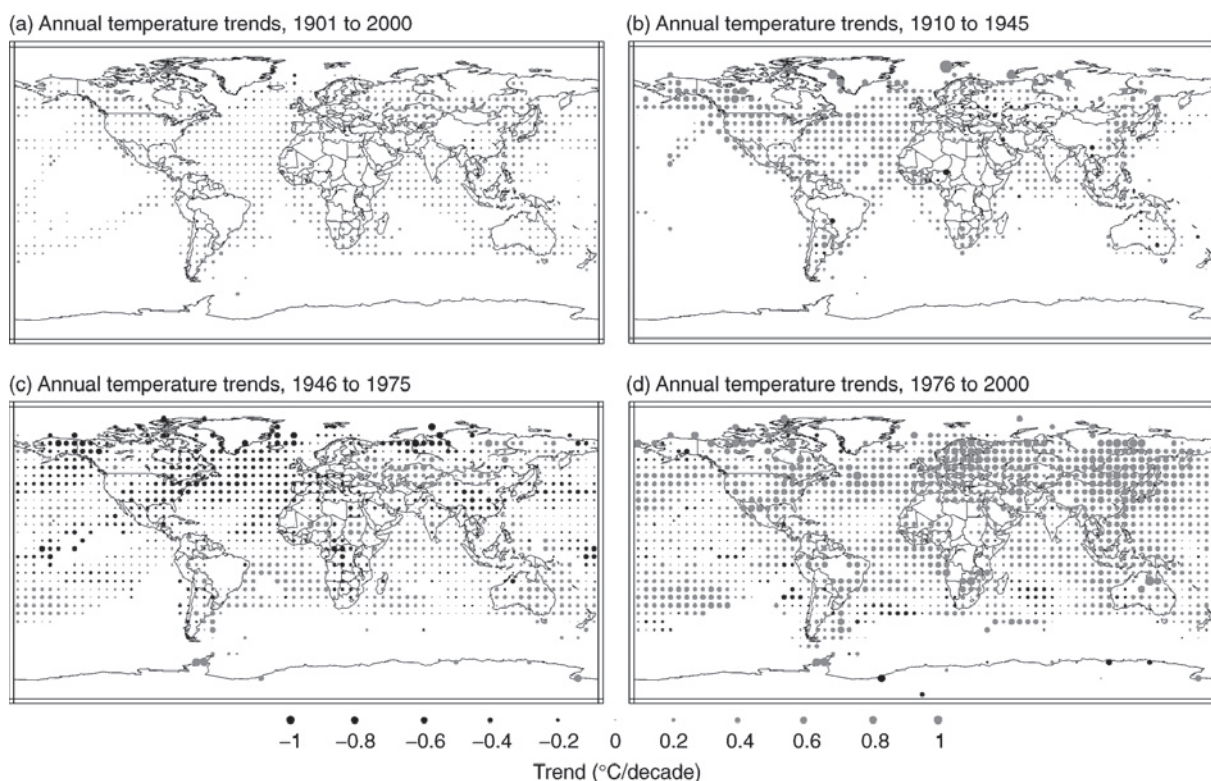


Most of this increase has occurred in two periods, from about 1910 to 1945 and since 1976 (Figure 2). Winter and nighttime minimum temperatures are continuing to increase faster than summer and daytime maximum temperatures, respectively, reducing seasonal and diurnal temperature ranges. New record high night-time minimum temperatures are shortening the frost season in many mid- and high latitude regions. Furthermore, most of this warming occurred on land, which tracks temperature change faster than large water bodies, although the oceans have also warmed significantly in the last 50 years, especially in the upper 300 metres. Since the late 19th century, the global average sea surface temperature has increased by 0.6°C, consistent with the increase in global air temperature. The Baltic and North Seas and the western Mediterranean show a warming of about 0.5°C over the past 15 years (EEA ETC/ACC et al., 2004). Sea surface temperatures in the North Atlantic has been rising since the mid-1980s, which could have been part of a fluctuation over several decades. This is, however, unlikely because the warming has accelerated over the last five years. This contributed to the rapid parallel increases of surface air temperature in much of Europe (KNMI, 2003).

Figure 2 Regional trends in annual temperature during the 20th century (after Houghton et al., 2001).



Because of the increase in the temperature of the North Atlantic, Europe has warmed more than the global average, with a 0.95°C increase since 1900. The warming has been greatest in north-west Russia and the Iberian Peninsula (EEA ETC/ACC et al., 2004). Additionally, in the past 100 years the number of cold and frost days has decreased in most parts of Europe, whereas the number of days with temperatures above 25°C and of heatwaves has increased considerably (EEA ETC/ACC et al., 2004).

The increase in global temperatures has thus resulted mainly from a significant reduction in the frequency of much below normal seasonal mean temperatures across much of the globe, with a correspondingly smaller increase in the frequency of much above “normal” temperatures. The high temperatures of the European summer in 2003 were partly caused by a simultaneous lack of soil moisture and evaporation, which raised temperatures over land much more rapidly than anticipated. Such systemic interactions could well lead to

larger extreme events in the future (Klein Tank, 2004).

Annual precipitation trends in Europe for the period 1900–2000 show a contrasting picture between northern Europe (10–40% wetter) and southern Europe (up to 20% drier). Changes have been greatest in winter in most parts of Europe (EEA ETC/ACC et al., 2004). The IPCC (2001) states that there has likely been a widespread increase in very heavy rain in regions where total precipitation has increased. In some regions, increases in heavy rainfall have been identified where the total precipitation has decreased or remained constant, such as east Asia. This is attributed to a decrease in the frequency of precipitation. Where data are available, changes in annual river run-off relate well to changes in total precipitation and partly explain the increase in the frequency and severity of floods.

Although the temperature changed significantly in the past decades, there seems to be little sign of long-term changes in storm intensity and frequency, but inter-decadal variations are pronounced. Recent analyses of changes in severe local weather (tornadoes, thunder, lightning and hail) in a few selected regions provide evidence for widespread systematic long-term changes. This is because it is extremely difficult to relate individual events to larger scale trends. However, the unusual intensity of hurricanes and typhoons in 2004 cannot be explained by natural variability alone and could well be linked to human-induced climate change, as shown by new model results from Sumi et al. (2004).

The costs of extreme weather events have risen rapidly in recent decades, despite significant and increasing efforts at strengthening infrastructure and enhancing disaster preparedness (McCarthy et al., 2001). Also in Europe, a larger number of all catastrophic events since 1980 are attributable to weather and climate extremes: floods, storms, droughts and heatwaves (EEA ETC/ACC et al., 2004). Part of the observed upward trend in historical disaster losses is linked to socio-economic factors such as population growth, increased wealth, and urbanization in vulnerable areas, and also to climatic factors such as observed changes in precipitation, flooding and drought events. Precise attribution is complex, and there are differences in the balance of these two causes by region and by type of event. Many of the observed trends in weather-related losses, however, are consistent with what would be expected under climate change. Notably, the growth rate in human-induced losses and those unrelated to weather has been far lower than that of weather-related events.

Klein Tank (2004) recently analyzed European patterns of climate change and came to a surprising conclusion: although there have been obvious changes in the mean climate, most of the observed ongoing climate change can be attributed to changes in extremes. He and his colleagues have created a meticulous database of long daily temperature and precipitation series. This series clearly showed statistically significant and non-trivial changes in extremes: fewer cold extremes, more warm extremes (heatwaves), smaller diurnal and seasonal ranges, more precipitation that comes mostly in the form of intense showers. Selten et al. (2004) showed that these changes could not be the result of natural variability but are linked to anthropogenic changes of the climate system. Klein Tank (2004) concludes that larger extreme events can be expected in the future, often also aggravated by systematic interactions. This was well illustrated by the exceptionally hot summer in Europe in 2003. The high temperatures were partly caused by a simultaneous lack of soil moisture and evaporation, which raised temperatures over land much more rapidly than anticipated.

The next sections discuss the consequences of these changes. First, the changes in the physical environment are reviewed (glaciers, ice sheets, snow cover, the hydrology of rivers, sea level rise and fires). Most of these changes are well documented (e.g. Figure 1) and their links with climate change are established. Second, the changes in ecosystems are presented and discussed. These changes occur on a much smaller scale and cannot always be unequivocally connected to ongoing climate change. These reviews indicate that many more impacts have been identified since the last IPCC assessment (2001) and the last update of the World Impact Map (cf. Box 1). Now not a single region is unaffected.

2.2 Observed changes in the physical environment

2.2.1 Changes in the cryosphere

The cryosphere consists of land-based ice, sea ice and permafrost. Ice accumulates during cold periods and melts during warm periods. A glacier, ice cap or ice sheet gains mass by accumulating snow, which is gradually turned into ice, and loses mass (ablation) mainly by melting at the surface or base with subsequent run-off or evaporation of the meltwater. Some meltwater may refreeze within the snow instead of being lost, and some snow may sublimate (i.e. escape as water vapour) or be blown off the surface. The mass balance for an individual body of ice is usually expressed as the rate of change of the equivalent volume of liquid water (in m³/yr). The mass balance is zero for a steady state. The winter mass balance mostly measures accumulation; the summer surface melting. Changes have been observed in the cryosphere over the last century. For many decades, most of the glaciers have been retreating, ice has been getting thinner, permafrost has disappeared and the season of snow and ice cover has shortened (McCarthy et al., 2001). Most of the recent changes are consistent with observed and simulated warming. Over the last few years the rate of change in the cryosphere has accelerated (Diaz et al., 2003).

Lake ice duration

Although in the early 1990s, data for some regions, such as eastern Canada, do not apparently show decreasing trends in lake ice duration (Walsh, 1995), there is nowadays a clear decreasing trend globally (Caine, 2002).

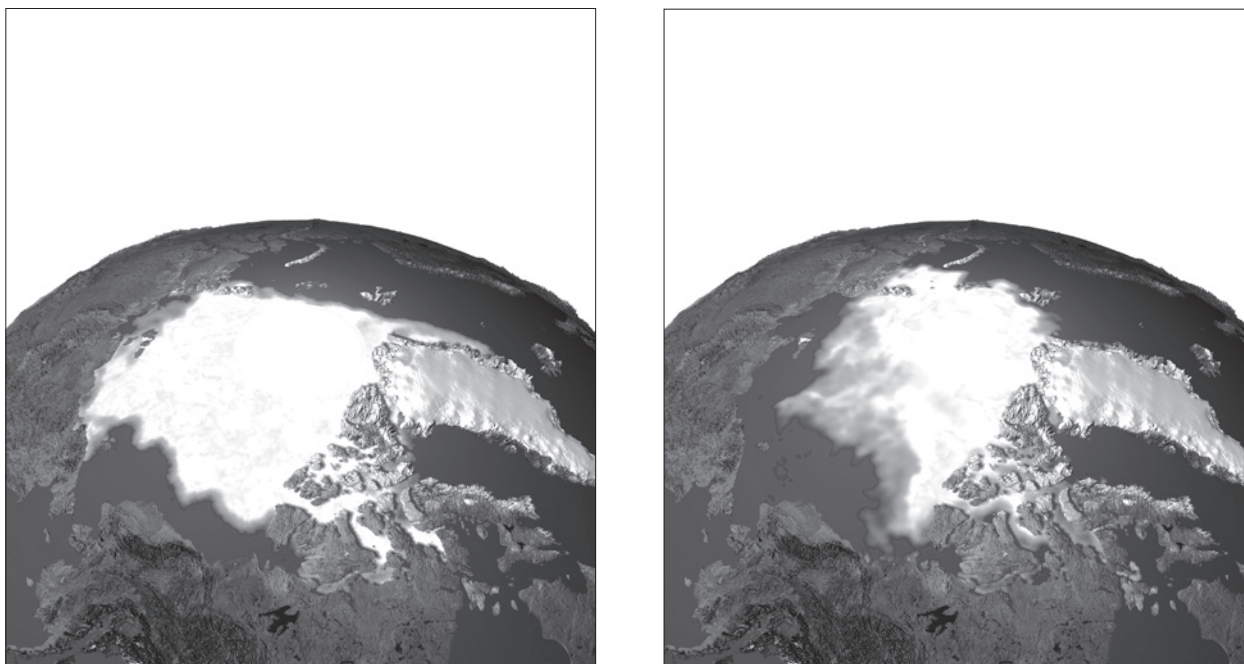
Sea ice cover and thickness

The potential of monitoring by satellite has been realized for several variables (extent of sea ice, snow cover). This has unambiguously shown that the extent of the Arctic ice has decreased considerably in the last decade. These changes are probably also attributable to recent warming.

The total area of Arctic sea ice shrank by more than 7% during the last two decades (Figure 3). Recent data from submarines indicate that the thickness of the ice submerged under the sea at the end of the melting season decreased from three to less than two metres. The volume is down by about 40% on average (i.e. near 4cm per year) between the late 1950s and the present, albeit with large regional variability (Grumet et al., 2001, Arctic Climate Impact Assessment, 2004). The duration of the summer melt season over a large proportion of the perennial Arctic sea ice increased by 11 days since the 1970s. The reduction in sea ice in the Arctic spring and summer is consistent with an increase in spring temperatures, and to a lesser extent with summer temperatures in the high latitudes. There is little indication of reduced Arctic sea ice extent during winter, when temperatures are still far below freezing, despite apparent warming.

Similar trends are observed in Antarctica. The sea ice around Antarctica declined over the last century. This has been reconstructed by using the well-documented location of whale catches (de la Mare, 1997). The melting of sea ice and the consequent decrease in its extent has continued (Curran et al., 2003). These changes in Arctic and Antarctic sea ice cover have significant consequences for vulnerable wildlife, such as polar bears, seals and penguins.

Figure 3 The extent of Arctic seas ice in 1979 (left) and 2003 (right)
 (Source: NASA, <http://earthobservatory.nasa.gov/Newsroom/>).



The new satellite instruments show that the Greenland Ice Sheet is losing mass by near-coastal thinning, and that the West Antarctic Ice Sheet, with thickening in the west and thinning in the north, is probably thinning overall (Shepherd et al., 2003). The mass imbalance of the East Antarctic Ice Sheet is small. Large sectors of ice in southeast Greenland, the Amundsen Sea Embayment of West Antarctica, and the Antarctic Peninsula are changing quite rapidly (Rignot and Thomas, 2002). All these changes are a consequence of greater than average warming in Antarctica (Vaughan et al., 2003).

Snow cover

Although many data collections suggest an increase of snowfall over high latitudes, Myneni et al. (1997) show that annual snow cover extent has decreased by about 10% in the northern hemisphere. The snow-cover period in the northern hemisphere land areas between 45°N and 75°N grew shorter by an average of nine days per decade between 1971 and 1994. This results in earlier and more rapid melting, which has consequences for river run-off and water availability (Serreze et al., 2000). There is a highly significant correlation visible between increases in the northern hemisphere spring land temperatures and a reduction in the snow cover since measurement data have been collected.

Size of glaciers

Most mountain glaciers are receding rapidly. For example, the hundreds of glaciers in the US Glacier National Park and adjacent Canadian Waterton Lakes National Park are expected to disappear completely by 2030 (Arendt et al., 2002). However, glaciers in a few maritime regions are advancing, mainly due to increases in precipitation (e.g., Norway, New Zealand). Many glaciers in the Alps receded more than 5% in 2003 alone. During the extremely warm summer of 2003, some of these glaciers did not retreat but actually collapsed. Such rapid melting creates unstable slopes when the sun melts surface ice. Rockfalls can then pose a hazard to climbers and tourists. All these changes have large implications for tourism (mountaineering, hiking and skiing), water resources and

hydroelectric power, and land-use management and planning. For example, the recent outlawing of climbing on the Swiss Eiger's north face due to unstable snow and rock shows that alpine climbing may soon face crisis.

In the tropics, all glaciers (South America, Africa and Asia) are retreating rapidly (e.g. Schotterer et al., 2003). The last ice of the glacier on mount Kilimanjaro in Kenya/Tanzania will likely melt before 2020 (Thompson et al., 2002), threatening several unique alpine ecosystems and local biodiversity and run-off volumes. Similar trends are observed for most of the Himalayan glaciers (Sharma et al., 2000, Singh and Sontakke, 2002). The shrinking of glaciers could threaten water availability downstream in the warmer seasons and adversely impact many ecosystems, biodiversity and the livelihoods of many people.

Permafrost

Permafrost is permanently frozen soil. Changes in permafrost are not as easily detected as those in ice and snow, but have far-reaching consequences. In constructing infrastructure in polar regions, such as roads and pipelines, it is generally assumed that permafrost provides a stable foundation. Anisimov (1989) was among the first to show that nowadays this assumption is flawed. He analyzed long-term data for Russia and Siberia and concluded that permafrost is already thawing, resulting in a polewards shift of seasonally unfrozen ground. The melting of the polar permafrost areas actually began in the middle of the 19th century, due to somewhat warmer temperatures (Overpeck et al., 1997). Their analyses clearly demonstrate the sensitivity of permafrost regions to even slight warming. Warming has accelerated more over the last decades here than in any other region of the world. Yet increased melting trends are now observed in all the world's polar systems (e.g. Kwong and Gan, 1994, Serreze et al., 2000). In Fairbanks, for example, the mean annual temperature of the soil increased with by between 2°C and 3°C in the last 50 years. The temperature at a soil depth of one metre increased to just below freezing point. The accelerated melting of permafrost will alter the hydrology of many northern rivers (van der Linden et al., 2003). Major implications for vegetation structure and processes are also foreseen. Jorgenson et al. (2001), for example, experimented with the warming of ecosystems and unambiguously showed that warming of a few degrees leads to release of carbon (e.g. Waelbroeck et al., 1997, Welker et al., 2000). This process might explain recent observed accelerated rapid increase in atmospheric CO₂ concentrations.

2.2.2 Changes in river discharge

The water that flows in the world's rivers originally comes from precipitation. Run-off results from the balance between precipitation, groundwater recharge, groundwater discharge and evaporation. There are many delays in the system. Precipitation can be stored in winter as snow and ice and is only released during the melting season. Some water slowly infiltrates the soil, flows as groundwater and re-emerges in spring. These storage processes often buffer water sources and determine water availability for human use, even when there is little precipitation.

The declining glaciers and snowfields in the Himalayas, for example, strongly affect run-off and water availability in the Indo-Gangetic plains region of India and Bangladesh, which is very important for the food security of South Asia. The region's population grew at a rate of about 1% per annum during the past four decades, which has led to a strong intensification of crop irrigation and of agricultural land use. Although temperature and precipitation increased somewhat, the river data indicated an overall decrease in discharge (Sharma et al., 2000). The decreasing trends of stream flow were more significant during the low-flow months when most of the water originates from snow melt, which permits a constant water supply throughout the year (Sharma et al., 2000, Singh and Sontakke, 2002). All these factors make the society of the Indo-Gangetic plains region one of the most vulnerable in the world to changes in climate.

Annual river discharge has changed over the past few decades across Europe. In some regions, including eastern Europe, it has increased, while it has fallen in others, including southern Europe. Some of these changes can be attributed to observed changes in precipitation. The combined effect of projected changes in precipitation and temperature will in most cases amplify the changes in annual river discharge. Annual discharge is projected to decline strongly in southern and south-east Europe but to increase in almost all parts of northern and north-east Europe, with consequences for water availability. Between 1975 and 2001, 238 flood events were recorded in Europe. Over this period the annual number of floods clearly increased. The number of people affected rose significantly, with adverse physical and psychological consequences for people. Deaths per flood decreased significantly due likely to improved warning and rescue measures (EEA ETC/ACC et al., 2004).

2.2.3 Sea level rise

Over the last 100 years, the global sea level has risen by about 10cm to 25cm. Sea level change is difficult to measure. Relative sea level changes have been derived mainly from tide data. In the conventional tide-gauge system, the sea level is measured relative to a land-based tide-gauge benchmark. The problem is that land suffers vertical movement (e.g. isostatic effects and sedimentation) and these complicate measurement. However, improved methods to remove the effects of long-term vertical land movements, as well as a greater reliance on the longest tide-gauge records and new satellite measurements for estimating trends, have provided greater confidence that the volume of ocean water has indeed been increasing, causing the sea level to rise within the given range. The major causes of this increase are thermal expansion of the surface waters and melting of glaciers and snow on land and the Greenland ice cap (McCarthy et al., 2001).

2.2.4 Fire in ecosystems

Climatic changes have increased the length and intensity of summer drought in many regions. This has increased the susceptibility of ecosystems to fires. Over the last decade fire frequency increased in many regions:

- Spain lost more than 485,622 hectares of forest to wildfires in 1994 and 149,734 hectares burned away in Italy in 1998 (Pinol et al., 1998).
- Fires due to dry conditions and record-breaking heat consumed one-fifth of vegetation on the island of Samos, Greece in July 2000 (C. Körner, personal communication). Temperatures reached 40°C in some localities. Simultaneously, many of the mountain springs dried up. Together they are clear indicators of unprecedented warming trends.
- Fires burned up to 809,371 hectares of rainforest in Indonesia (Page et al., 2002), including almost 101,172 hectares of primary forest and parts of the already severely reduced habitat of the Kalimantan orang-utang .

2.2.5 Treeline and growing season

Since the nineteen seventies, satellite measurements have been made to monitor changes in the environment. Myneni et al. (1997) have analyzed this data to detect if there were indications of widespread global warming over land in the northern hemisphere. From their NDVI (an index of plant growth) data for 1981 to 1991 they found a surprisingly large increase over large regions. They found an earlier greening of vegetation in spring of up to ten days and a later decline of a few days in autumn over large parts of the northern hemisphere. Although it was confirmed later by Los (1998), many have criticized this kind of analysis and blamed it on drift in the satellite instruments (similar arguments arose when the ozone hole was first measured over Antarctica). Lucht et al. (2002) have used a global vegetation model and an independent high-resolution database of observed climate. They simulated a similar trend over the 1980s and a marked setback in this trend

after the 1991 volcanic eruption of Mount Pinatubo, which caused a temporary cooling. The observed trend toward earlier spring budding and increased maximum leaf area in the 1980s is reproduced by the model, but restored the two subsequent years after the eruption. They also simulate a small increase in carbon uptake due to this cooling (decomposition was reduced more than primary productivity), which could well explain the slower increase of atmospheric CO₂ in those years.

The satellite-observed changes indicate a longer growing season for vegetation. Such phenomena have also been observed elsewhere. Several studies, for example, report a polewards shift of the treeline border between trees and tundra (e.g. Lavoie and Payette, 1994, Walsh, 1995). Increases in the width of tree rings (e.g. Villalba et al., 1994, Villalba et al., 2003) have also been detected near the treeline. These observations are made in many different parts of the world. The next sections discuss them in detail.

2.3 Observed ecological changes

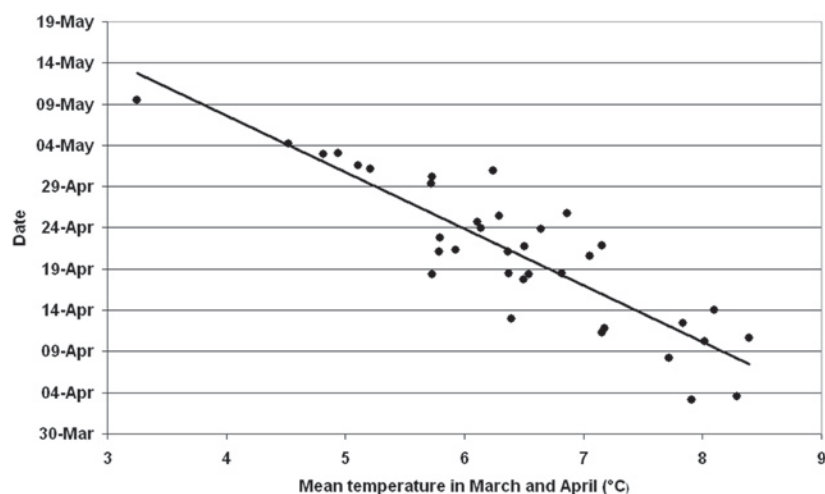
In this chapter we discuss a large number of observed ecological changes. Some were included in the third assessment report of the IPCC (2001) but many are new. We focus on Europe and The Netherlands. Comprehensive global reviews are available elsewhere (e.g. Root et al., 2003). Our aim is not to provide a complete overview of all known impacts but to make clear that ecological changes are already large, and that all species groups show changes which occur in every ecosystem on Earth. We make a distinction between two main biological responses to changes in climate: phenological changes which are changes in the timing of life cycle events, and distributional changes in populations of plants and animals in specific areas.

2.3.1 Phenological changes as a response to climate change

One of the most obvious indicators of ecological impacts of climate change are phenological changes. Phenology deals with the times of annual natural events like flowering, leaf unfolding, ripening of fruits, leaf colouring, leaf fall, bird migration, frog spawning, and bird nesting which can be observed by satellites or in the backyard. The timing of these events is often closely related to temperature and the amount and timing of precipitation. Figure 4 illustrates this relation. It shows that the average temperature in March and April determines the start of flowering of Birch (*Betula pubescens*) in The Netherlands. In temperate zones an increase in temperature leads to an earlier start of the growing season and a later end. The length of the growing season is expected to increase with warming. Only in those places where environmental conditions like drought, flooding or large amounts of snowfall limit plant growth will an increase in temperature not immediately result in a lengthening of the growing season.

Plants are flexible in adjusting the timing of their phenological events to changes in climate conditions (cf. Figure 4). In warm springs, Birch trees flower at the end of March in The Netherlands while in very cold springs the start of flowering only starts at the end of April. The observed recent increases in temperature should have become visible as changed timings of phenological events. Historical observations are needed to document these changes. One must know dates of the start of past flowering or bird migration events. Fortunately, centuries ago, people recorded the timing of both life-cycle events and weather to help agriculture and hunting. By observing the timing of flowering they knew when to plant and harvest their crops or when to hunt. The documentation of these observations now helps us to assess long-term changes.

Figure 4 Relation between timing of Birch flowering in The Netherlands and the spring temperature.



Phenological networks that monitor the timing of life cycle events have been established in many countries. The records go back hundreds of years and many are still being expanded (e.g. in Japan, Finland and the United Kingdom). A detailed overview of the existing networks is provided at the phenological meta-database (<http://www.dow.wau.nl/msa/ejn>). The documentation of these observations now helps us to assess long-term changes. These long-term observations also play a key role in visualizing the ecological impact of climate change on the timing of life cycle events. In the Netherlands, for example, systematic phenological observations have been made from 1869 till 1968. In 2001 this Dutch network was successfully revived under the name Nature's Calendar (Natuurkalender, <http://www.natuurkalender.nl>). Since then, thousands of volunteer observers have submitted their own phenological observations on plants, butterflies, birds and dragonflies. Because of the availability of historic observations, the visibility of life cycle events and their quick response to climate variations, climate change induced changes in the timing of life cycle events have significantly contributed to the conclusion of IPCC (IPCC, 2001) that the recent changes in climate already have an impact on ecological systems. Many scientific papers on this topic have been published recently (Parmesan and Yohe, 2003, Root et al., 2003). All species groups examined have showed significant changes in the timing of their own life cycle events. Below, an overview of species group responses is given.

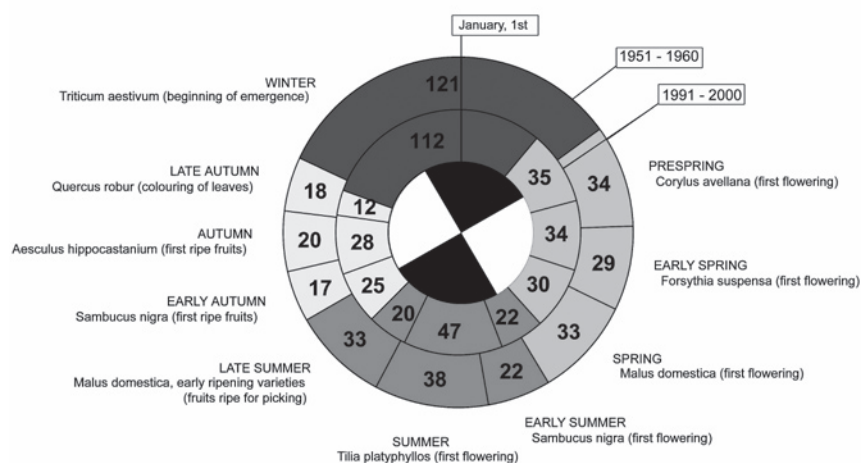
Plants

Most of the phenological networks focus on plants. Observers are asked to record the start of flowering, leaf unfolding, fruits ripening, leaf coloring and leaf fall. These events indicate the length of the growing season. In the last few years a large number of studies demonstrated that the length of the growing season is indeed increasing. Menzel (2000) studied phenological changes in international phenological gardens from all over Europe from 1959 till 1996, determining that spring events such as leaf unfolding have advanced on average by 6.3 days whereas autumn events such as leaf coloring have been delayed on average by 4.5 days. The annual growing season thus increased on average with 10.8 days since the early 1960's (Menzel and Fabian, 1999, Menzel, 2000). Even an analysis of the satellite data since 1975 showed a clear signal of lengthening growing seasons over large parts of the Northern hemisphere (Myneni et al., 1997).

Although the first day of meteorological spring, summer, autumn and winter start at the same date every year, the biological start and end of the seasons varies from year to

year. This is illustrated by analyses of the German Meteorological Service. Instead of four seasons they divide the year into 10 different seasons: Pre-spring, early spring, spring, early summer, summer, late summer, early autumn, autumn, late autumn and winter. The start of the next season is determined by the timing of certain life cycle events. Figure 5 presents the changes in seasons that are taking place. It compares the start of various seasonal growth phases in the period 1951 – 1960 with the start in the period 1991-2000.

Figure 5 Phenological calendar for Rhineland-Palatinate, Germany. Ten phenological seasons (outer sections with the length in days) and the climatological seasons clockwise in the center (source: Y. Henniges, German Meteorological Service).



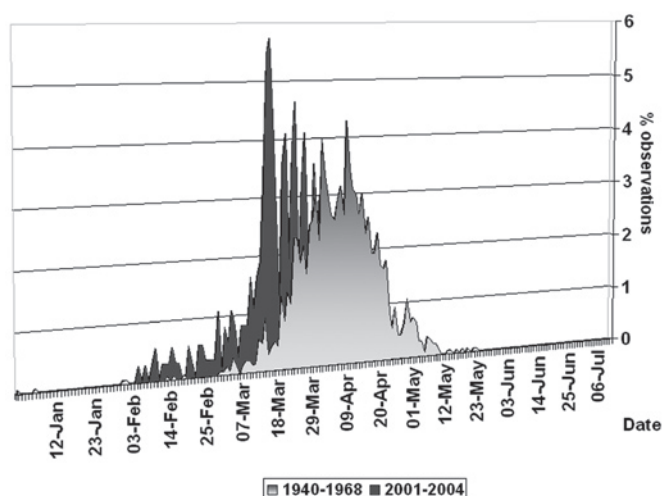
Large changes have been observed in the start of the growing season in the Netherlands. Observations are available from various sources, including the Natuurkalender. The Netherlands experienced several record temperatures. These records show a significant impact on the timing of flowering and leaf unfolding. 2004 was no exception to this trend (Table 1, Figure 6). Already in the beginning of February maximum temperatures rose to 18°C, which was never experienced before. In 2004, the timing of life cycle events in plants was on average 16 days earlier than observations in the past (1868 till 1968). Not all phases advanced in the same way. Yellow Water-Lily, for example, was only 4 days earlier but plants like Snowdrop, Alder, and Cow-parsley were, on average, more than three weeks earlier. In several European countries a significant advance has been observed in the flowering time of Wood Anemone. In Estonia, for example, it advanced its flowering with 17 days in 78 years (Ahas, 1999) and in Norfolk (UK) every 1°C increase in temperature of January to March advances flowering with 7 days (Sparks and Menzel, 2002) while the average advance for the whole of the UK is only 4 days (Sparks et al., 2000).

Table 1 Difference of the timing of life cycle events in the past compared with 2004. Data are taken from the Dutch Natuurkalender.

Species	Average date in historic series	Average date in 2004	Number of days difference
Hazel (<i>Corylus avellana</i>), flowering	11-Feb	23-Jan	18
Snowdrop (<i>Galanthus nivalis</i>), flowering	19-Feb	25-Jan	25
Common Alder (<i>Alnus incana</i>) flowering	28-Feb	01-Feb	27
Alder, (<i>Alnus glutinosa</i>) flowering	28-Feb	10-Feb	18
Colt's foot (<i>Tussilago farfara</i>) flowering	21-Mar	01-Mar	20
Small selandine (<i>Ranunculus ficaria</i>) flowering	23-Mar	03-Mar	20
Blackthorn (<i>Prunus spinosa</i>) flowering	18-Apr	09-Mar	39
Sweet violet (<i>Viola odorata</i>) flowering	28-Mar	10-Mar	18
Wood Anemone (<i>Anemone nemerosa</i>) flowering	05-Apr	21-Mar	15
King-cup (<i>Caltha palustris</i>) flowering	16-Apr	27-Mar	20

Species	Average date in historic series	Average date in 2004	Number of days difference
Ground ivy (<i>Glechoma hederacea</i>) flowering	19-Apr	29-Mar	21
White deadnettle (<i>Lamium album</i>) flowering	23-Apr	04-Apr	19
Horse chestnut (<i>Aesculus hippocastanum</i>) leaf unfolding, flowering	13-Apr	05-Apr	8
Lady's mock (<i>Cardamine pratensis</i>) flowering	21-Apr	05-Apr	15
Birch (<i>Betula pendula</i>) , flowering	20-Apr	07-Apr	13
Cow-parsley (<i>Anthriscus sylvestris</i>) flowering	04-May	09-Apr	24
Bird cherry (<i>Prunus padus</i>), leaf unfolding	15-Apr	11-Apr	3
Beech (<i>Fagus sylvatica</i>), leaf unfolding	29-Apr	13-Apr	15
Mouse-ear chickweed (<i>Cerastium arvense</i>) flowering	02-May	14-Apr	18
Garlic mustard (<i>Alliaria petiolata</i>) flowering	02-May	17-Apr	14
Broom (<i>Cytisus scoparius</i>) flowering	11-May	17-Apr	23
Meadow buttercup (<i>Ranunculus acris</i>) flowering	04-May	19-Apr	15
Bird cherry (<i>Prunus padus</i>), flowering	04-May	20-Apr	14
Pedunculate oak (<i>Quercus robur</i>), leaf unfolding	05-May	20-Apr	15
Common lilac (<i>Syringa vulgaris</i>), flowering	09-May	26-Apr	13
Horse chestnut (<i>Aesculus hippocastanum</i>), flowering	11-May	27-Apr	13
Hawthorn (<i>Crataegus monogyna</i>), flowering	16-May	28-Apr	18
Creeping buttercup (<i>Ranunculus repens</i>), flowering	07-May	28-Apr	8
Rowan (<i>Sorbus aucuparia</i>), flowering	13-May	01-May	12
Laburnum (<i>Laburnum anagyroides</i>), flowering	17-May	02-May	14
Ragged robin (<i>Lychnis flos-cuculi</i>), flowering	14-May	09-May	5
Ox-eye daisy (<i>Leucanthemum vulgare</i>), flowering	23-May	10-May	13
Yellow flag (<i>Iris pseudacorus</i>), flowering	25-May	17-May	8
Elder (<i>Sambucus nigra</i>), flowering	04-Jun	20-May	15
Yellow water-lily (<i>Nuphar lutea</i>), flowering	28-May	23-May	4
Bog heather (<i>Erica tetralix</i>), flowering	20-Jun	24-May	27
White water-lily (<i>Nymphaea alba</i>), flowering	03-Jun	28-May	5
Meadow sweet (<i>Filipendula ulmaria</i>), flowering	02-Jul	19-Jun	13
Purple loosestrife (<i>Lythrum salicaria</i>), flowering	06-Jul	25-Jun	10
Tansy (<i>Tanacetum vulgare</i>), flowering	17-Jul	01-Jul	16
Heather (<i>Calluna vulgaris</i>), flowering	03-Aug	07-Jul	26
Rowan (<i>Sorbus aucuparia</i>), fruits ripe	24-Aug	27-Jul	27

Figure 6 Flowering of Wood anemone (*Anemone nemerosa*) in The Netherlands in two different periods (Source, De Natuurkalender).



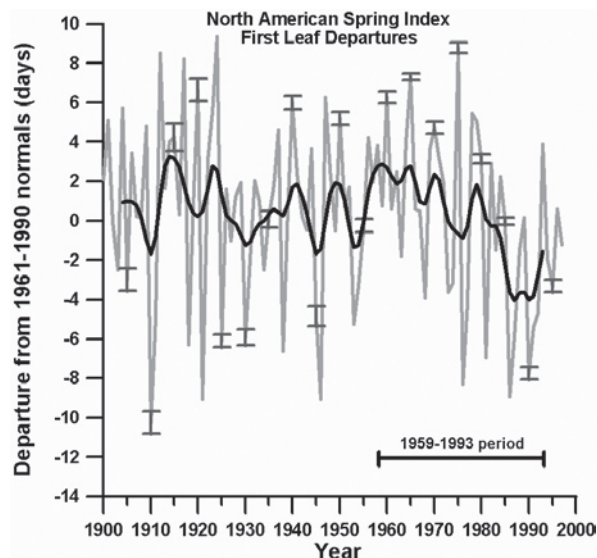
Phenological networks are not the only source of phenological information. Pollen monitoring networks, for example, also are able to provide phenological information. The members of the European Pollen information and the European Aeroallergen Network have set up a database with daily pollen information on 17 pollen types from 450 stations from all over Europe from 1974 onwards. With this pollen database Jäger (2001) calculated

trends for start, peak and end of pollen season as well as trends for intensity and duration of pollen seasons during the past three decades. In general, an earlier start and peak of pollen seasons was clearly evident, being more pronounced in species that flower earlier in the year (up to 20 days). The later the flowering time, the less significant trends become towards earlier start of the season. A later end of the season becomes more likely the later the flowering period. Overall, the pollen season expands. Pollen seasons became longer in particular for species flowering after March/April. An increase of the amount of pollen in the air is not common, but is more frequently observed for grass and weed pollen than for trees (Huynen et al., 2003). The trend towards earlier flowering has also been observed in the Netherlands. The start of the pollen season in the Netherlands advanced with up to 22 days between 1969 and 2000. The smallest advance of three days was seen for Ash (*Fraxinus excelsior*) while the largest advance (22 days) was shown by Elm (*Ulmus procera*) (van Vliet et al., 2002).

Other examples of observed phenological changes in plants are:

- Flowering dates of the Locust Tree (*Robinia pseudoacacia*) in Hungary occurred 3-8 days earlier during the period 1983-1994 compared to 1851-1930. The study indicates that a rise in temperature of 1°C causes an advanced flowering by 7 days (Walkovszky, 1998).
- The growing season has lengthened by over 10 days over the last century in Turku, central Finland. Throughout the Nordic region the start of the growing season has become progressively earlier by between 4 and 12 days (Carter, 1998).
- Primack et al (2004) provided a revealing record. They compared the flowering times of 229 living plants in 2003 at the Arnold Arboretum in Boston, Massachusetts, combined with 372 records of flowering times from 1885 to 2002 using herbarium specimens of the same individual plants. During this period, Boston experienced a 1.5 °C increase in mean annual temperature. Flowering times became progressively earlier: plants flowered 8 days earlier from 1980 to 2002 than they did from 1900 to 1920. Most of this shift toward earlier flowering times is explained by the influence of temperature, especially in the months of February, March, April, and May. Plants with a long flowering duration appear to be as useful for detecting responses to changing temperatures as plants with a short flowering duration.
- An increase of average air temperature between February and April of 1.6°C between 1961 and 2000 led to an advance cherry tree blossom in Germany of eight days. The start of flowering of apple trees and the beginning of stem elongation of Winter Rye follow the same pattern (Roetzer and Chmielewski, 2001, Chmielewski, 2003).
- Schwartz and Reiter (2000) examined spring seasons across North America over the 1900-1997 period using modelled and actual Lilac phenological data (Figure 7). Regional differences were detected, as well as an average 5-6 day advance toward earlier springs over a 35-year period from 1959-1993.
- Chen (2003) analyzed phenological research in east Asia. He presented results of an analysis of data from 104 phenological stations in Japan during 1953 to 1990 which concluded that with an increase of 1°C in mean monthly temperatures, the flowering dates of *Prunus yedoensis* and *Prunus mume* would advance by 2.7-4.8 days and 4-13 days, respectively. In autumn, the leaf colour changing dates of *Ginkgo biloba* and *Acer palmatum* would be delayed by between 2-7 days. However, as the temperature in Japan decreased with 0.16-0.4°C per ten years, the average start of flowering of *Prunus yedoensis* was delayed.

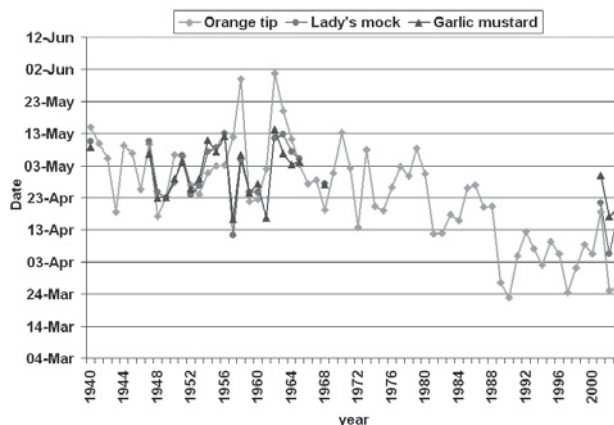
Figure 7 North American Spring Index, first leaf departures (Source: Schwartz and Reiter, 2000).



Insects

The Dutch phenological monitoring network also includes butterflies in its monitoring programme. The high temperatures have resulted in remarkable changes. The programme includes two migratory butterflies, the Red Admiral (*Vanessa atalanta*) and Painted Lady (*Vanessa cardui*). Every year they migrate to the Netherlands from southern Europe and used to arrive in May. However, the recent warm years have resulted in a large number of first sightings in January. There is evidence that the Red Admiral now manages to winter in the Netherlands. It probably benefitted from now common warm winter winds from the south, explaining many of the early sightings in 2004. At the same time a number of Painted Ladies were observed in the south-west Netherlands and in the south of the United Kingdom. These migratory butterflies are not the only ones that showed a response to warm weather. Most of the butterflies appeared early in the last couple of years. For example, the Orange Tip (*Anthocharis cardamines*) butterfly appeared early May in the 1940s (Figure 8) while it nowadays appears already early April. The first appearance advanced on average a month in the observation series (source: Dutch Butterfly Conservation). Because of the early start of the flight period, the active season increased substantially and many butterfly species were able to produce more generations each year.

Figure 8 First appearance of the Orange tip (*Anthocharis cardamines*) butterfly in The Netherlands in relation to the flowering time of two host plants (Sources: Dutch Butterfly Conservation and De Natuurkalender).



The advancing first appearance was already studied by Ellis et al. (1997) who found that the flight peak of Microlepidoptera (moths) advanced an average of 11.6 days between 1975 and 1996. A recent analysis of dragonfly data revealed that the first appearance advanced in a spectacular way, sometimes by more than a month (Ketelaar, 2003). Part of the advance is probably caused by an advance in the timing of observers going into the field. However, Ketelaar (2003) also looked at the changes in peak flight of 10 common dragonfly species and found changes ranging from no advance of the Common Blue Damselfly (*Enallagma cyathigerum*) to an advance of 18.3 days of the Large Red Damselfly (*Pyrrhosoma nymphula*). It is highly likely that many other insect species respond in the same way as the butterflies and dragonflies. The warm start of 2004 which was followed by a warm summer resulted in a very early appearance of wasps in the Netherlands. Also the number of nests was substantially higher than in other years (source: Dutch Butterfly Conservation).

The first appearances of most British butterflies have also advanced in the last two decades and are strongly related to earlier peak appearance, and for multi-brooded species a longer flight period (Roy and Sparks, 2000). In the UK the first appearance of Peach-Potato aphid (*Myzus persicae*) in the UK advanced by 16 days with an increase of 1°C (Cannell et al., 1999). These analyses indicate that a 1°C increase in temperature advances first and peak appearance of most butterflies by 2-10 days.

Birds

Birds are monitored intensively by thousands of people. A lot of birdwatchers record the arrival and to a lesser extent departure of migratory birds. Furthermore, the timing of first singing, egg-laying, egg-hatching and moulting are recorded. As with plants and insects, the timing of these events is determined by climate variables like temperature and rainfall. Changes in the timing have been observed in the past decades. The recent change in timing of the arrival of many migratory birds, however, has not been as large as the changes recorded for plants and insects. According to Sparks and Menzel (2002) a temperature response in bird migration timing has been reported across Europe. An example of the change in recent times is provided by the arrival dates of the Sand Martin (*Riparia riparia*) in Essex, UK. This is now some 20 days earlier than it was 50 years ago, and a strong response to March temperature of four days per °C is apparent. This is greater than recorded for many bird species, and there is a suggested differential response between species that may lead to changed competition for resources. This was evident also in Poland, where the advance of short-distance (European) migrants was more marked than that for long-distance (African) migrants (Tryjanowski et al., 2002). In some other cases no clear trends in arrival dates have been found. The first arrival dates of the River Warbler (*Locustella fluviatilis*), for example, varied between 23 April and 10 May with no significant directional trend during the period 1963-2003 (Kaõušèák et al., 2004). A study of the relation between the arrival of 81 migratory birds at two Finnish bird observatories (1960-1999) and the North Atlantic Oscillation (NAO) concluded that there is a negative correlation between the NAO index and the arrival date. As a high NAO index is an indicator of mild and rainy winters in northern Europe, this means that mild winters result in earlier appearances. As the NAO index did not show a significant trend during the study period, no trends in arrival dates were found (Vähätalo et al., 2004).

Sparks et al. (2003) conclude that in many regions including the US state of Wisconsin, Russia and the UK, the majority of the bird life-cycle events have tended to become earlier. They present an example from the Essex Bird Reports in the UK which shows a trend towards earlier arrival over the last two decades of Whimbrel (*Numenius phaeopus*) and Hobby (*Falco subutteo*), which showed a significant trends towards earlier arrival of 39 and 12 days respectively. They note, however, that population increases might have contributed to the advance. In addition to observing the timing of arrival of migratory birds, the timing of egg laying is often recorded. A number of studies have demonstrated

that the timing is changing too (Forchhammer et al., 1998, McCleery and Perrins, 1998, Crick and Sparks, 1999). The Blue Tit (*Parus caeruleus*) in the Netherlands advanced its egg-laying date by about 10 days since 1986 (Majoor et al., 2001). Both and Visser (2001) concluded that the Pied Flycatcher (*Ficedula hypoleuca*) advanced the timing of egg-laying by 7 days. A more detailed study of the breeding dates of 25 populations of *Ficedula* Flycatchers across Europe, studied over a long period, determined whether other environmental variables might have been the cause of the advance. The conclusion was that the advancement of egg-laying was stronger in areas where the spring temperatures were greater. Hence, climate change might cause an advance in breeding date (Both et al., 2004).

The observations made of the Pied Flycatcher by Both and Visser (Both and Visser, 2001) were part of a larger study of the impact of climate change on interaction between species. The study revealed that although the Pied Flycatcher advanced its laying date by 7 days, the main food source for its young, caterpillars of the Winter Moth (*Operophtera brumata*), appear 14 days earlier. Therefore there is now a timing mismatch, which rapidly reduces the ability of the Pied Flycatcher to breed successfully. The number of studies evaluated the occurrence of this kind of predator-prey mismatches because of a change in climate is very limited. With the enormous complexity of the food webs in natural systems, it is highly likely that many more problems will occur, although our lack of knowledge makes it difficult to quantify the problem.

Mammals

Mammals have also been the subject of phenological research, albeit to a much lesser extent than birds, insects and plants. Monitoring has focused on when hibernation begins and ends, and migration arrival and departure. Innouye et al. (2000), for example, report that marmots in Colorado are emerging from hibernation on average 23 days earlier than 23 years ago. This coincides with an increase in average May temperatures of about 1°C over the same time period.

The survival of caribou is determined by single climate events. Miller and Gunn (2003) studied the Peary Caribou (*Rangifer tarandus pearyi*) which is an endangered species in Canada. It has been in decline since 1961 when the total population consisted of 24,000 individuals. Sightings of Peary caribou were compared from two aerial searches, in 1993 and 1998, on Bathurst and its neighbouring islands in the western Queen Elizabeth Islands in the Canadian Arctic. The comparison suggested a near-total (98%) loss of Peary Caribou seen per unit of search effort. In summer 1993, 2400 caribou were counted during 33.8 hours of low-level helicopter searches. In contrast, in summer 1998, only 43 caribou were seen within the same area during 35.2 hours of low-level, helicopter searches. Widespread, prolonged and exceptionally severe snow and ice conditions from 1994-95 to 1996-97 probably caused the animals to die. Increasing snowfall is consistent with predictions for global warming in the western Canadian High Arctic. Future climate change may increase the frequency of years with unfavourable snow and ice conditions, which could prevent (or at least impede) recovery of Peary Caribou populations on the western Queen Elizabeth Islands, particularly to sustainable population sizes that would support subsistence harvesting.

Weladji and Holand (2003) studied the impact of climate change on reindeer. They concluded that the expected large climatic change in northern Europe and Scandinavia may lead to smaller, fewer calves, especially in regions where warm and snowy winters become more severe, as previously reported for red deer in Norway (Post et al. 1997) and Soay Sheep in St Kilda, Scotland (Forchhammer et al., 1998). This will affect conservation.

Aquatic species

Most phenological networks look at terrestrial plants and animals. However, changes in the timing of life-cycle events are also taking place in aquatic ecosystems. This is illustrated by amphibians. In the UK they have advanced their spawning 9 to 10 days earlier over a 17-year period (Beebee, 2002, Walther et al., 2002). Tryjanovsky et al. (2003) also concluded that in spawning dates of two anuran species (*Rana temporaria* and *Bufo bufo*) from western Poland (1978-2002) a trend towards earlier breeding was found, corresponding to an 8 to 9-day shift over the 25-year period. The advances are associated with increased temperatures in winter and early spring. As with other species groups, not all amphibian species show the same change and some do not change at all. According to Beebee (2002) this can be because climate has not changed in all sites where amphibians have been studied, or because of differences between species in reproductive strategies and cues.

Amphibians are partly dependent on air temperatures, so advance might be caused completely by a change in air temperature. This is not the case for fish, but phenological research on fishes is more difficult than with terrestrial species. In Estonia, the spawning dates of Pike (*Esox lucius*) and Bream (*Abramis brama*) have been studied. In 44 years of observation, the advance of spawning was 6 and 8 days respectively (Ahas, 1999). Changes in the timing of fish-spawning also sometimes unexpectedly become visible. In order to protect cod in the North Sea, the European Commission restricted fishing in certain areas. After evaluation, it became clear that the timing of the rule, which was based on observations from the 1970s, was wrong; the timing of fish spawning had advanced. The spawning period had already half finished when the closure started. Moreover, the spawning areas had moved to the north in response to increased water temperatures (Rijnsdorp et al., 2002).

In the climate change indicator report by the European Environmental Agency (EEA ETC/ACC et al., 2004) phytoplankton biomass was presented as an indicator for the marine growing season. The biomass has increased considerably over the past few decades in parts of the north-east Atlantic and the North Sea. From the late 1940s to the 1980s, the majority of production was restricted to bloom periods in spring and autumn. However, production has significantly increased since the late 1980s during the winter and especially the summer season. Particularly high increases have been observed since the mid-1980s in the North Sea and west of Ireland between 52°N and 58°N. During the 1990s, phytoplankton biomass increased in winter months by 97% compared to the long-term mean. Changes in annual phytoplankton biomass and the extension of the seasonal growing period already appear to have considerable impacts on overall biological production and the food web. Change in the seasonal timing of decapod larvae (as an example for zooplankton) over the period 1948–2000 shows a similar behaviour. Although there is considerable inter-annual variability of decapod larvae in the period 1948–2000, since 1988 the seasonal development of the larvae has occurred much earlier than the long-term average. The seasonal cycle was up to 4–5 weeks earlier in the 1990s than the long-term mean (EEA ETC/ACC et al., 2004).

Reptiles also have changed in the timing of their life cycle in response to temperature. Weishampel et al. (2004) examined 15 years of Loggerhead Sea Turtle (*Caretta caretta*), nesting patterns on the Atlantic coast of Florida, which is among the most important nesting area for this threatened species. The nesting date became earlier by roughly 10 days. This was significantly correlated with near-shore, May sea surface temperatures that warmed an average of 0.8°C over this period.

Sea turtles display strong sensitivity to climate change. Hays et al. (2003) reconstructed nest temperatures of a major green turtle (*Chelonia mydas*) at Ascension Island since 1855. The temperature of the sand varied around 3°C between different beaches. This variation has persisted for at least a century. Reconstructed nest temperatures varied, however, by only 0.5°C over the course of the nesting season, but differed for the individual beaches. Nest temperature strongly determines the sex: the coldest sites