative costs (as a proportion of GDP) in some countries. Belgium, Denmark, the Netherlands, Portugal and the United Kingdom are ranked in the top five most costly countries for damage costs relative to GDP.

River floods

There are also European-wide damage cost estimates for river flooding. Floods already cause major economic costs in Europe and climate change could increase the magnitude and frequency of these events, leading to higher costs. However, these events need to be seen in the context of other socio-economic drivers. A range of European and Member State assessments have emerged over recent years. Analysis from the ClimateCost project (Feyen et al., 2011) using the LISFLOOD model has assessed the potential costs of river flooding across Europe. The expected annual damage (EAD) costs under an A1B scenario led to estimated costs of EUR 20 billion by the 2020s (2011–2040), EUR 46 billion by the 2050s (2041–2070) and EUR 98 billion by the 2080s (2071–2100) (mean ensemble results, combined effects of socio-economic and climate change, current values, undiscounted) in the EU-27. However, a large part of these future costs (and the increase in exposure) is driven by socio-economic change (population and economic growth), noting these drivers vary among EU Member States. Analysis at the country level shows high climate-related costs in Belgium, Ireland, Italy, the Netherlands and the United Kingdom. The results also show a very wide range around these central (mean ensemble) estimates, representing the range of results from different climate models. At the EU level, the potential damage costs were found to vary by a factor of two (higher or lower) across the range of models sampled (12 regional climate models): at the country level the differences were even more significant, with different models even reporting differences in the sign of change. This highlights the need to consider this variability (uncertainty) in formulating adaptation strategies. Under the E1 stabilisation scenario, the costs were estimated to fall to EUR 15 billion by the 2020s, EUR 42 billion by the 2050s and EUR 68 billion by the 2080s in the EU-27 (current values, undiscounted). There has also been work on European-wide assessments of drought risks and water scarcity risks, as part of the ClimWatAdapt project (see Section 5.2), though this has not produced damage costs.

Energy

Some of the largest potential costs (and also benefits) of climate change in Europe are likely to occur in the energy sector (see Section 4.5). Climate change will have negative and positive effects on future energy demand, increasing summer cooling but reducing winter heating demand. The ClimateCost study has assessed the potential impacts and economic costs of climate change on energy demand in Europe using the POLES model (Mima et al., 2012). Considering cooling demand first, the study reports a strong increase in cooling (and electricity) demand in Europe under the A1B scenario, with the additional cooling costs from climate change alone estimated at around EUR 30 billion/year in the EU-27 by 2050, rising to EUR 109 billion/year by 2100 (current values, undiscounted). There is a strong distributional pattern of cooling increases across Europe, with a much higher increase in southern Europe, and as for other sectors, a very wide range around the central (mean ensemble) estimates, representing the range of results from different climate models. However, a similar level of economic benefit is projected from the reduction in winter heating demand from warmer temperatures under the A1B scenario, estimated also at just over EUR 100 billion/year by 2100, though the benefits generally arise in different countries due to the costs of increased cooling. Under the E1 scenario, the total costs of cooling demand due to climate change (alone) are much lower, estimated at approximately EUR 20 billion/year across the period 2050–2100.

Climate change will also have effects on energy supply, notably on hydro-electric generation, but also potentially on thermal power (nuclear and fossil) plants and on some renewables. The combined effects of these supply effects could be significant (at up to a few per cent of European generation) and have potentially large economic costs, potentially similar in size to the demand effects described above.

Human health

For non-market sectors, a key focus has been on the health sector (see also Section 4.4). The largest economic costs are likely to arise from heat-related mortality, though the potential effects of food-borne disease and flood-related health effects are also important. ClimateCost provided European estimates of the impacts and economic costs of climate change on health in Europe (Kovats et al., 2011). The costs of heat-related mortality were estimated, though the reported values vary strongly according to whether acclimatisation is assumed, and on the metric used for mortality valuation. The estimated costs of heat-related mortality — from climate change and socio-economic change (including the population age distribution) — were estimated at over EUR 200 billion/year by the 2050s (2041–2070) when using a full Value of a Statistical Life (VSL); however, these estimates are driven by future socio-economic change. The estimated costs of heat related mortality — from climate change alone (over and above socio-economic change) — were estimated at EUR 31 billion/year by the 2020s (2011–2040), EUR 103 billion/year by the 2050s (2041–2070) and EUR 147 billion/year by the 2080s (2071–2100) for the A1B scenario when using a full VSL. These values fell by over a factor of ten when using the Value of a Life Year Lost (VOLY) approach, which adjusts for the average period of life lost. Including (autonomous) acclimatisation also reduced these A1B impacts significantly, by around a factor of three for later time periods. The greatest impacts arise in the most populated countries (in absolute) terms, but there are relatively higher increases (per population) for Mediterranean countries, reflecting higher warming and risk factors. The results also show a very wide range around the central (mean ensemble) estimates, representing the range of results from different climate models. In all cases, the costs in later years fall significantly under an E1 (2 °C) scenario, by almost half by the 2080s, and more than this under scenarios where acclimatisation is included. Additional economic costs were estimated for food-borne disease (salmonellosis) and flood-related deaths, though these were found to be relatively low compared to heat-related mortality. It is also stressed that there are potentially very large economic benefits from climate change reducing winter (cold-related) mortality in Europe. Previous estimates (Watkiss and Hunt, 2012) estimate that these are likely to be at least as large — in terms of the reduction in cases of mortality/life years gained and economic benefits — as the increases in heat-related mortality.

Biodiversity and ecosystems services

The valuation of the effects of climate change on biodiversity and ecosystems services is extremely complex and while a number of studies have undertaken case studies, this remains an under-explored area. There has been wider progress on ecosystem service valuation, notably through the Economics of Ecosystems and Biodiversity (TEEB) study (TEEB, 2010). There have also been assessments of the economic benefits that ecosystems services (forests) provide in terms of carbon sequestration (regulating services) and the effects of climate change on these under future scenarios. However, the results are highly determined by assumptions about CO_2 fertilisation (Watkiss, 2011). Some work has also looked at ecosystem shifts from climate change on bioclimatic species and ecosystem envelopes and using restoration costs (Hunt, 2008). However, the wider application of ecosystem service valuation to assess the impacts of climate change remains a major priority for future analysis.

6 Indicator and data needs

Key messages

- For many indicators of past climate change and climate change impacts in Europe improvements in data are needed (e.g. to extend the length of time series and the geographical coverage).
- Enhanced monitoring is needed of Essential Climate Variables (ECVs) relevant for adaptation, both from in situ stations and using satellites and there is also a need for further reanalysis of European climate data.
- Enhanced monitoring is also needed of climate change impacts in Europe on environmental systems, socio-economic systems and health, and of costs of damages of extreme weather events.
- Climate change impacts indicators are only to a very limited extent included within existing and emerging European thematic and sectoral indicator sets, but this should be considered in future improvements of these indicator sets.
- Currently, indicators in this report are based on EU-wide research and/or global databases. For many indicators this could continue in the future while some selected indicators may in the future be based on direct data collected from member countries, for example through the Climate-ADAPT platform and/or through reporting of indicators by Member States to the European Commission and the EEA.
- Improved comparability of climate change impact indicators may be achieved if consistent and comparable methods and data would be implemented across EEA member countries.
- Future EU research on climate change impacts, vulnerability and adaptation is expected to increase, which can help improve the coverage and quality of European-wide indicators.

Introduction

This chapter covers the existing indicator frameworks at EU level and thematic and sectoral indicator sets and shows that these have included climate change and climate change impacts only to a very limited extent.

The chapter also summarises the existing and planned improvements of observation systems for ECVs and the role of Global Monitoring for Environment and Security (GMES). It shows that enhanced monitoring of ECVs, both from in situ stations and using satellites, is needed.

Finally, the chapter provides a short overview of climate change impacts, vulnerability and adaptation research activities in Europe. Although much research has been done, further research will be needed, through Horizon 2020, the EU financial instrument on future research and innovation. It is expected that around 35 % of the Horizon 2020 budget will be climate-related expenditure, which is for mitigation and adaptation together.

6.1 Policy needs for indicators

6.1.1 Indicator frameworks at EU level

In the EU a number of indicator sets exist or are being developed for various policy purposes. These initiatives do not yet explicitly take climate change impact, vulnerability and adaptation (CC IVA) aspects into account, although the indicator global temperature increase is included in a few sets (either as contextual or as key indicator). Here some of the main policy and related indicator developments are presented that are expected to have an influence on the future development of more specific indicators on CC IVA.

The focus of this chapter is on data and indicators on past and present climate change and its impacts. Vulnerability, usually focusing on future projections and scenarios, was addressed in Chapter 5, while the introduction mentioned the importance of socio-economic scenarios within vulnerability assessments.

A key policy development the past years was an increased focus on green economy and *resource efficiency,* in relation to the Europe 2020 – Europe's growth strategy. Climate change mitigation is covered in this strategy through targets on GHG emissions aimed to be 20 % lower than 1990 (or 30 %, if the conditions are right), 20 % of energy to come from renewables and a 20 % increase in energy efficiency. Climate change adaptation is covered to a lesser extent, although the strategy does mention: 'We must also strengthen our economies' resilience to climate risks, and our capacity for disaster prevention and response'.

The resource-efficiency initiative under the Europe 2020 strategy supports the shift towards a resource-efficient, low-carbon economy to achieve sustainable growth. The European Commission published in 2011 a roadmap for a resource-efficient Europe ([79]). It sets out a vision for the structural and technological change needed up to 2050, with milestones to be reached by 2020. It proposes ways to increase resource productivity and decouple economic growth from resource use and its environmental impact. A set of indicators is being developed by the European Commission (including Eurostat) and also involving the EEA. A stakeholder consultation process takes place in 2012 (July–October) ([80]).

Another related development is an increasing recognition of the need to measure progress in society, sustainability, well-being and quality of life, through for example a European Commission communication on 'Beyond GDP' and an overview in a report from the 'Sponsorship Group on Measuring Progress, Well-being and Sustainable Development' ([81]).

The resource efficiency and beyond GDP indicator developments have so far not included CC IVA explicitly.

Structural Indicators represent a set of 79 indicators developed to measure the progress towards the objectives of the Lisbon Strategy. However, after the conclusion of the Lisbon process in year 2010 and the adoption of the Europe 2020 strategy, the maintenance of this set by EUROSTAT is being progressively stopped.

Sustainable Development Indicators (SDIs) are used to monitor the EU Sustainable Development Strategy (EU SDS) in a report published by Eurostat every two years. They are presented in 10 themes. Of more than 100 indicators, 11 have been identified as headline indicators. They were intended to give an overall picture of whether the EU has achieved progress towards sustainable development in terms of the objectives and targets defined in the strategy. As one 'explanatory variable', global temperature increases was included.

The European Commission's *annual Environment Policy Review* is a report designed to monitor recent environmental trends and policy developments at EU and national levels and the progress towards the EU's key environmental goals as set out in the 6th Environment Action Programme. It contains about 30 key environmental indicators for EU environment policy and includes environmental goals as set out in the 6th Environment Action Programme. Regarding CC IVA, the following indicators are included: global air temperature change (compared to the goal of limiting the increase of global temperature to 2 °C above pre-industrial levels); concentrations of CO_2 in the atmosphere (compared to a stabilisation level in the range of 350 to 400 ppm); and natural disasters linked to climate change (floods, wind storms, extreme temperatures and droughts) ([82]).

A European Strategy for *Environmental Accounting* managed by Eurostat ([83]) provides the framework for environmental accounts. It was followed by an EU Regulation adopted in 2011. These accounts track the links between the environment and the economy at EU, national, regional and industry levels and complement environmental statistics and indicators. They facilitate an in-depth analysis of environmental concerns, since the different modules are broken down by industry (in the manner of National Accounting Matrix including Environmental Accounts (NAMEA)) at country level.

Regarding CC IVA issues, the developments of specifically water accounts and possibly also in the future ecosystem accounts can be relevant. The EEA collaborates with Eurostat on ecosystem accounting and is preparing several initial accounts by 2012, including on water (see below).

([79]) See http://ec.europa.eu/environment/resource_efficiency/index_en.htm.
([80]) See http://ec.europa.eu/environment/resource_efficiency/targets_indicators/stakeholder_consultation/index_en.htm.
([81]) See http://epp.eurostat.ec.europa.eu/portal/page/portal/pgp_ess/about_ess/measuring_progress.
([82]) See http://ec.europa.eu/environment/pdf/policy/EPR_2009.pdf.
([83]) See http://epp.eurostat.ec.europa.eu/portal/page/portal/environmental_accounts/introduction.

6.1.2 Thematic and sectoral indicator sets

A number of sectors are particularly relevant from the point of view of vulnerability to climate change. These include water; marine environment; terrestrial biodiversity; human health; and energy, transport and agriculture. Consequently there is also a particular interest to develop indicators for these themes, for which the current state of play is described below.

Water (water quality, floods, water scarcity and droughts)

Data and indicators on water quality and water resources (floods, water scarcity and droughts) are available in WISE, the Water Information System for Europe ([84]).

Within the WFD ([85]), first River Basin Management Plans for 2009–2015 were submitted in 2009/2010. While the first River Basin Management Plans (2009/2010) do not take climate change into account in most cases, the second plans (2015) should take into account the impacts of climate change, using guidance published in 2009. In addition, climate change should also be integrated in the implementation of the Floods Directive ([86]) and the Strategy on Water Scarcity and Drought (WSD) ([87]). The Floods Directive required Member States to first carry out a preliminary assessment by 2011 to identify the river basins and associated coastal areas at risk of flooding. For such zones they would then need to draw up flood risk maps by 2013 and establish flood risk management plans focused on prevention, protection and preparedness by 2015. The European Commission and the EEA will include information on (preliminary) flood risk maps in WISE. The reporting on flood risk management plans, due 2015, is expected to include information on climate change adaptation.

Regarding currently available data and indicators on WSD, in particular the Water Exploitation Index (WEI) is relevant, available at national scale ([88]). The spatial and temporal detail of the WEI is currently being improved by the EEA, encouraging countries to provide data at river basin-scale and for different seasons (see also below on water accounts). The EEA report 'Towards efficient use of water resources in Europe' (2012) includes an initial analysis of a more disaggregated WEI ([89]).

A SOER 2010 thematic assessment was published on 'Water resources: quantity and flows' ([90]). The Directorate-General for Environment (DG ENV) has commissioned a study 'ClimWatAdapt' aimed at an Integrated Assessment Framework to address water quantity/quality and climate change adaptation. Within ClimWatAdapt, various vulnerability indicators have been developed, including on water stress and flood risks ([91]). Other important projects and organisations, which include indicators on projected risks of floods at European level, are ESPON Climate ([92]) and the JRC ([93]).

Indicators on past impacts (on economy, human health, ecosystems) of natural hazards, including floods and droughts are included in an EEA report on natural hazards (2011) ([94]). The report used primarily data from EM-DAT/CRED ([95]) and Munich RE ([96]). In a workshop held in May 2011 and in a related paper, the need for improved quality for data on impacts of floods on human health, ecosystems and economy was highlighted ([97]).

By the end of 2012 the European Commission will publish a 'Blueprint to Safeguard Europe's Water' as the EU policy response to achieving EU water policy goals by 2020 (and beyond) addressing also new challenges such as climate change ([98]). The EEA will during 2012 publish various reports to support the blueprint, including a report on vulnerability. The European Commission and EEA include the

([84]) See http://water.europa.eu/data-and-themes.
([85]) See http://ec.europa.eu/environment/water/water-framework/index_en.html.
([86]) See http://ec.europa.eu/environment/water/flood_risk/index.htm.
([87]) See http://ec.europa.eu/environment/water/quantity/scarcity_en.htm.
([88]) See http://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources/use-of-freshwater-resources-assessment-2.
([89]) See http://www.eea.europa.eu/publications/towards-efficient-use-of-water.
([90]) See http://www.eea.europa.eu/soer/europe/water-resources-quantity-and-flows.
([91]) See http://circa.europa.eu/Public/irc/env/wfd/library?l=/framework_directive/climate_adaptation/climwatadapt_report&vm=detailed&sb=Title.
([92]) See http://www.espon.eu/main/Menu_Projects/Menu_AppliedResearch/climate.html.
([93]) See http://floods.jrc.ec.europa.eu.
([94]) See http://www.eea.europa.eu/publications/mapping-the-impacts-of-natural.
([95]) See http://www.emdat.be.
([96]) See http://www.munichre.com/en/reinsurance/business/non-life/georisks/natcatservice/default.aspx.
([97]) See http://forum.eionet.europa.eu/eionet-air-climate/library/public/workshops/expert_2011_louvain.
([98]) See http://ec.europa.eu/environment/water/blueprint/index_en.htm.

WEI and results from the ClimWatAdapt project and propose some processes to improve data quality and the collection, production and analysis of the WEI.

The European Strategy for Environmental Accounting (see above) also includes 'water accounts'. These 'water accounts' can show the linkages between water resources and the economy. The EEA is developing a water accounting method based on water balances on catchment level which may help to monitor water use in the context of increased risk of droughts due to climate change (see also the EEA 2012 report mentioned above on water efficiency).

Biodiversity and ecosystems

A pan-European initiative, SEBI 2010 (Streamlining European 2010 Biodiversity Indicators), was launched in 2004 ([99]). Its aim was to develop a European set of biodiversity indicators to assess and inform about progress towards the European 2010 targets.

The work is performed in collaboration between the EEA, DG ENV of the European Commission, the European Centre for Nature Conservation (ECNC), UNEP/Pan-European Biological and Landscape Diversity Strategy (PEBLDS) Secretariat with the lead of the Czech Republic and UNEP-WCMC (the World Conservation Monitoring Centre).

In 2010 a biodiversity assessment based on the SEBI indicators for the pan-European region was published ([100]). The technical report containing specifications of the 26 indicators selected was published in 2007 ([101]). In 2009, the SEBI 2010 indicator fact sheets were published ([102]). Furthermore, a number of other reports and messages on biodiversity were published by the EEA in 2010, including a baseline study related to the 2020 target ([103]).

In 2011, the European Commission adopted a new EU Biodiversity Strategy which identifies 6 priority targets and 20 actions ([104]). The adoption of new biodiversity targets at international and European levels has also required the review of the SEBI indicator set. The SEBI process has undertaken an initial mapping of the 26 SEBI indicators against the Aichi and EU targets. The analysis shows that all the SEBI indicators can be used to measure progress against the six new EU Targets and the 20 Aichi Targets. Gaps have also been identified, and further consideration by thematic experts on how to fill the gaps is necessary. SEBI also carried out a consultation with EEA member countries to find out how the indicators are being used. The revision of the SEBI indicator set provides opportunities for the updating and improvement of existing indicators and the development of new indicators to address gaps (e.g. ecosystems services). Regarding CC IVA, some analysis would be useful on how climate change can be addressed in the updating of the SEBI indicator set.

The EEA's ETC/ACM has analysed some of the aspects related to climate change adaptation and biodiversity ([105]). The paper considered proposed 'high-level' biodiversity adaptation indicator categories and concluded that there is a need to undertake an in-depth review of the complete spectrum of EU indicators to identify those that are most relevant for climate change adaptation and biodiversity and where existing indicators need to be modified or new indicators developed.

Regarding ecosystem assessments, Action 5 of the EU Biodiversity Strategy foresees that: 'Member States, with the assistance of the Commission, will map and assess the state of ecosystems and their services in their national territory by 2014, assess the economic value of such services, and promote the integration of these values into accounting and reporting systems at EU and national level by 2020'. Such ecosystem assessments should take CC IVA aspects into account.

Marine

The EEA marine indicators are presently part of the Core Set of Indicators (CSI) and energy sets. The Marine Strategy Framework Directive (MSFD ([106])), adopted in 2008, has a considerable emphasis on indicators for determining good environmental status, with a total of 56 indicators being identified

([99]) See http://ec.europa.eu/environment/nature/knowledge/eu2010_indicators/index_en.htm.
([100]) See http://www.eea.europa.eu/publications/assessing-biodiversity-in-europe-84.
([101]) See http://reports.eea.europa.eu/technical_report_2007_11/en.
([102]) See http://www.eea.europa.eu/publications/progress-towards-the-european-2010-biodiversity-target-indicator-fact-sheets.
([103]) See http://www.eea.europa.eu/themes/biodiversity.
([104]) See http://ec.europa.eu/environment/nature/biodiversity/comm2006/2020.htm.
([105]) See http://acm.eionet.europa.eu/reports/ETCACM_TP_2011_14_CCadapt_ind_biodiv.
([106]) See http://ec.europa.eu/environment/water/marine/ges.htm.

in a European Commission Decision. Building on a legal provision also in the MSFD for making data and information stemming from reporting obligations available to the EEA, and a high level commitment from Member States towards a WISE-marine, the EEA plans to eventually host multiple indicators on the marine environment. They are expected to cover the status of the marine ecosystem, as well as pressures and impacts of human activities in EU marine waters. Although the first reporting cycle will occur in 2012, there is still considerable effort needed to agree with Member States on the specifics of the data and methods needed for purpose of the EEA's tasks and products, including issues such as regional coherence, prioritisation and standardisation of datasets. Therefore, the EEA is on the one hand streamlining its current indicators with the MSFD requirements but also establishing a new set of marine indicators (MAR) to expand the number of indicators and better align with the descriptors and indicators of the MSFD. The MSFD indicators should take CC IVA into account.

Human health

WHO/Europe and the European Commission established the 'Climate, Environment and Health Action Plan and Information System' (CEHAPIS) project in 2008. This project aims to identify the current and future health risks of climate change for the European Region, and assess policy options proposed as well as developing indicators for measuring trends over time. As part of the CEHAPIS project a report on 'The health effects of climate change in the European Union: evidence for action' is expected to be published in 2012. Also a part of CEHAPIS is a proposal for possible indicators on health and climate change, based on the following issues: extreme weather events (excess heat, floods), air quality (ambient air quality, air-borne pollen/allergens) and infectious diseases (food-borne diseases, water-borne diseases, vector-borne diseases).

The ECDC developed the E3 Network, the 'European Environment and Epidemiology' Network ([107]), which provides infectious disease indicators for climate change and risk maps (*A. albopictus* and Dengue), and a risk assessment for the impact of climate change on food-, water- and vector-borne diseases.

Agriculture and environment

Agri-environmental indicators (AEIs) track the integration of environmental concerns into the Common Agricultural Policy (CAP) at EU, national and regional levels ([108]). The European Commission adopted 28 AEIs to assess the interaction between the CAP and the environment, and which track:

- farm management practices;
- agricultural production systems;
- pressures and risks to the environment;
- the state of natural resources.

The EEA cooperates with Eurostat (and the Directorate-General for Agriculture and Rural Development (DG AGRI), DG ENV and the JRC through a MoU, 2008) on the development and publication of these indicators (see EEA Report No 2/2006 'Integration of environment into EU agriculture policy — the IRENA indicator-based assessment report' ([109]). A few AEIs are potentially relevant for climate change including Water Abstraction, Land-Use Change due to agriculture, Soil Erosion, and Cropping patterns. Further analysis is needed regarding how climate change impacts can best be integrated in these indicators and/or whether additional indicators are needed.

Transport and environment

The main aim of the Transport and Environment Reporting Mechanism (TERM) ([110]) is to monitor the progress and effectiveness of transport and environment integration strategies on the basis of a CSI. The TERM indicators were selected and grouped to address seven key questions. The TERM process is steered jointly by the European Commission (Eurostat, DG ENV, the

([107]) See http://www.ecdc.europa.eu/en/healthtopics/climate_change/Pages/index.aspx.
([108]) See http://epp.eurostat.ec.europa.eu/portal/page/portal/agri_environmental_indicators/introduction.
([109]) See http://www.eea.europa.eu/publications/eea_report_2006_2.
([110]) See http://www.eea.europa.eu/themes/transport/term.

Directorate-General for Mobility and Transport (DG MOVE), and DG CLIMA) and the EEA. The EEA member countries and other international organisations provide input and are consulted on a regular basis. The TERM indicator list covers the most important aspects of the transport and environment system (driving forces, pressures, state of the environment, impacts and societal responses — the DPSIR framework). Some of the TERM indicators are relevant for climate change adaptation, for example those addressing the trans-European networks. Further analysis is needed regarding how climate change impacts can best be integrated in these indicators and/or whether additional indicators are needed.

Energy and environment

One of the EEA's key activities in the field of energy is monitoring the integration of environmental considerations in the energy sector ([111]). A set of 'energy and environment indicators' is updated and published regularly and the EEA publishes an energy and environment report on a regular basis, as well as assessments of the expected environmental benefits and pressures from different shares of renewable energy. The energy–environment indicators are organised around six policy questions. Some of these indicators are relevant for climate change adaptation, for example those addressing electricity production by various energy sources. The EEA is presently reviewing energy indicators addressing those needed in relation to the Europe 2020 strategy, and particularly focusing on energy efficiency and renewable energy. Further analysis is needed regarding how climate change impacts can best be integrated in these indicators and/or whether additional indicators are needed.

6.2 Observations

6.2.1 Essential Climate Variables

There are various ongoing efforts to improve climate change-related data availability at a global level and within Europe.

The 2009 World Climate Conference-3 (WCC-3) decided to establish a new Global Framework for Climate Services (GFCS ([112])) to provide a full range of climate information and prediction services for all climate-sensitive sectors in all countries. Meeting the full observational needs of the GFCS would involve the substantial investment in establishment and strengthening of national climate observing networks in most countries. The World Meteorological Organization (WMO) and its partners (e.g. member countries) are working on an implementation plan and governance structure of the Framework.

The Global Climate Observing System (GCOS) is supporting the objectives of the GFCS and is intended to be a long-term, user-driven operational system capable of providing the comprehensive observations required for:

- monitoring the climate system;
- detecting and attributing climate change;
- assessing impacts of, and supporting adaptation to, climate variability and change;
- application to national economic development;
- research to improve understanding, modelling and prediction of the climate system.

GCOS agreed on various monitoring principles ([113]). GCOS also has identified 50 ECVs (2010) that are technically and economically feasible for systematic observation and that are required to support the work of the UNFCCC and the IPCC ([114]) (see also Table 6.1).

The GCOS Implementation Plan (2010–2015) ([115]) describes the path toward an integrated observing system that depends upon both in situ and satellite-based measurements. Both types of measurement are regarded as vital. Total annual costs for existing observations and infrastructure contributing to GCOS are estimated to be USD 5–7 billion/year while the additional annual costs of implementing all actions in the GCOS

([111]) See http://www.eea.europa.eu/themes/energy/eea-energy-activities.
([112]) See http://www.wmo.int/pages/gfcs/index_en.php.
([113]) See http://www.wmo.int/pages/prog/gcos/index.php?name=ClimateMonitoringPrinciples.
([114]) See http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables.
([115]) See http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf.

Table 6.1 Essential Climate Variables that are both currently feasible for global implementation and have a high impact on UNFCCC requirements

Domain	GCOS Essential Climate Variables
Atmospheric (over land, sea and ice)	Surface: ([a]) Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget. Upper-air: ([b]) Temperature, wind speed and direction, water vapour, cloud properties, earth radiation budget (including solar irradiance). Composition: Carbon dioxide, methane, and other long-lived greenhouse gases ([c]), ozone and aerosol, supported by their precursors ([d]).
Oceanic	Surface: ([e]) Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton. Sub-surface: Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers.
Terrestrial	River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, soil moisture.

Note: ([a]) Including measurements at standardised, but globally varying heights in close proximity to the surface.

([b]) Up to the stratopause.

([c]) Including nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs).

([d]) In particular nitrogen dioxide (NO_2), sulphur dioxide (SO_2), formaldehyde (HCHO) and carbon monoxide (CO).

([e]) Including measurements within the surface mixed layer, usually within the upper 15 m.

implementation plan are estimated to be about USD 2.5 billion/year. A 'Satellite Supplement' ([116]) provides additional technical detail related to satellite-based observations for climate for each of the ECVs. Table 6.2 provides the list of ECVs considered particularly feasible for sustained monitoring from satellites.

Various ECVs are directly (or indirectly) relevant for the indicators on climate change and its impacts as presented in this report, such as near-surface atmospheric conditions, sea-surface temperature, ice and snow cover, and permafrost.

Table 6.2 Essential Climate Variables for which satellite observations make a significant contribution

Domain	Essential Climate Variables
Atmospheric (over land, sea and ice)	Surface wind speed and direction; precipitation; upper-air temperature; upper-air wind speed and direction; water vapour; cloud properties; Earth radiation budget (including solar irradiance); carbon dioxide; methane and other long-lived greenhouse gases; and ozone and aerosol properties, supported by their precursors.
Oceanic	Sea-surface temperature; sea-surface salinity; sea level; sea state; sea ice; ocean colour.
Terrestrial	Lakes; snow cover; glaciers and ice caps; ice sheets; albedo; land cover (including vegetation type); Fraction of absorbed photosynthetically active radiation (FAPAR); Leaf area index (LAI); above-ground biomass; fire disturbance; soil moisture.

([116]) See http://www.wmo.int/pages/prog/gcos/documents/SatelliteSupplement2011Update.pdf.

6.2.2 Global Monitoring for Environment and Security

The EU 'Global Monitoring for Environment and Security' (GMES) programme ([117]) aims to provide data to help users deal with a range of environmental and safety issues by a combination of satellite- and ground-based data. The aim is to provide faster, easier and (preferably) free access to data. GMES is expected to become a fully operational service programme in the coming years with services that can be divided into land, marine and atmosphere, and emergency response and climate change. These services are in various stages of development.

The European Commission's proposal for a 2014–2020 Multi-annual Financial Framework did not include GMES. In 2011/2012 discussions are taking place between the European Commission, the European Parliament and the European Council on the future financing of GMES.

The foreseen GMES climate change service was discussed at a stakeholder conference in 2011 (Helsinki, Finland) ([118]). The proposals ([119]) for the content of a potential GMES climate service were broadly agreed by the participants, including:

- a climate monitoring service using integrated and cross-calibrated data sets (including model output);
- a next generation reanalysis using historic data to better characterise and interpret past, recent and current changes;
- a portal for climate indicators providing global and European climate trends which give a more informed indication of what changes are occurring;
- an attribution service which delivers tools and results for interpretation of extreme events in terms of climate change or other causes;
- continued support for Europe's contribution to GCOS.

Currently, the European Commission is funding various GMES climate-relevant projects including EURO4M (European high resolution reanalyses) ([120]) and ERA-CLIM (global reanalyses) ([121]).

The ESA Climate Change Initiative (ESA-CCI ([122])) is an existing programme which is funding projects to develop climate quality datasets of a number of GCOS ECVs which are observable from satellites. The initial set of 10 ECV projects which are already funded through the ESA-CCI are:

- Atmosphere: Clouds; Ozone; Greenhouse Gases; Aerosols;
- Marine: Sea Surface Temperature; Sea Level; Ocean Colour;
- Terrestrial: Glaciers and Ice Caps; Land Cover; Fire.

6.3 Climate change impacts, vulnerability and adaptation research

In the EU's FP7 (2007–2013) climate-relevant research ([123]) is dealt with across various themes. Targeted climate change research focuses on:

- the Earth system and climate, and related abrupt changes;
- natural and anthropogenic emissions;
- the global carbon cycle;
- greenhouse gases;
- future climate;
- the natural, social and economic impacts of climate change;
- mitigation and adaptation strategies, including novel responses to climate change;

([117]) See http://www.gmes.info/ and http://ec.europa.eu/enterprise/policies/space/gmes.
([118]) See http://ec.europa.eu/enterprise/policies/space/gmes/services/climate_change_conference_en.htm.
([119]) See http://ec.europa.eu/enterprise/policies/space/files/gmes/climate-change-conf-helsinki-june-2011/gmes_climateservice_draft_en.pdf.
([120]) See http://www.euro4m.eu/index.html.
([121]) See http://www.era-clim.eu.
([122]) See http://www.esa-cci.org.
([123]) See http://ec.europa.eu/research/environment/index_en.cfm?pg=climate.

- natural climate-related hazards such as floods, droughts, storms or forest fires;
- climate change impacts on health.

See for an overview of all climate change projects the European Commission's website ([124]). Furthermore, Climate-ADAPT contains a database with all main EU FP6/FP7 projects over the past years dealing with climate change impacts, vulnerability and adaptation ([125]). The EU CIRCLE-2 ('Climate Impact Research & Response Coordination for a Larger Europe') ERA-NET project ([126]) contains an extensive database on relevant national research activities.

Although much research has been done on CC IVA, further research will be useful on a range of questions or issues that may need further attention, such as links between mitigation and adaptation and societal transformation to sustainable development and a green economy.

Horizon 2020 ([127]) is the EU financial instrument implementing the 'Innovation Union', a Europe 2020 flagship initiative. Priorities and research focus for Horizon 2020 are being discussed in 2011/2012. Climate action is amongst the priorities identified in the proposal by the European Commission (2011 ([128])). At least 60 % of the total Horizon 2020 budget would be related to sustainable development, the vast majority of this expenditure contributing to mutually reinforcing climate and environmental objectives. It is expected that around 35 % of the Horizon 2020 budget will be climate-related expenditure, which is for both mitigation and adaptation together. The European Parliament and European Council are discussing the content and budget for Horizon 2020 and by end-2013 adoption of legislative acts on Horizon 2020 are expected.

The concept of Joint Programming was introduced by the European Commission in 2008. It is one of the initiatives for implementing the European Research Area (ERA ([129])). The aim of Joint Programming is to increase the value of relevant national and EU research and development (R&D) funding by concerted and joint planning, implementation and evaluation of national research programmes. A Joint Programming Initiative 'Connecting Climate Knowledge for Europe' (JPI Climate ([130])) was initiated which will cover research related to improving climate projections, climate services, societal transformation and decision support tools. It was launched by the European Council in December 2011 ([131]) (as part of the launching of five JPIs for research) and a range of recommended actions were mentioned.

([124]) See http://ec.europa.eu/research/environment/index_en.cfm?pg=projects&area=climate.
([125]) See http://climate-adapt.eea.europa.eu/web/guest/research-projects.
([126]) See http://www.circle-era.eu/np4/10.
([127]) See http://ec.europa.eu/research/horizon2020/index_en.cfm?pg=h2020.
([128]) See http://ec.europa.eu/research/horizon2020/pdf/proposals/communication_from_the_commission_-_horizon_2020_-_the_framework_programme_for_research_and_innovation.pdf#view=fit&pagemode=none.
([129]) See http://ec.europa.eu/research/era/index_en.htm.
([130]) See http://www.jpi-climate.eu.
([131]) See http://www.consilium.europa.eu/uedocs/cms_Data/docs/pressdata/en/intm/126583.pdf.

7 Abbreviations and acronyms

7.1 General abbreviations and acronyms

Table 7.1 presents all abbreviations and acronyms used in this report, except for the acronyms of fixed--time research projects that are presented in Table 7.2.

Table 7.1 Abbreviations and acronyms (except research projects)

Acronym or abbreviation	Name	Reference
A1	See SRES	
A1B	See SRES	
A1FI	See SRES	
A1T	See SRES	
A2	See SRES	
AEI	Agri-environmental indicator	
AMAP	Arctic Monitoring and Assessment Programme	http://www.amap.no
AOGCM	Atmosphere-Ocean Global Circulation Models	
AR5(4)	IPCC Fifth (fourth) Assessment Report	
ASCAT	EUMETSAT Advanced SCATterometer	http://www.eumetsat.int/Home/Main/Satellites/Metop/Instruments/SP_2010053161611647?l=en
ASTI	Arctic Species Trend Index	http://www.caff.is/asti
B1	See SRES	
B2	See SRES	
BAMBU	Business-As-Might-Be-Usual scenario	
BSH	Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency, Germany)	http://www.bsh.de/en/
C	Carbon	
CAP	Common Agricultural Policy	http://ec.europa.eu/agriculture/capexplained/index_en.htm
CC IVA	Climate change impacts, vulnerability and adaptation	
CCRA	UK Climate Change Risk Assessment	http://www.defra.gov.uk/environment/climate/government/risk-assessment/
CDD	Consecutive Dry Days	
CGCM	Coupled General Circulation Model	
CGE model	Computable general equilibirium model	
CH_4	Methane	
Climate-ADAPT	European climate adaptation platform	http://climate-adapt.eea.europa.eu/
CMCC	Centro Euro-Mediterraneo sui Cambienti Climatici, (Euro-Mediterranean Centre on Climate Change)	http://www.cmcc.it/
CO_2	Carbon dioxide	
Corine Land Cover	Coordination of Information on the Environment Land Cover database	

Acronym or abbreviation	Name	Reference
CPR	Continuous Plankton Recorder	http://www.eea.europa.eu/data-and-maps/data#c5=all&c11=landuse&c17=&c0=5&b_start=0
CRED	Centre for Research on the Epidemiology of Disasters	http://www.cred.be/
CSI	EEA Core Set of Indicators	
CTD	Conductivity/Temperature/Depth	
CTI	Community Temperature Index	
CWD	Consecutive Wet Days	
Defra	UK Department for Environment, Food and Rural Affairs	http://www.defra.gov.uk/corporate/
DFO	Dartmouth Flood Observatory	http://floodobservatory.colorado.edu/
DG	Directorate General (of the European Commission)	
DIVA	Dynamic Interactive Vulnerability Assessment	http://www.diva-model.net/
DJF	Winter (months December, January, February)	
DMI	Danish Meteorological Institute	
DPSIR	Drivers, Pressures, State, Impact, Responses indicator framework	
EAD	Expected Annual Damages	
EAP	Expected Annual Population exposed	
ECDC	European Centre for Disease Prevention and Control	http://www.ecdc.europa.eu
EcF	Economy First scenario (for water)	
ECHAM5	5th generation of the ECHAM general circulation model	http://www.mpimet.mpg.de/en/science/models/echam/echam5.html
ECHAM5/MPI-OM1	A coupled global general circulation model	http://www.mpimet.mpg.de/en/science/models.html
ECMWF	European Centre for Medium-Range Weather Forecasts	http://www.ecmwf.int/
ECV	GCOS Essential Climate Variables	http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables
EDO	European Drought Observatory (JRC)	http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000
EEA	European Environment Agency	http://www.eea.europa.eu/
EEZ	Exclusive Economic Zone (sea areas)	
EFFIS	European Forest Fire Information System (JRC)	http://effis.jrc.ec.europa.eu/
EM-DAT	Emergency Events Database (CRED)	http://www.emdat.be/
ENFIN	European National Forest Inventory Network	http://enfin.info/
ENSO	El Niño-Southern Oscillation	
ERA	European Research Area	
ESA	European Space Agency	http://www.esa.int/esaCP/index.html
ESA-CCI	ESA Climate Change Initiative	http://www.esa-cci.org/
ESDM	Empirical-statistical downscaling modelling	
ESPON	European Observation Network for Territorial Development and Cohesion	http://www.espon.eu/main/Menu_Programme/
ETC-ACM	European Topic Centre on Air Pollution and Climate Change Mitigation	http://acm.eionet.europa.eu/
ETC-BD	European Topic Centre on Biological Diversity	http://bd.eionet.europa.eu/
ETC-CCA	European Topic Centre on Climate Change impacts, vulnerability and Adaptation	http://cca.eionet.europa.eu/
ETC-ICM	European Topic Centre on Inland, Coastal and Marine waters	http://icm.eionet.europa.eu/
ETC-LUSI	(Former) European Topic Centre on Land Use and Spatial Information	
EU SDS	EU Sustainable Development Strategy	
EU-27	The 27 Member States of the European Union	
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites	http://www.eumetsat.int/Home/Main/AboutEUMETSAT/index.htm?l=en
Eurostat	The Statistical Office of the European Union	http://ec.europa.eu/eurostat

Acronym or abbreviation	Name	Reference
FAO	The UN Food and Agriculture Organization	http://www.fao.org
FoE	Fortress Europe scenario (for water)	
FP(5/6/7)	EU's Framework Programme(s) for Research	http://cordis.europa.eu/fp7/home_en.html
FWI	Canadian Fire Weather Index (forest fires)	
GCM	General circulation model	
GCOS	Global Climate Observing System	http://www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS
GDP	Gross domestic product	
GFCS	Global Framework for Climate Services	http://www.wmo.int/pages/gfcs/index_en.php
GHG	Greenhouse gas; the most important anthropogenic greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)	
GISS	NASA Goddard Institute for Space Studies	http://www.giss.nasa.gov/
GMES	EU Global Monitoring for Environment and Security	http://www.gmes.info/
GMSL	Global mean sea level	
GVA	Gross value added	
HadCM3	Hadley Centre Coupled Model, version 3	http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadcm3
HadCRUT3	Gridded dataset of global historical surface temperature anomalies (Met Office, United Kingdom)	http://www.metoffice.gov.uk/hadobs/hadcrut3/
HadEX	Global land-based climate extremes dataset (Met Office, United Kingdom)	http://www.metoffice.gov.uk/hadobs/hadex/
HadISST1	Hadley Centre Sea Ice and Sea Surface Temperature data set	http://www.metoffice.gov.uk/hadobs/hadisst/
HC	Hadley Centre, United Kingdom Meteorological Office	
HDD	Heating degree day	
HIRHAM	Regional climate model (developed by the Danish Meteorological Institute DMI)	http://www.dmi.dk/eng/index/research_and_development/introduction_climate.htm
HORIZON 2020	The next EU Framework Programme for Research and Innovation	http://ec.europa.eu/research/horizon2020/index_en.cfm
HPA	UK Health Protection Agency	http://www.hpa.org.uk/
IAEA	International Atomic Energy Agency	http://www.iaea.org/
IAM	Integrated assessment model (of climate change)	
ICP Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests	http://icp-forests.net/
IMAGE	Integrated Model to Assess the Global Environment (PBL, the Netherlands)	http://themasites.pbl.nl/image
INGV	Istituto Nazionale di Geofisica e Vulcanologia, National Institute on Geophysics and Volcanology	http://www.ingv.it/en/
IPCC	Intergovernmental Panel on Climate Change	http://www.ipcc.ch/
IWT	Inland waterway transport	
JJA	Summer (months June, July, August)	
JPI	Joint Programming Initiative	
JRC	The Joint Research Centre of the European Commission	http://ec.europa.eu/dgs/jrc/index.cfm
KMNI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)	http://www.knmi.nl
LISFLOOD	GIS-based hydrological rainfall-runoff-routing model (JRC)	http://floods.jrc.ec.europa.eu/lisflood-model
MAM	Spring (months March, April, May)	
MARS/STAT	Monitoring Agriculture with Remote Sensing database	http://mars.jrc.ec.europa.eu/mars/About-us/The-MARS-Unit
MERRA	Modern-Era Retrospective Analysis for Research and Applications (NASA)	http://disc.sci.gsfc.nasa.gov/daac-bin/DataHoldings.pl
METNO	Norwegian Meteorological Institute	http://met.no/

Acronym or abbreviation	Name	Reference
MLOST	Merged Land-Ocean Surface Temperature Analysis (NOAA)	http://www.ncdc.noaa.gov/ersst/merge.php
MO	UK Meteorological Office	http://www.metoffice.gov.uk/
MOC	Atlantic Meridional Overturning Circulation	
MOON	Mediterranean Operational Oceanography Network	http://www.moon-oceanforecasting.eu/
MSFD	EU Marine Strategy Framework Directive	
MSL	Mean sea level	
N_2	Nitrogen (gas)	
NAMEA	National Accounting Matrix including Environmental Accounts	
NAO	North Atlantic Oscillation	
NAP	National Adaptation Plan	
NatCatSERVICE	Natural catastrophe loss database (Munich RE)	http://www.munichre.com/en/reinsurance/business/non-life/georisks/natcatservice/default.aspx
NCDC	NOAA National Climatic Data Center	http://www.ncdc.noaa.gov/oa/ncdc.html
NOAA	US National Oceanic and Atmospheric Administration	http://www.noaa.gov/
NFI	National Forest inventory	
NMVOC	Non-methane volatile organic compounds	
NODUS	GIS based software model which provides a tool for detailed analysis of freight transportation over extensive multimodal networks	
NO_x	Nitrogen oxides	
NPP	Net primary production	
NUSAP	The Management of Uncertainty and Quality in Quantitative Information	http://www.nusap.net/
NUTS(2,3)	Nomenclature of Territorial Units for Statistics; NUTS2 = states/provinces; NUTS3 = regional areas, counties, districts	http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction
NWP	Nairobi Work Programme (of the UNFCCC)	http://unfccc.int/adaptation/nairobi_work_programme/items/3633.php
O_2	Oxygen (gas)	
O_3	Ozone (gas)	
OECD	The Organisation for Economic Co-operation and Development	http://www.oecd.org
OHC	Ocean heat content	
OIE	Office International des Epizooties (World Organisation for Animal Health)	http://www.oie.int/
OSI SAF	EUMETSAT Satellite Application Facility on Ocean and Sea Ice	http://www.osi-saf.org/
PDO	Pacific decadal oscillation	
PERMOS	Swiss Permafrost Monitoring Network	http://www.permos.ch/
pH	Decimal logarithm of the reciprocal of the hydrogen ion activity (measure of acidity)	
PIOMAS	Pan Arctic Ice-Ocean Modeling and Assimilation System	http://psc.apl.washington.edu/wordpress/research/projects/projections-of-an-ice-diminished-arctic-ocean/data-piomas/
PM_{10}	Particles in the atmosphere with a diameter of less than or equal to a nominal 10 micrometres	
$PM_{2.5}$	Particles in the atmosphere with a diameter of less than or equal to a nominal 2.5 micrometres	
POLES	Prospective Outlook on Long-term Energy Systems	http://www.enerdata.net/enerdatauk/solutions/energy-models/poles-model.php
PoR	Policy Rules scenario (for water)	
ppm	Parts per million	
PROVIA	Programme of Research on Climate Change Vulnerability, Impacts and Adaptation	http://www.provia-climatechange.org/HOME/tabid/55173/Default.aspx
RACMO(2)	Regional Atmospheric Climate Model (KNMI)	http://www.knmi.nl/bibliotheek/knmipubTR/TR302.pdf
RCM	Regional climate model	

Acronym or abbreviation	Name	Reference
RCP	Representative concentration pathway	
RU GSL	Rutgers University Global Snow Lab	http://climate.rutgers.edu/snowcover/index.php
S550e	Greenhouse gas emission scenario targeting stabilisation of concentrations at 550 ppm CO_2 equivalent	http://ec.europa.eu/clima/policies/international/negotiations/future/docs/pm_summary2025_en.pdf
Sat-Alt	Satellite data (on sea level)	
SDI	Sustainable development indicators	
SEBI 2010	Streamlining European 2010 Biodiversity Indicators	http://ec.europa.eu/environment/nature/knowledge/eu2010_indicators/index_en.htm
SMOS	Soil Moisture and Ocean Salinity mission (ESA)	http://www.esa.int/SPECIALS/smos/
SOC	Soil organic carbon	
SOER	EEA State of the Environment Report	
SOM	Soil organic matter	
SON	Autumn (months September, October, November)	
SRES	IPCC Special Report on Emissions Scenarios	http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0
SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation	http://www.ipcc-wg2.gov/SREX/
SSR	Seasonal Severity Rating (index of forest fire risk)	
SST	Sea surface temperature	
SuE	Sustainability Eventually scenario (for water)	
SWE	Snow water equivalent	
SYKE	Suomen ympäristökeskus (Finnish Environment Institute)	http://www.environment.fi/syke
TBE	Tick-borne encephalitis	
TCI	Tourism climatic index	
TERM	Transport and Environment Reporting Mechanism	http://www.eea.europa.eu/themes/transport/term
UHI	Urban heat island effect	
UNCCD	United Nations Convention to Combat Desertification	http://www.unccd.int/en/Pages/default.aspx
UNECE	United Nations Economic Commission for Europe	http://www.unece.org/
UNFCCC	United Nations Framework Convention on Climate Change	http://unfccc.int/
USGS	US Geological Survey	http://www.usgs.gov/
VBORNET	European Network for Arthropod Vector Surveillance for Human Public Health	http://www.vbornet.eu/
VOLY	Value of a Life Year Lost	
VSL	Value of a Statistical Life	
WCC-3	World Climate Conference-3	http://www.wmo.int/wcc3/page_en.php
WEI	Water Exploitation Index	
WFD	Water Framework Directive	
WHO	World Health Organization	http://www.who.int
WISE	Water Information System for Europe	http://water.europa.eu/
WMO	World Meteorological Organization	http://www.wmo.int/
WNV	West Nile Virus (disease-causing agent)	
WSD	Water scarcity and drought	
XBT	Expandable bathythermograph (device to measure water temperature at different depths)	

7.2 Acronyms of research projects

Table 7.2 presents those research projects that are explicitly mentioned in the text of this report. Many more projects have contributed to the publications cited in this report and to the data presented therein, but compilation of a complete overview was not feasible.

Table 7.2 Acronyms of research projects

Project acronym	Project name	Website	Funding
ACCESS	Arctic Climate Change, Economy and Society	http://www.access-eu.org	FP7
AdaptAlp	Adaptation to Climate Change in the Alpine Space	http://www.adaptalp.org/	ERDF
ARISCC	Adaptation of Railway Infrastructure to Climate Change	http://www.ariscc.org/	European Rail companies
BaltAdapt	Baltic Sea Region Climate Change Adaptation Strategy	http://www.baltadapt.eu/	ERDF
cCASHh	Climate change and adaptation strategies for human health in Europe	http://ec.europa.eu/research/environment/pdf/env_health_projects/climate_change/cl-ccashh.pdf	FP5
CEHAPIS	Climate, Environment and Health Action Plan and Information System	http://www.euro.who.int/climatechange (not yet published)	WHO, DG SANCO
CIRCE	Climate Change and Impact Research: the Mediterranean Environment	http://www.circeproject.eu/	FP6
CIRCLE-2	Climate Impact Research & Response Coordination for a Larger Europe	http://www.circle-era.eu/	
ClimAlpTour	Climate Change and its impact on tourism in the Alpine Space	http://www.climalptour.eu/	ERDF
ClimateCost	The Full cost of climate change	http://www.climatecost.cc/	FP7
Climate-TRAP	Training, Adaptation, Preparedness of the Health Care System to Climate Change	http://www.climatetrap.eu/	EAHC
ClimSAVE	Climate Change integrated assessment methodology for cross-sectoral adaptation and vulnerability in Europe	http://www.climsave.eu/climsave/index.html	FP7
ClimWatAdapt	Climate adaptation — modelling water scenarios and sectoral impacts	http://www.climwatadapt.eu/	DG ENV
CLISP	Climate Change Adaptation by Spatial Planning in the Alpine Space	http://www.clisp.eu/content/?q=node/2	ERDF
Conscience	Concepts and Science for Coastal Erosion management	http://www.conscience-eu.net/	FP6
COST725	Establishing a European Phenological Data Platform for Climatological Applications	http://topshare.wur.nl/cost725/	FP7 COST
CryoClim	Monitoring Climate Change in the Cryosphere	http://www.cryoclim.net	NSC and ESA
Deduce	Sustainable development of European coastal zones	http://www.deduce.eu/	Interreg IIIC South
ECA&D	European Climate Assessment & Dataset project	http://eca.knmi.nl/	KNMI, EC, EUMETNET
ECCONET	Effects of climate change on the inland waterway networks	http://www.ecconet.eu	FP7
EDEN	Emerging Diseases in a changing European eNvironment	http://www.eden-fp6project.net/	FP6
EDENext	Biology and control of vector-borne infections in Europe	http://www.edenext.eu/	FP7
emBRACE	Building Resilience Amongst Communities in Europe	http://embrace-eu.org/	FP7
ENSEMBLES	ENSEMBLES	http://www.ensembles-eu.org/	FP6
ERA-CLIM	European Reanalysis of Global Climate Observations (GMES)	http://www.era-clim.eu/	EU
ESPON Climate	Climate Change and Territorial Effects on Regions and Local Economies	http://www.espon.eu/main/Menu_Projects/Menu_AppliedResearch/climate.html	ERDF
ESPON-DEMIFER	Demographic and Migratory Flows Affecting European Regions and Cities	http://www.espon.eu/main/Menu_Projects/Menu_AppliedResearch/demifer.html	ERDF
EURO4M	European Reanalysis and Observations for Monitoring	http://www.euro4m.eu/	GMES, FP7

Project acronym	Project name	Website	Funding
Euro-Argo	European contribution to Argo program	http://www.euro-argo.eu/	FP7 ESFRI
EuroMOMO	The European Mortality Monitoring Project	http://www.euromomo.eu/	DG SANCO
Eurosion	European initiative for sustainable coastal erosion management	http://www.eurosion.org/	DG ENV
EWENT	Extreme weather impacts on European networks of transport	http://ewent.vtt.fi/about.htm	FP7
JRA-25	Japanese 25-year Reanalysis Project	http://www.jreap.org/indexe.html	JMA
MEDIATION	Methodology for Effective Decision-making on Impacts and AdaptaTion	http://mediation-project.eu/	FP7
MyOcean	Ocean Monitoring and Forecasting	http://www.myocean.eu	FP7, GMES
NCEP CFSR	National Centers for Environmental Prediction Climate Forecast System Reanalysis	http://cfs.ncep.noaa.gov/cfsr/	NOAA
PACE	Permafrost and Climate in Europe	http://www.geo.uzh.ch/~hoelzle/pace.html	EU
PESETA	Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis	http://peseta.jrc.ec.europa.eu/	JRC
PLUREL	Peri-urban Land Use Relationships	http://www.plurel.net/	FP6
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects	http://prudence.dmi.dk	FP5
RESPONSES	European responses to climate change: deep emissions reductions and mainstreaming of mitigation and adaptation	http://www.responsesproject.eu/	FP7
SCENES	Water Scenarios for Europe and for Neighbouring States	http://www.environment.fi/syke/scenes	FP6
WEATHER	Weather Extremes: Impacts on Transport Systems and Hazards for European Regions	http://www.weather-project.eu	FP7

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Chapter 1: Introduction

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Chapter 3: Climate impacts on environmental systems

Section 3.1: Oceans and marine environment

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Section 3.4: Terrestrial ecosystems and biodiversity.

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