5.4 Marine biodiversity and ecosystems

5.4.1 Introduction

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

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

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

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

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

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

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

Box 5.5 Ocean acidification

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

Implications for European seas

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

Table 5.1 Average ocean surface pH values

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

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

5.4.2 *Sea-level rise*

Key messages

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

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

Tide gauge with observation record of at least
- 100 years (reference station)
- 50 years
- 50 years (reference station)

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

Source: Novotny and Groh, 2007.

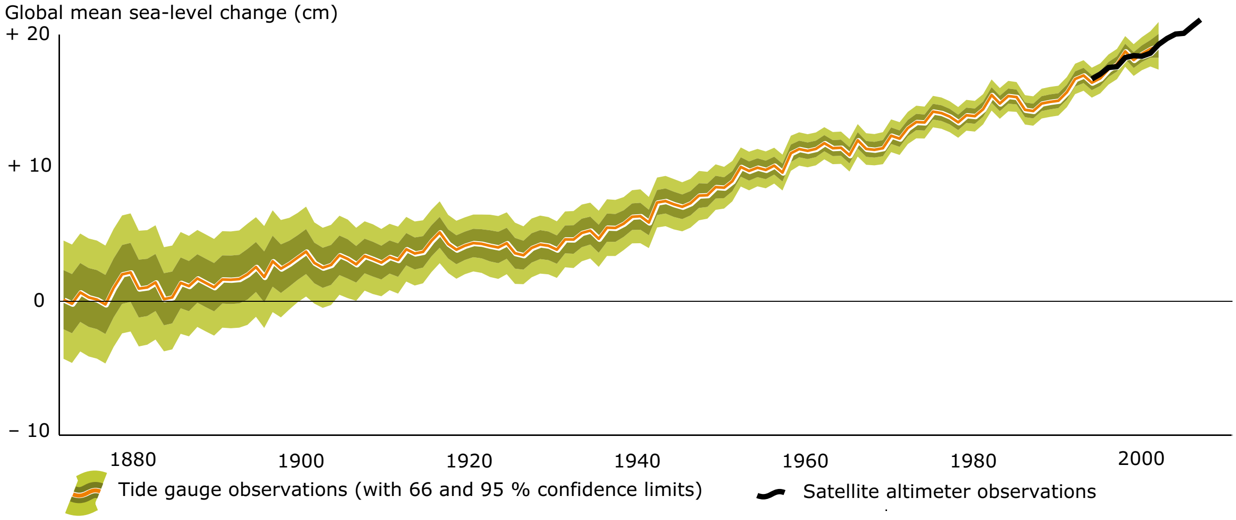
Relevance

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

Past trends

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

Figure 5.19 Changes in global sea level 1870–2006



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

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

Satellite observations indicate a large spatial variability of SLR trends in the European seas (Map 5.19; Table 5.2). For instance in the Mediterranean and the Levantine Sea positive trends are observed while negative trends are observed in the northern Ionian Sea. These local variations could be explained by variability of the North Atlantic Oscillation (NAO), inter-annual wind variability, changes in global ocean circulation patterns, or specific local structures of the circulation (e.g. gyres) (Demirov and Pinardi, 2002).

Projections

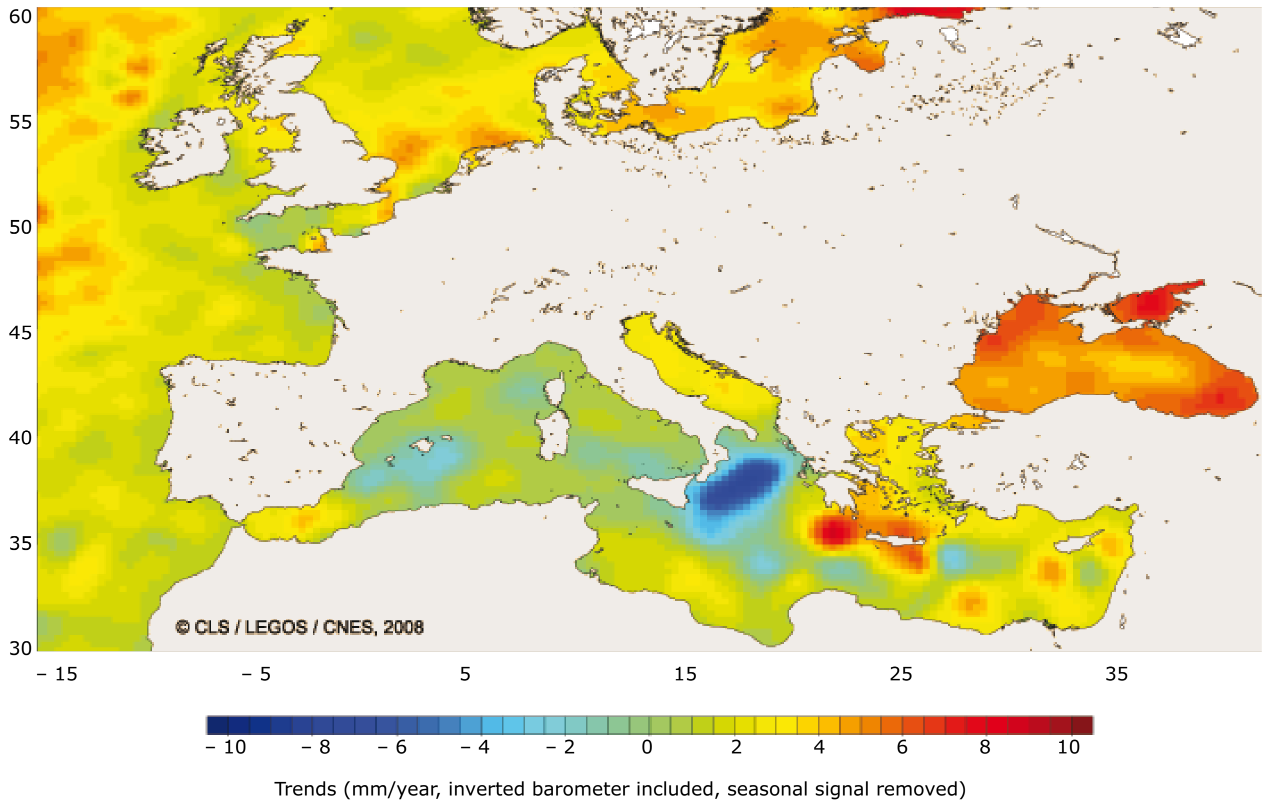
Sea-level rise by the end of this century (2090–2099) is projected, under the SRES-scenarios, to be 0.18–0.59 m above the present (1980–1999) level,

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

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

Source: IPCC, 2007a.

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



Note: Map based on satellite altimeter data.

Source: Guinehut and Larnicol, 2008.

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

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

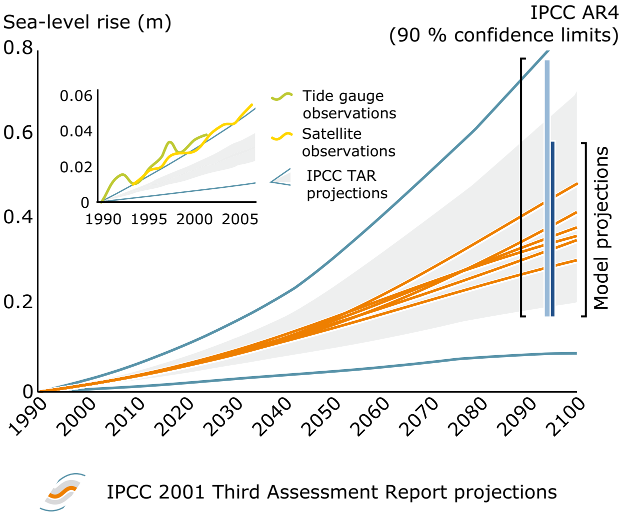
SLR projections for the Baltic and Arctic coasts based on SRES scenarios indicate an increased risk of flooding and coastal erosion after 2050 but always lower than the risk in the North Sea and the Mediterranean (Johansson *et al.*, 2004; Meier *et al.*, 2004, 2006b; Nicholls, 2004). The A1F1-scenario,

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

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

Source: Guinehut and Larnicol, 2008.

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



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

Source: UNEP, 2007; IPCC, 2001.

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

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

Photo: © Pavel Šťastný

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

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

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

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

5.4.3 *Sea surface temperature*

Key messages

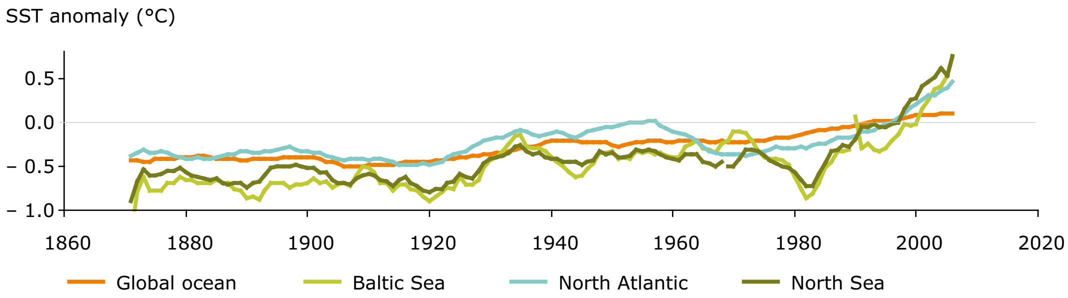
- Sea surface temperature (SST) in European seas is increasing more rapidly than in the global oceans. The rate of increase is higher in the northern European seas and lower in the Mediterranean Sea.
- The rate of increase in sea surface temperature in all European seas during the past 25 years has been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

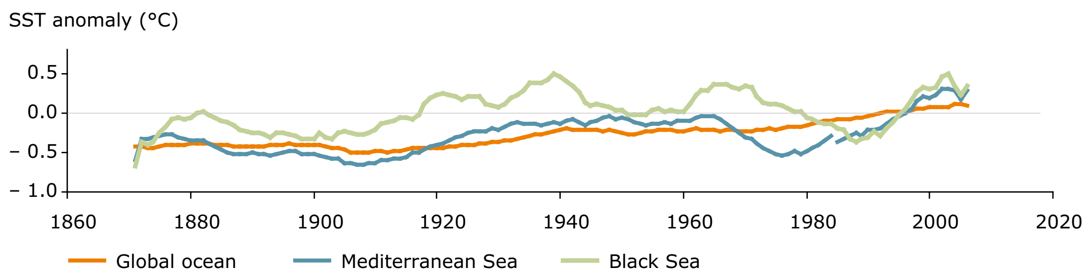
Table 5.4 Summary of sea surface temperature changes in the global ocean and the four European regional seas

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

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

Figure 5.21 Sea surface temperature anomaly for period 1870–2006

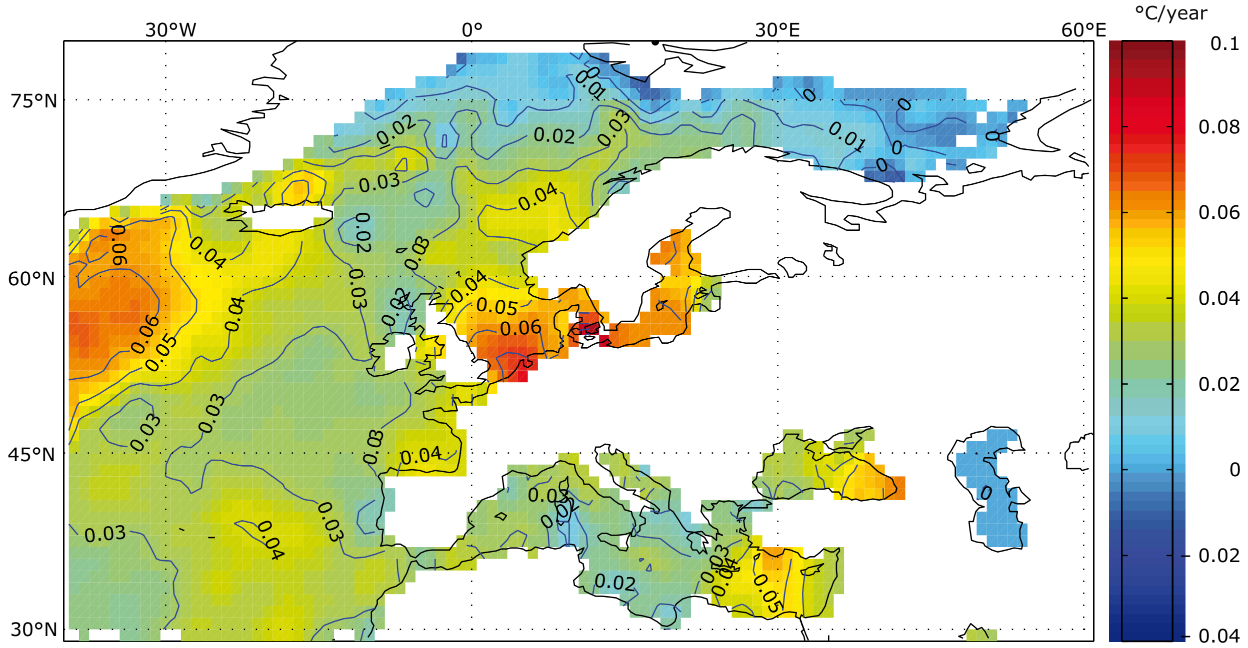




Note: Data (°C) show the difference between annual average temperatures and the period 1982–2006 mean in different European seas. Data sources are: SST datasets from the Hadley Centre (HADISST1 (global)), MOON (Mediterranean Sea), and Bundesamt für Seeschifffahrt und Hydrographie (Baltic and North Seas).

Source: Coppini *et al.*, 2007.

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



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

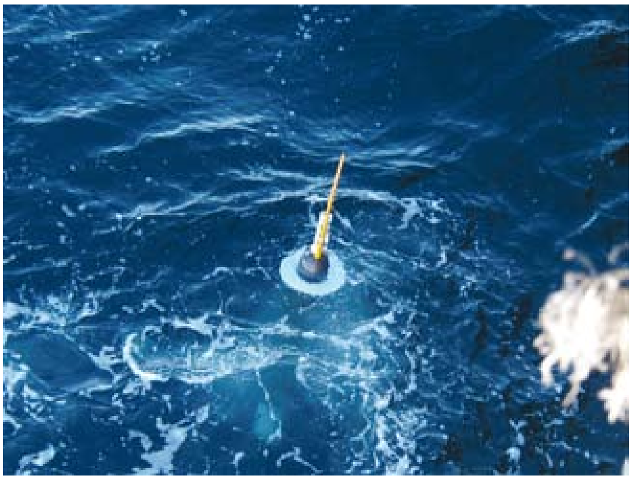
Source: Coppini and Pinardi, 2007.

Relevance

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

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

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



An Argo PROVOR float measuring sea surface temperature

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

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

Past trends

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

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

Projections

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

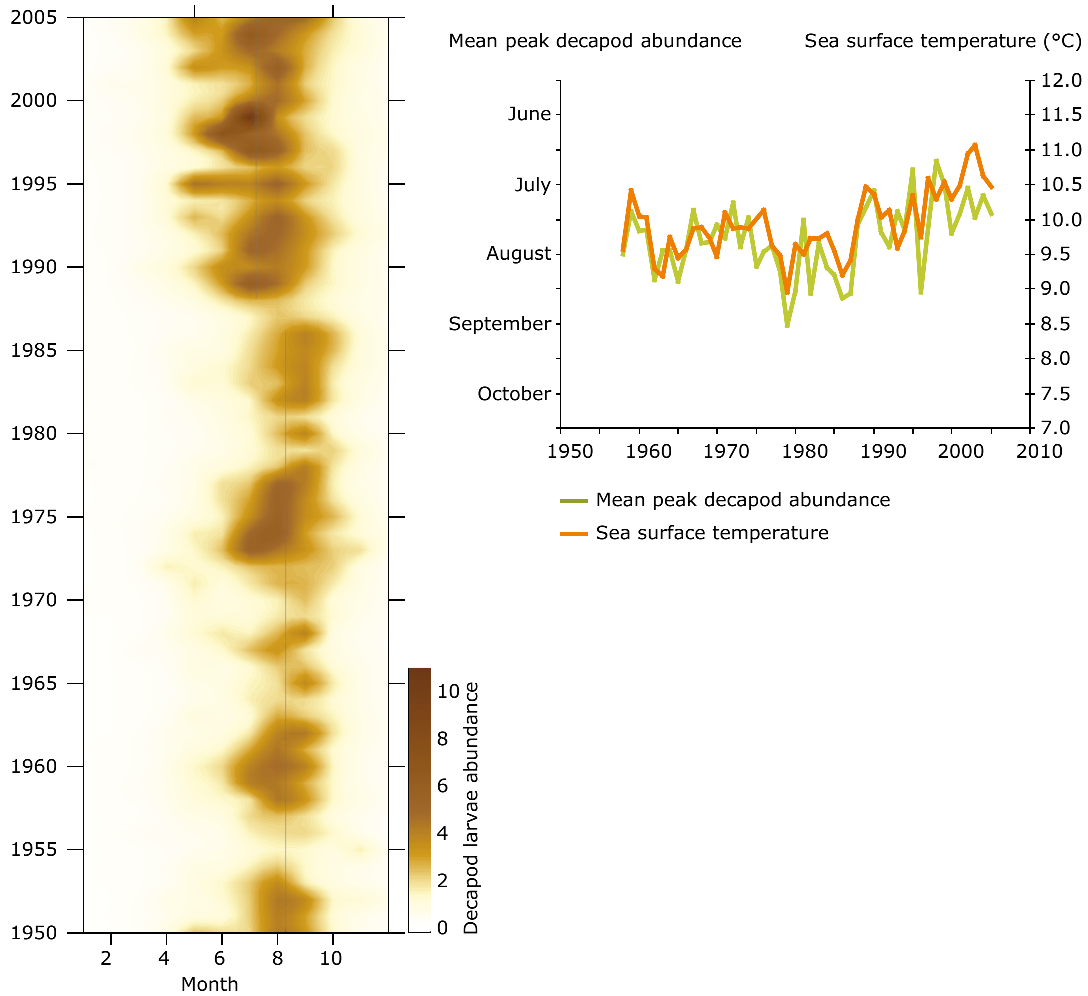
The scenario projects ocean warming to be relatively large in the Arctic and along the equator in the eastern Pacific, with less warming over the North Atlantic and in the Southern Ocean (e.g. Xu *et al.*, 2005). Enhanced oceanic warming along the equator is also evident, and can be associated with oceanic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

5.4.4 *Marine phenology*

Key messages

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

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



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

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

Relevance

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

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

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

The 'Continuous Plankton Recorder'

Photo: © SAHFOS, 2003

Past trends

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

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

Projections

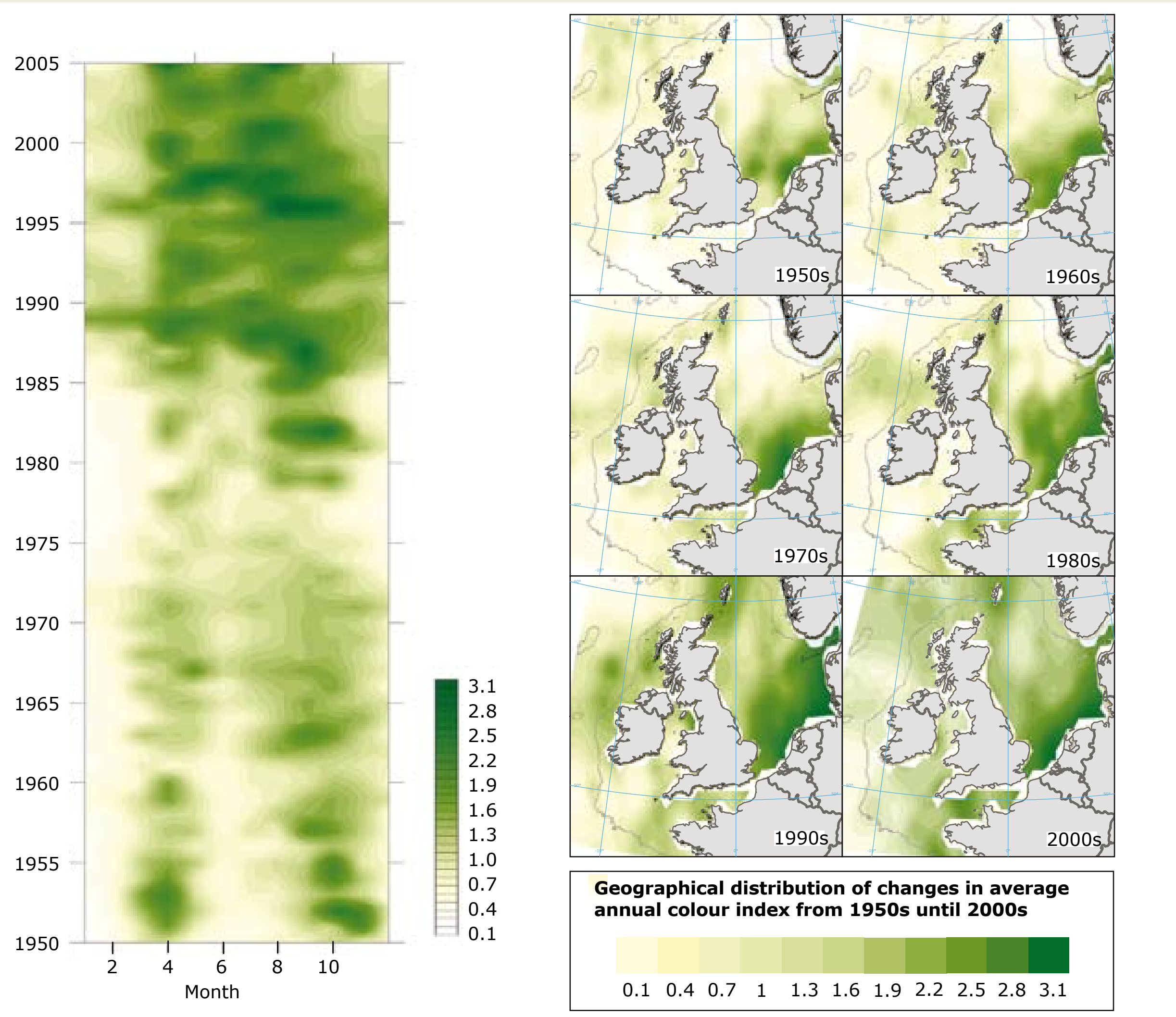
Projections of how individual species react to future climate change have not yet been made, but the empirical evidence suggests that it is very likely that phenological changes will continue to occur as climate warming continues to accelerate. It is currently much less certain to what degree genetic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

Box 5.7 Phytoplankton biomass and growing season

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

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

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



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

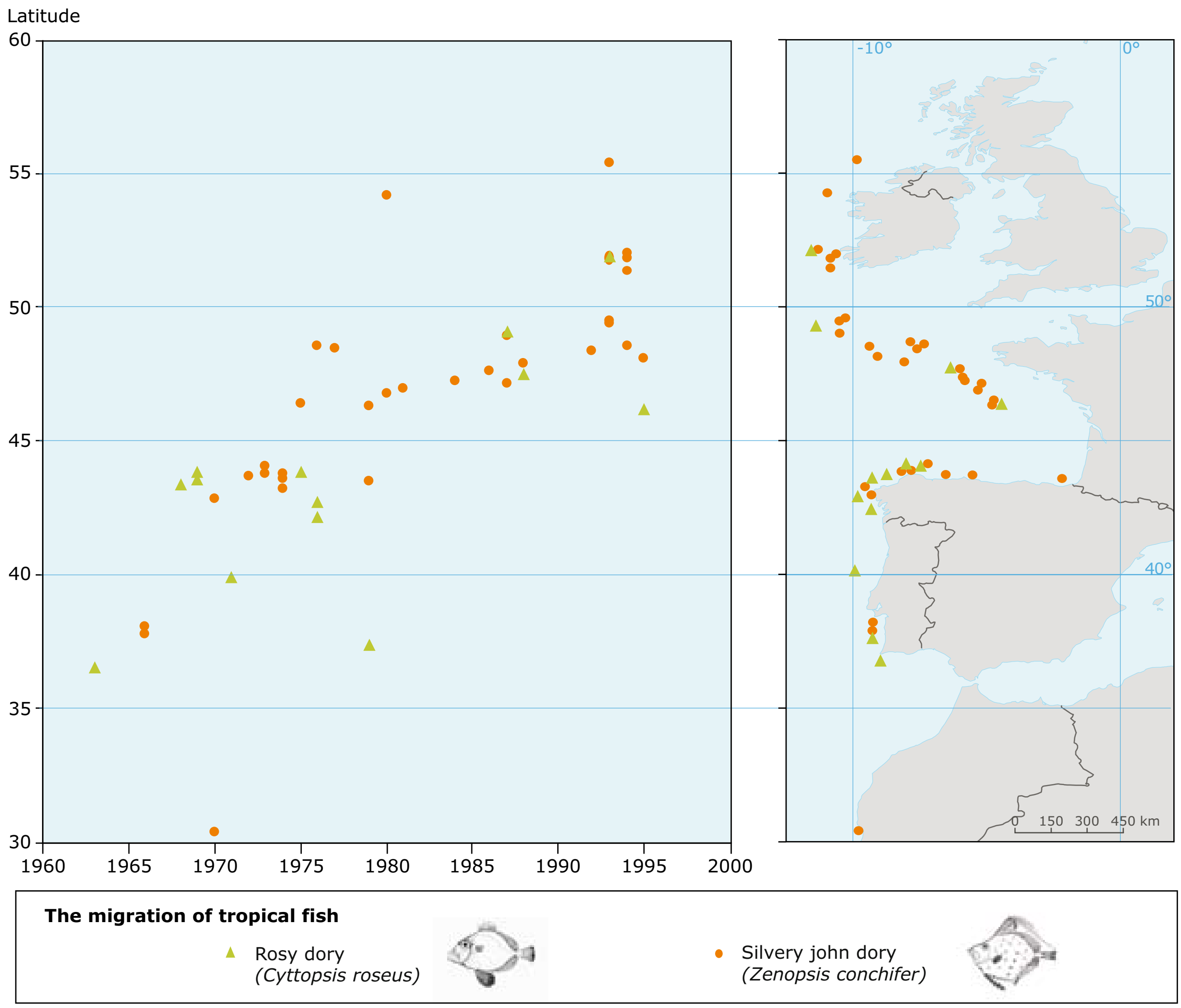
Source: Updated from Reid *et al.*, 1998 and Edwards *et al.*, 2001.

5.4.5 Northward movement of marine species

Key messages

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

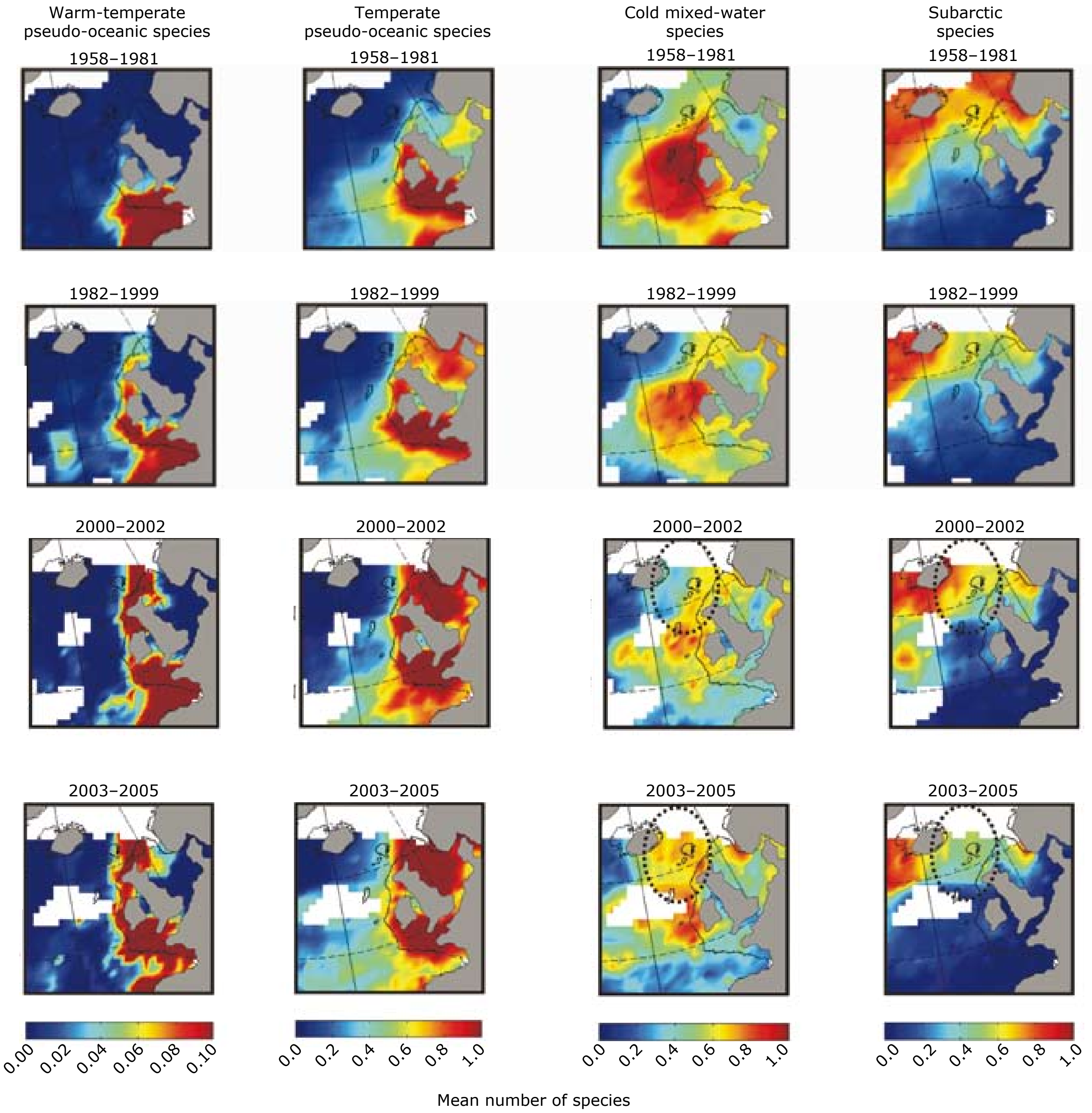
Figure 5.24 Recordings of two tropical fish 1963–1996



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

Source: Quero *et al.*, 1998.

Map 5.21 Northward movement of zooplankton between 1958–2005



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

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

Relevance

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

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

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

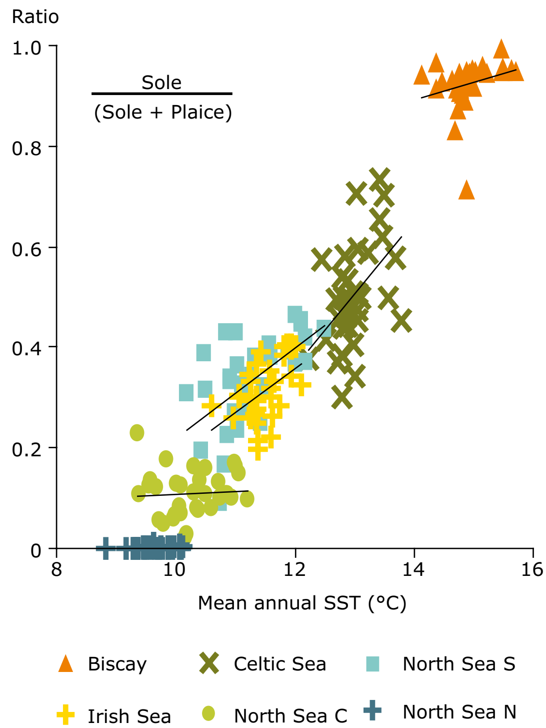
Past trends

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

Common sole (*Solea solea*)

Photo: © Biopix.dk; JC Schou

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



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

Source: Brander *et al.*, 2003.

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

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

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

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

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

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

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

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

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

Projections

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

5.5 Water quantity, river floods and droughts

5.5.1 Introduction

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

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

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

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

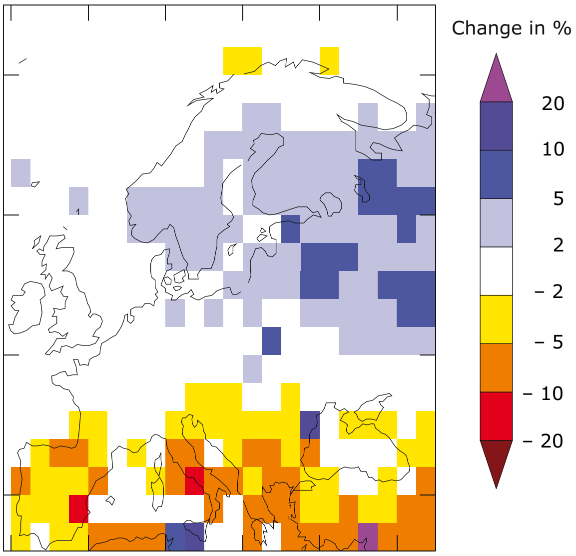
The projected climate-induced changes will aggravate the impact of other stresses (such as land-use, demographic and socio-economic changes) on water availability, freshwater ecosystems, energy production, navigation, irrigation, tourism, as well as on several other sectors. In the face of these uncertain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

5.5.2 *River flow*

Key messages

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

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



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

Source: Milly *et al.*, 2005.

Relevance

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

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

Past trends

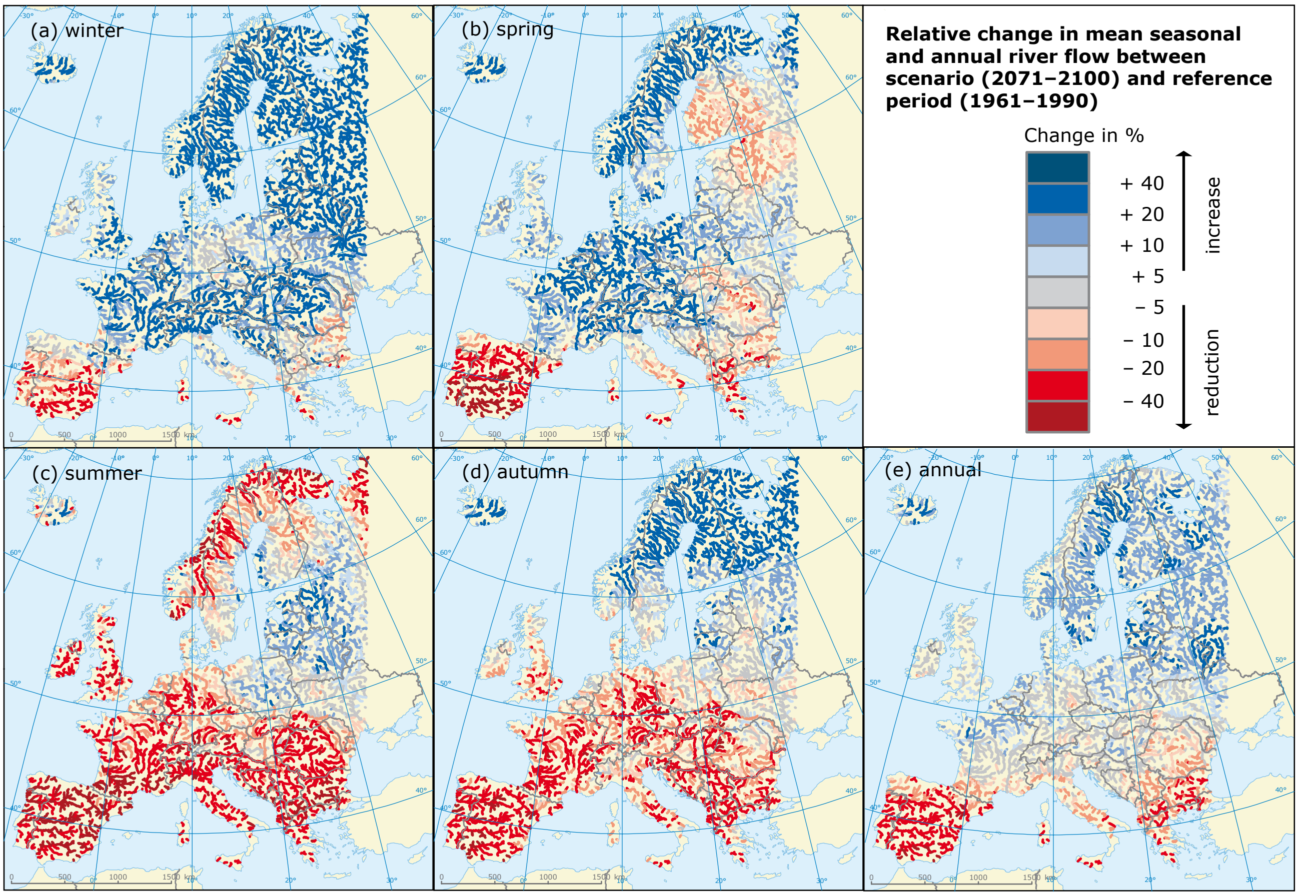
In accordance with the observed changes in precipitation and temperature (see Sections 5.2.2 and 5.2.3), there is some evidence for climate-induced changes in annual river flow, as well as in the seasonality of flow, in Europe during the 20th century. However, anthropogenic interventions in the catchment,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

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

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

Photo: © European Environment Agency

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



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

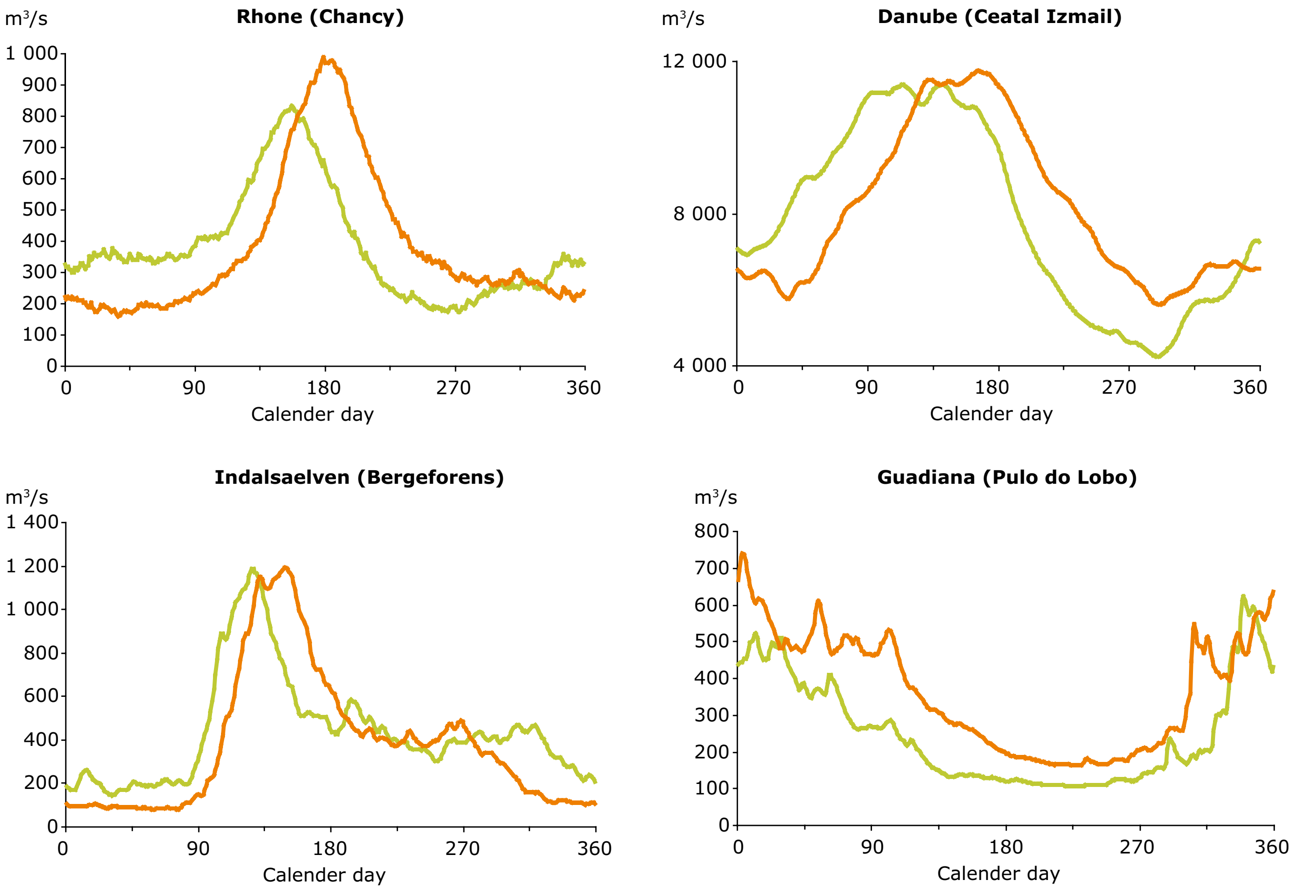
Source: Dankers and Feyen, 2008a.

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

Projections

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

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



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

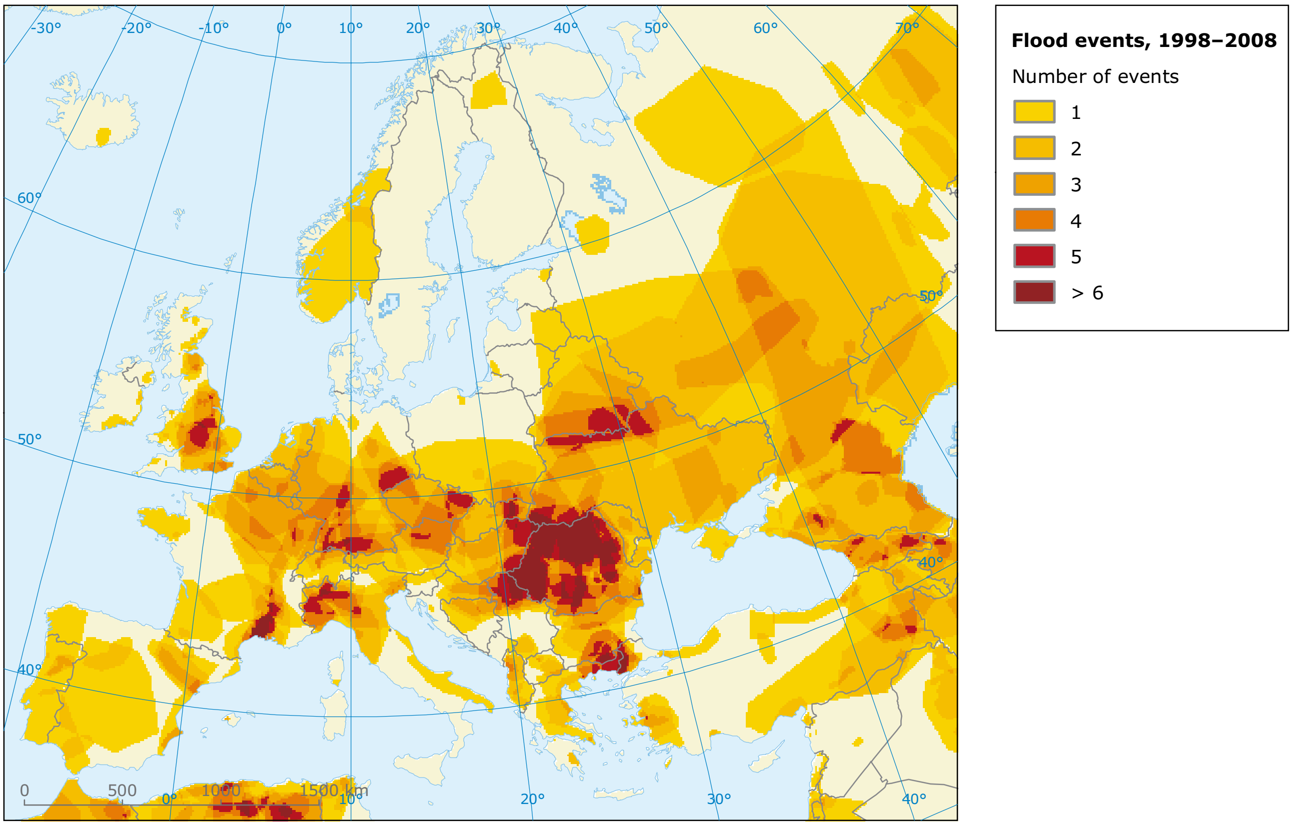
Source: Dankers and Feyen, 2008a.

5.5.3 River floods

Key messages

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

Map 5.24 Occurrence of flood events in Europe 1998–2008



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

Relevance

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

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

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

Past trends

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

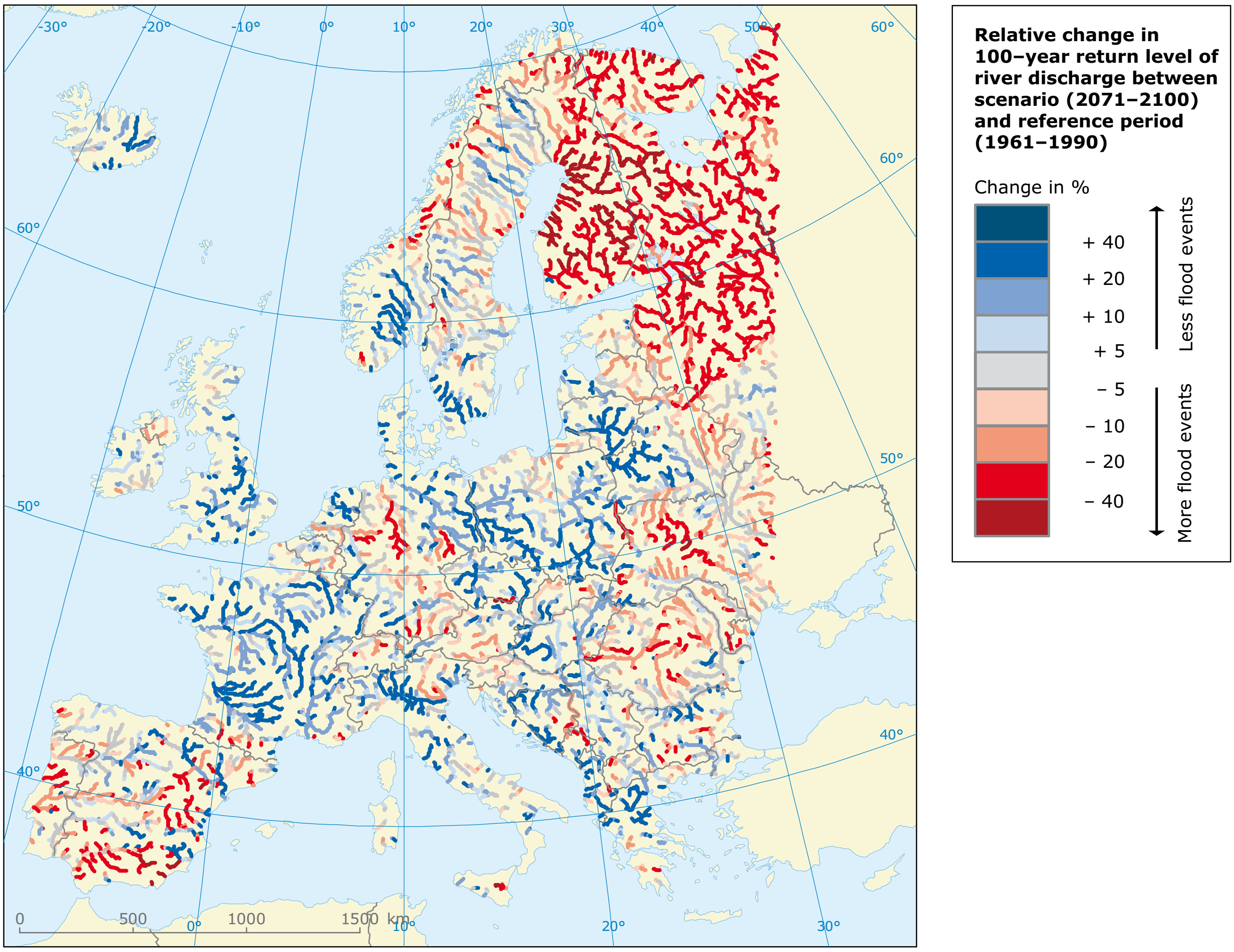
Some changes, however, have been reported that may be linked to climate change. For example, in Europe twice as many river flow maxima occurred between 1981 and 2000 than between 1961 and 1980 (Kundzewicz *et al.*, 2005), whereas globally there has probably been an increase in the frequency of extreme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

Photo: © Pavel Šťastný

Projections

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

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



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

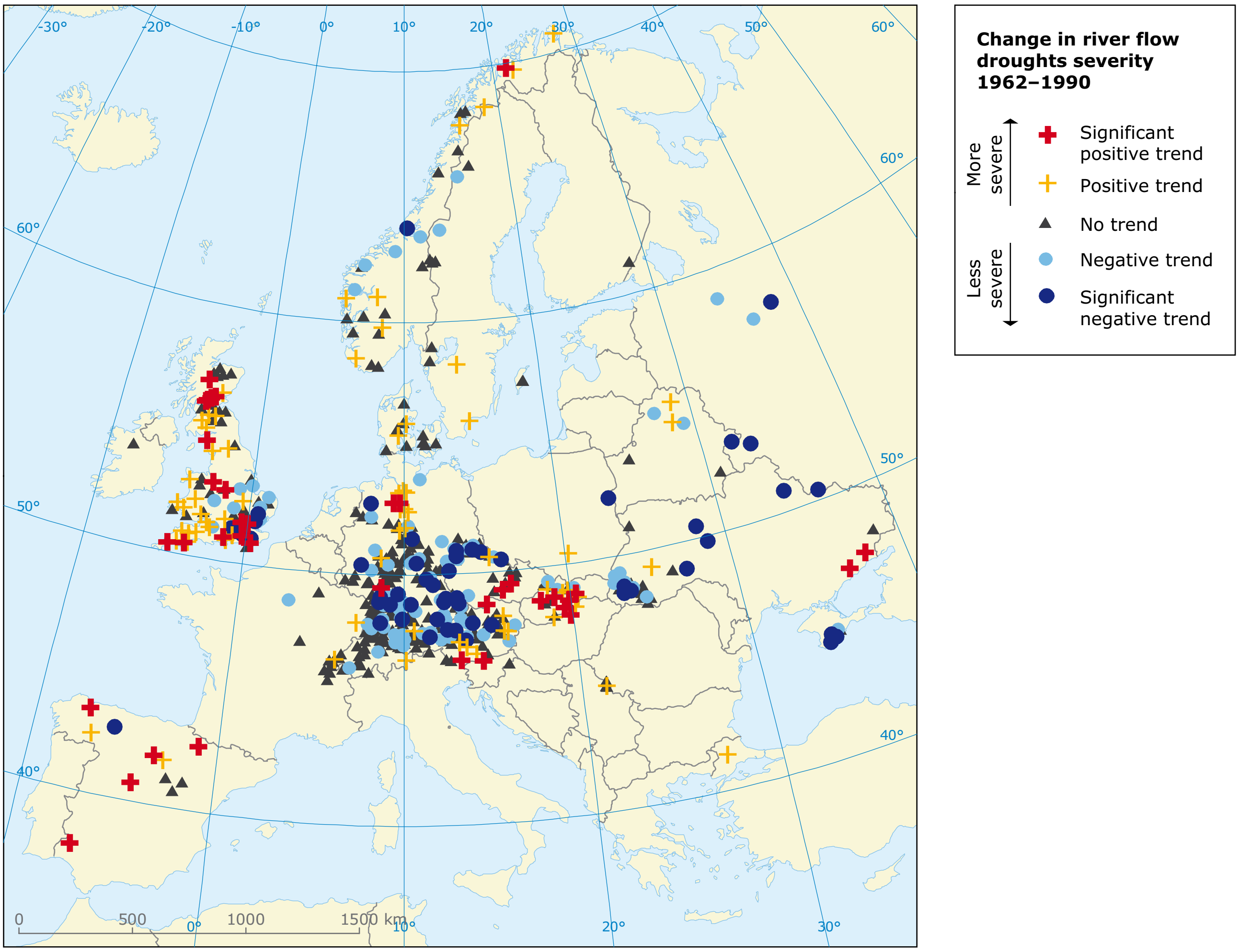
Source: Dankers and Feyen, 2008b.

5.5.4 *River flow drought*

Key messages

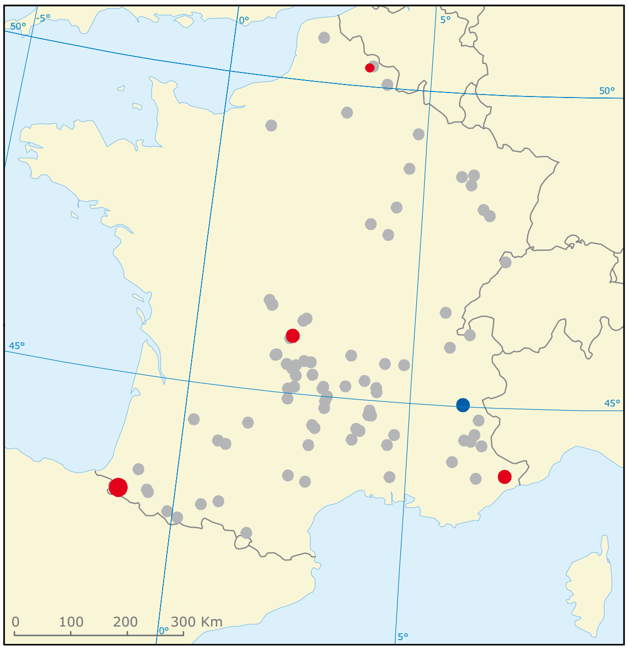
- Europe has been affected by several major droughts in recent decades, such as the catastrophic drought associated with the summer 2003 heatwave in central parts of the continent and the 2005 drought in the Iberian Peninsula.
- Despite the absence of an overall trend in Europe as a whole, climate change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

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



Source: Hisdal *et al.*, 2001.

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



Change in the severity of river flow drought in France for the period 1960–2000

Trend — More severe ← | Not significant | → Less severe

Source: Lang *et al.*, 2006.

Relevance

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

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

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

Past trends

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

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

Box 5.9 Groundwater

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

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

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

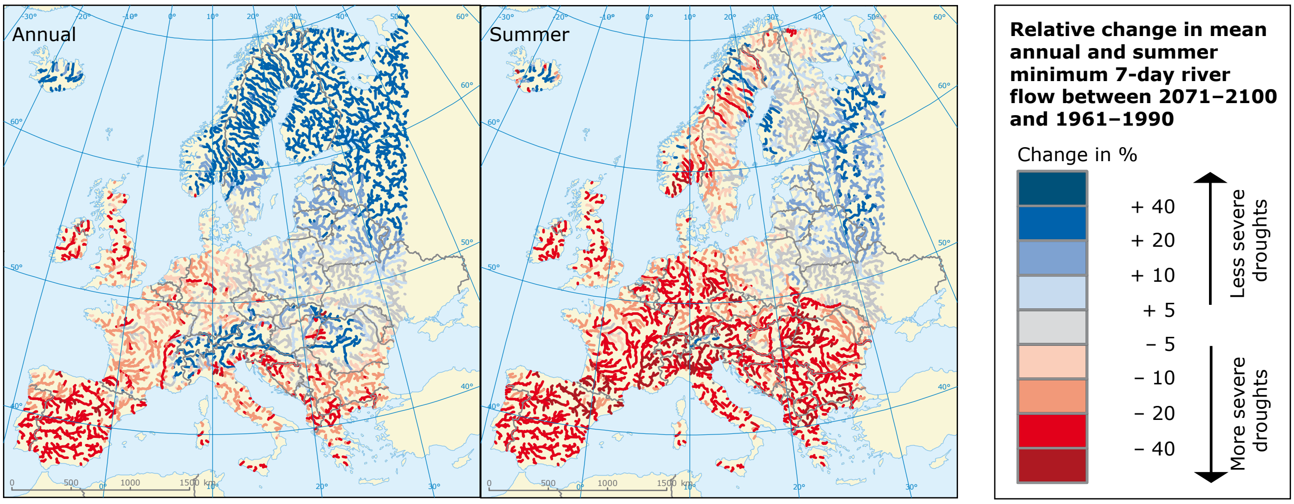
over the period for which there are records (Svensson *et al.*, 2005).

Projections

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

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

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



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

Source: Feyen and Dankers, 2008.

5.6 Freshwater quality and biodiversity

5.6.1 Introduction

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

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

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

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

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

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

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

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

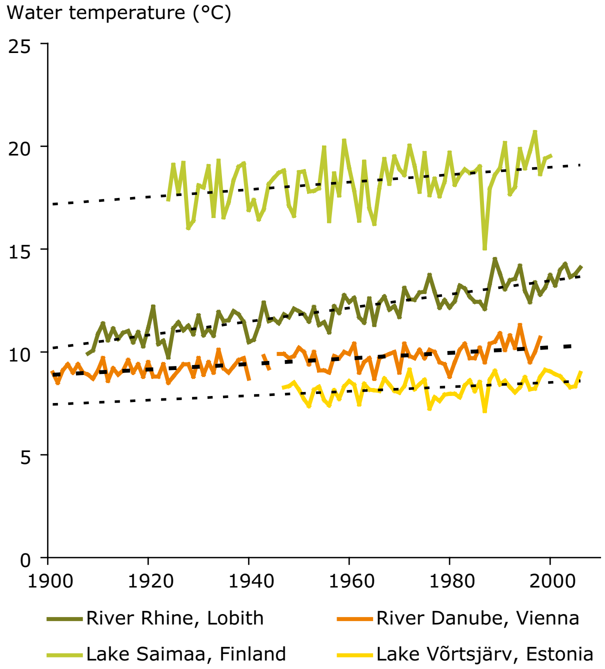
Currently many national and European research activities are producing relevant and valuable results on climate change impacts on Europe's freshwater; see for example, Euro-limpacs (http://www.eurolimpacs.ucl.ac.uk/index.php) and CLIME: Climate and Lake Impacts in Europe (http://clime.tkk.fi/). IPCC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

5.6.2 *Water temperature*

Key messages

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

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



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

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

Relevance

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

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

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

Past trends

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

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

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

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

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

Photo: © European Environment Agency

Projections

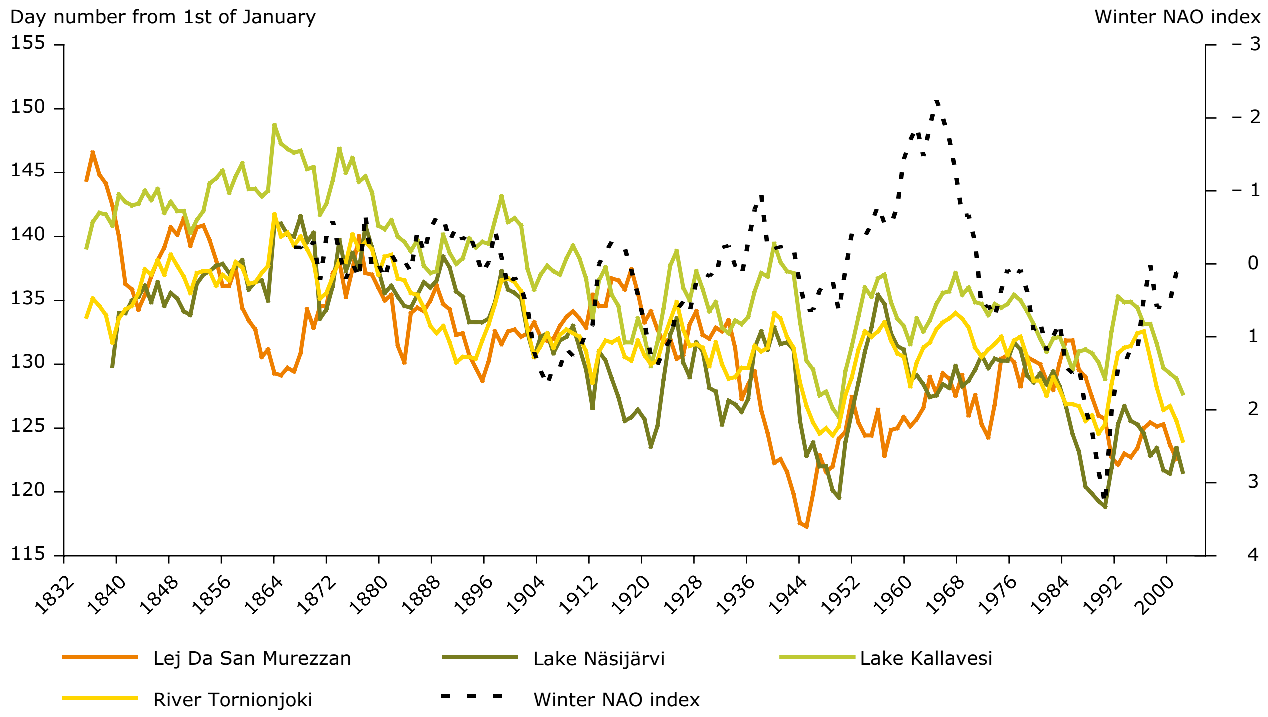
As water temperature is closely linked to change in air temperature, the predicted increase in air temperature due to climate change will be reflected in increased surface water temperature. This is in addition to temperature changes caused by other factors, such as changes in cooling water releases.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

5.6.3 *Lake and river ice cover*

Key messages

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

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



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

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

Relevance

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

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

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

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

Past trends

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

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

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

Photo: © European Environment Agency

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

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

Projections

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

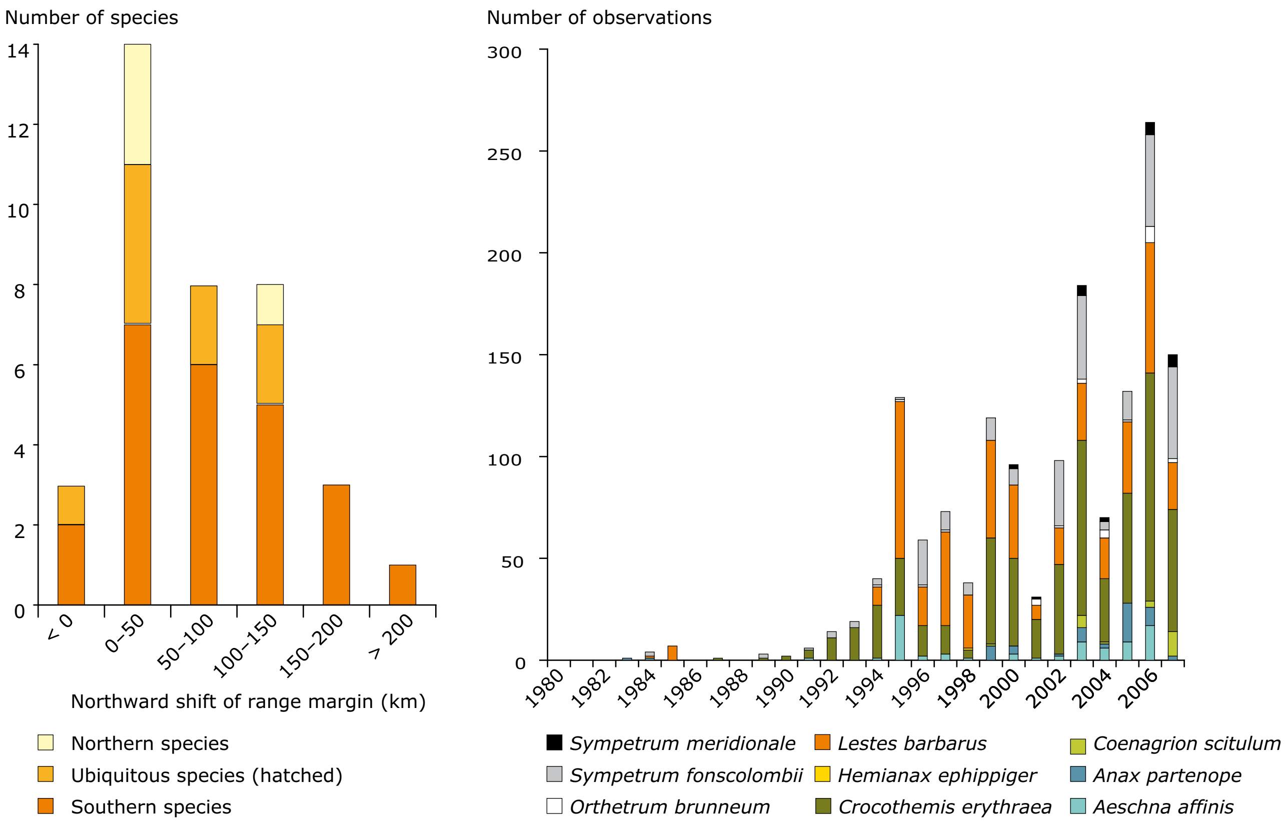
Regional climate model projections for northern Germany, based on the IPCC high emissions SRES A2 and intermediate emissions B2 climate scenarios, imply that for the Müggelsee, the percentage of ice-free winters will increase from about 2 % now to more than 60 % by the end of the century (Livingstone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

5.6.4 *Freshwater biodiversity and water quality*

Key messages

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

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



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

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

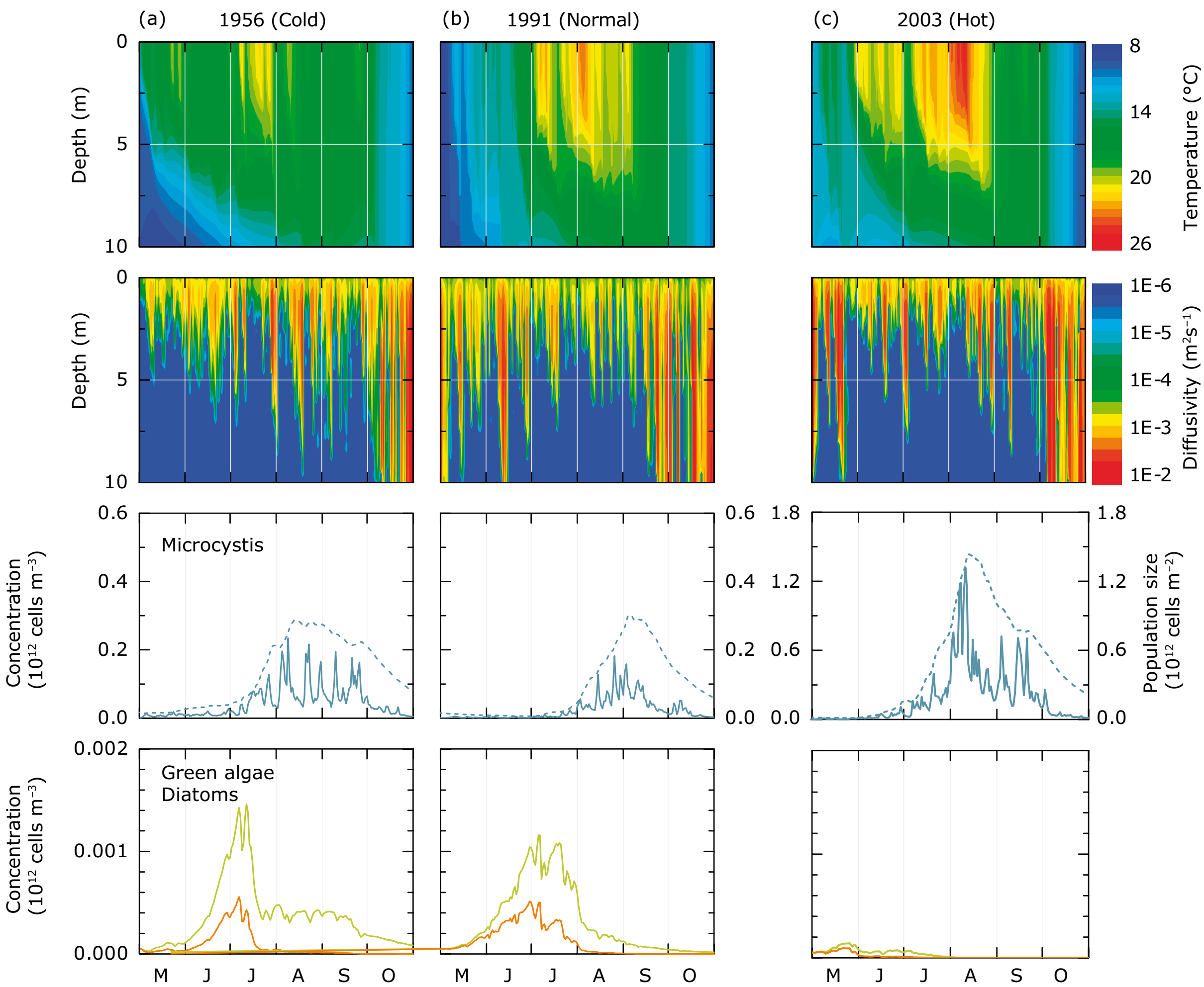
Relevance

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

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

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

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



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

Source: Jöhnk *et al.*, 2008.

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

Past trends

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

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

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

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

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

Projections

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

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

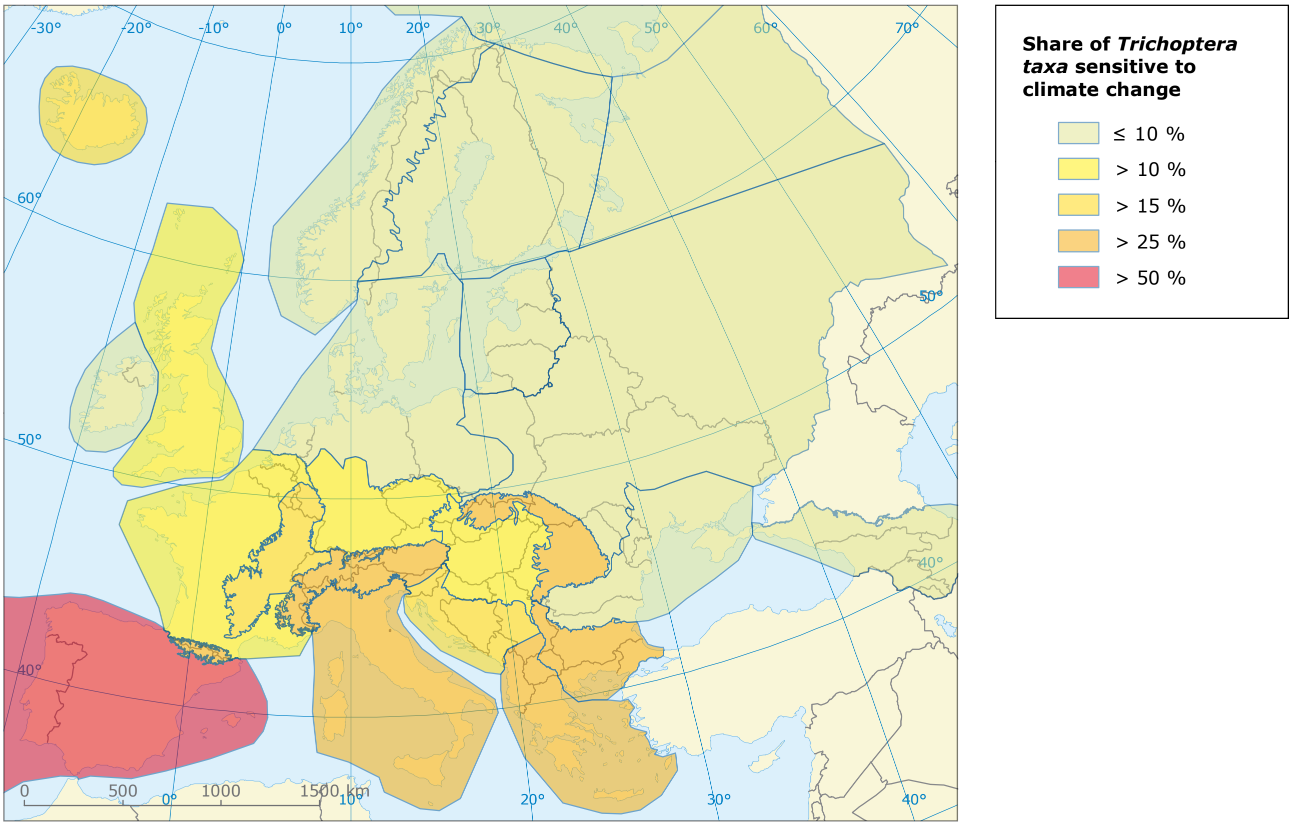
- A comparison of a large set of Danish shallow lakes with a corresponding one located in the colder climate of Canada (Jackson *et al.*, 2007) suggests that warming will decrease winter fish-kills and enhance the overwintering success of planktivorous fish which, in turn, suppress *Daphnia*/zooplankton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

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

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

Photo: © Jeroen van Wichelen, Ghent University

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



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

Source: Hering *et al.*, 2006.