1. Weather and Climate

1. Key points

i. Introduction

Atmospheric weather and climate interact with the ocean on short and long timescales, respectively. They affect the circulation, temperature and salinity of the ocean and consequently have an effect on marine ecosystems.

ii. How has the assessment been undertaken?

Observations of weather and climate for the UK and globally, along with peer-reviewed articles, have been assessed to gain an understanding of variability and trends. Projections using climate models have been used to provide information about likely future changes.

iii. Current and likely future status of weather and climate

- Central England Temperature (CET) has increased by approximately 1 °C since the beginning of the 20th century, as have annual mean air temperatures over Wales, Northern Ireland and Scotland. Although *Charting Progress* (Defra et al., 2005) reported a change of 0.5 °C in CET, more very warm years in CET since then have affected trend assessments. The warmest year in CET since records began in 1659 was in 2006 (section 4.2).
- The phase of the North Atlantic Oscillation (NAO) can affect the weather and climate of the UK and varies on periods of days to years. Over the past five years, the NAO has been in a positive phase, which leads to stronger winter westerly winds. The average number of storms in October to March recorded at UK stations has increased significantly over the past 50 years. However, the magnitude of storminess had similar values at the start and end of the 20th century (section 3).
- There remains a tendency towards wetter winters in north and west Scotland. Two out of the five wettest UK summers since records began in 1766 occurred in 2007 and 2008 (section 4.4).
- Global surface temperature (assessed using a combination of changes in air temperatures over land and sea surface temperatures) has increased by about 0.75 ± 0.2 °C since the late 19th century, 0.15 °C more than estimated in *Charting Progress*. All ten warmest years (globally) since records began in 1850 have occurred in the 12-year period 1997–2008 (section 4.1).
- Over the 21st century: all areas of the UK are predicted to get warmer, and the warming is predicted to be greater in summer than in winter; there is predicted to be little change in the amount of precipitation that falls annually, but it is likely that more will fall in the winter, with drier summers, for much of the U.K. (section 5).

iv. What has driven change?

Most of the observed increase in global average temperatures since the mid-20th century is very likely to be due to the observed increase in anthropogenic greenhouse gas concentrations in the atmosphere (IPCC, 2007).

v. What are the uncertainties?

The density of observations in space and time affects the accuracy of reported variability and trends; in particular, a reduction in the number of Voluntary Observing Ships has led to reduced confidence in trends in marine air temperature. Uncertainties in future projections result from imperfect knowledge of future greenhouse gas emissions, representation of climate processes in climate models and the effects of natural internal variability of the climate system.

vi. Forward look

To continue these assessments into the future, the existing observing array needs to be maintained. Uncertainties would be reduced by increasing the quality and quantity of meteorological observations.

2. Introduction

Here, the term *weather* is used to describe atmospheric changes which occur on time scales of up to about a week and *climate* to refer to those changes with timescales of a month to century or more; i.e. climate can be thought of as the average weather.

The three main weather parameters that drive ocean circulation are wind speed and direction, air/sea heat exchange and evaporation/precipitation. They affect the strength and character of the Atlantic thermohaline circulation, thereby altering the distribution of sea surface temperature and salinity on a broad scale.

On a local scale, the same parameters affect the distribution of temperature and salinity in UK waters. For example, stronger or more frequent westerly winds over the North Atlantic in winter will bring more rainfall and warmer air to the UK. Higher rainfall will result in lower salinities in coastal waters due to increased river runoff and this will enhance density driven coastal flows. The warmer air will warm the shallower areas of UK waters or at least slow their cooling. Water transport times through the Irish Sea and North Sea are of order one year or longer, whereas shallow-sea temperature adjusts to the atmosphere in a few months; hence most UK waters (except near inflows) adjust fairly closely to local atmospheric conditions (Sharples et al., 2006).

Changes in atmospheric pressure and wind speed and direction, particularly during storms, enhance the generation of surge levels, waves and associated currents; thus enhancing coastal erosion, flooding and mixing processes.

Rainfall affects the input of inorganic and organic terrestrial material from the land to the sea via rivers.

The Met Office Hadley Centre monitors a broad range of climate variables and indices. Meteorological variables (including air temperature, dew point, pressure, wind speed and direction) are measured routinely at a dense network of land stations. International agreements (e.g. through the World Meteorological Organisation – WMO) provide access to global data. At sea, meteorological data come from drifting buoys, Voluntary Observing Ships (VOS) and Marine Automatic Weather Stations (MAWS). The VOS Scheme is an international programme recruiting ships to record and transmit weather observations while at sea. There are presently about 400 ships in the UK fleet; coverage is global. The Met Office is one of two Global Collecting Centres for marine meteorological data. A network of MAWS includes eleven moored buoys, nine of which are in open-ocean locations mostly near the edge of the continental shelf to the west of the British Isles (Gascogne, K1, K2, K4, RARH, K3, Brittany, K5, K7), and two in coastal inshore waters (Aberporth, Turbot Bank). Additionally there are Island Stations (North Rona, Sule Skerry and Foula) and Light Vessels equipped with automated marine sensors (Seven Stones, Channel, Greenwich, Sandettie and F3). Meteorological and oceanographic variables (air temperature, dew point, pressure, wind speed and direction, maximum wind gust, visibility, sea temperature and wave height and period) are recorded at hourly intervals and the data transmitted to a meteorological database.

Descriptions of the monitoring networks that regularly measure marine weather data are given in the United Kingdom Directory of the Marine-observing Systems (UKDMOS) including details of how to access near real-time data: see www.ukdmos.org.

These data are used worldwide for climate monitoring and climate modelling, and in studies of the causes of climate change. The Met Office Hadley Centre produces and maintains a range of gridded datasets of meteorological variables for such use. These include, for the UK specifically: Central England Temperature (CET) – the longest continuous temperature record in the world (from 1659); gridded monthly temperatures over land; and national and regional precipitation series. Global data sets include: combined land and ocean analysis of surface temperature; sea-surface temperature and sea-ice analyses; sea-level pressure analyses; changes in indices of climate extremes for temperature and precipitation; and changes in upper-air temperature

2.1. El Niño Southern Oscillation

'El Niño' and 'La Niña' events are driven by a 'see-saw' of atmospheric pressure over the Pacific and Indian Oceans region, known as the Southern Oscillation. The term 'ENSO activity' is used to collectively describe the variability of the Southern Oscillation and associated El Niño and La Niña events. There is some evidence for an influence of ENSO on the North Atlantic and European weather, but this evidence is complex and requires careful analysis. For example, the effects of ENSO on the North Atlantic atmospheric circulation reverse between early winter and late winter (Fereday et al., 2008), so a whole-season analysis is likely to reveal no signal. There is a suggestion that the summer 2007 and 2008 conditions (jet stream and storm tracks further south than usual; frequent heavy rains over the UK) were associated with the La Niña then prevailing. There is also a correlation between the frequency and severity of tropical Atlantic storms and ENSO activity, with El Niño and La Niña events inhibiting or enhancing the activity respectively. Thus the number and severity of hurricanes and tropical storms in the North Atlantic Basin were above average in the La Niña years 2001, 2007 and 2008.

2.2 The North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is an important influence on the North Atlantic and European weather and climate. It is a 'see-saw' in atmospheric sea level pressure between the subtropical high and the polar low-pressure systems, most noticeable during November to April, which drives the strength of westerly winds over the North Atlantic.

During the winter season (December to February), the NAO accounts for more than one-third of the total variance in sea-level pressure (SLP) over the North Atlantic, and appears with a slight northwest-to-southeast orientation. In the so-called positive phase, higher-than-normal surface pressures south of 55° N combine with a broad region of anomalously low pressure throughout the Arctic to enhance the climatological meridional pressure gradient. The largest amplitude anomalies occur in the vicinity of Iceland and across the Iberian Peninsula. The positive phase of the NAO is associated with stronger-than-average surface westerlies across the middle latitudes of the Atlantic onto Europe.

By spring (March to May), the NAO appears as a north-south dipole with a southern centre of action near the Azores. The amplitude, spatial extent, and the percentage of total SLP variability explained by the NAO reach minima during the summer (June to August) season, when the centres of action are substantially north relative to winter. By autumn (September to November), the NAO takes on more of a southwest-to-northeast orientation, with SLP anomalies in the northern centre of action comparable in amplitude to those during spring.

The basic structure of the NAO arises from the internal, non-linear dynamics of the atmosphere. There is some evidence of a weak link between ENSO and the NAO (Fereday et al., 2008). The NAO is a regional expression of the see-saw of atmospheric pressure in the Northern Hemisphere, between the polar cap and the middle latitudes in both the Atlantic and Pacific Ocean basins, termed the Arctic Oscillation (Ambaum et al., 2001).

2.2.1 The NAO Index

The NAO's intensity is traditionally defined using a monthly, seasonal or annual index calculated as the normalized sea level pressure difference between a station characteristic of the subtropical high (Gibraltar or Lisbon or Ponta Delgada, Azores) and one characteristic of the polar low (Akureyri or Stykkisholmur, Iceland). Section 2.2.3 uses the NAO winter index from www.metoffice.gov.uk/climatechange/science/monitoring/indicators.html (but see *Charting Progress* for a discussion about slightly different NAO indices).

In winter, a positive index indicates a stronger than usual subtropical high-pressure centre and a deeper than normal Icelandic low. The increased pressure difference results in more and stronger storms crossing the Atlantic Ocean on a more northerly track, with increased mid-latitude westerly winds over the NE Atlantic and northern Europe. This results in mild and wet winters in the UK and northern Europe (Hurrell, 1995). A negative index in winter indicates a weak subtropical high and a weak Icelandic low pressure. The reduced pressure gradient results in weaker westerly winds and more occurrences of easterly winds. Anticyclones can dominate and winters become colder than normal in the UK and northern Europe. Positive index years are associated with winter warming in the southern North Atlantic and northwest European shelf seas, and with cooling in the Labrador and Nordic Seas; negative index years generally show the reverse. In summer, changes in the NAO index correspond to a see-saw in pressure between the northern UK–southern Scandinavian region and Greenland (Folland et al., 2009). When the summer NAO index is positive, northern Europe becomes warmer and drier while the Mediterranean is wetter than usual; when the summer NAO index is negative, these patterns are reversed.

2.2.2 NAO trends

There was a marked rise in the winter NAO index between the 1960s and the early 1990s, giving strengthened westerly winds, but there has since been a slight decline (Figure 1.1). The NAO index in the early 20th century also tended to be positive, with values typically similar to those in the 1990s. The 1960s were generally negative index years, with associated very weak westerly winds; whereas the 1980s and early to mid-1990s were generally positive index years, with associated very strong westerly winds and relatively mild and wet winters over NW Europe. Long instrumental records and palaeoclimatic reconstructions of the NAO using ice cores and tree ring chronologies indicate several earlier periods of comparable values over the past 500 years.

The 1960s-1990s rise in the NAO index is fairly unusual but, in view of the subsequent slight decline, might be part of a natural cycle. However, it was associated with a stratospheric trend toward much stronger westerly winds encircling the pole and an anomalously cold polar stratosphere (Thompson et al., 2003). Reductions in stratospheric ozone and increases in greenhouse gas (GHG) concentrations enhance the meridional temperature gradient in the lower stratosphere, via radiative cooling of the wintertime polar regions, implying a stronger polar vortex. It is possible, therefore, that the overall rise in the winter NAO index in recent decades is associated with trends in either or both of these trace-gases quantities. Gillett et al. (2003) examined 12 coupled ocean-atmosphere models and found that nine showed an increase in the winter NAO Index in response to increasing GHG concentrations, leading them to conclude that increasing GHG concentrations have contributed to a strengthening of the North Atlantic surface pressure gradient. Scaife et al. (2005) showed that the rise in the winter NAO could only be reproduced in climate model simulations with observed sea surface temperatures and GHG concentrations if observed trends in winds in the lower stratosphere were also imposed. Accordingly, the observed stratospheric circulation has had a major indirect influence on regional winter climate over eastern North America, the North Atlantic, and Europe.

The summer NAO index has tended to be more positive since the late 1960s than in the previous 100 years (Folland et al., 2009). However the index has been negative in some recent years (e.g. 2007 and 2008) and summers in south-east England have been wetter.

2.2.3 Effects of the NAO on ocean processes and climate parameters

The NAO changes the strength and direction of the winds over the North Atlantic. Accordingly, changes in the NAO induce significant changes in ocean surface temperature and heat content, ocean currents and their related heat transport, and sea ice cover in the North Atlantic, as well as changes in weather over land. Relevant parameter chapters consider these effects in more detail.

Such climatic fluctuations affect agricultural harvests, water management, energy supply and demand, and fisheries yields; the NAO thus has significant impact on a wide range of human activities as well as on marine, freshwater and terrestrial ecosystems (Dickson and Meincke, 2003).

Winter is when the atmosphere is most active dynamically and perturbations grow to their largest amplitudes. As a result, the influence of the NAO on surface temperature and precipitation, as well as on ecosystems (section 2.2.4), is also greatest then. But Hurrell et al. (2003) and Folland et al. (2009) document significant interannual to multi-decadal fluctuations in the summer NAO pattern, including a trend toward persistent anticyclonic flow over northern Europe that has contributed to anomalously warm and dry conditions in recent decades. Moreover, Hurrell et al. (2003) stated that the winter NAO can interact with the slower components of the climate system (the ocean, in particular) to leave persistent surface anomalies throughout the year that may significantly influence the evolution of the climate system.

Changes in the mean circulation patterns over the North Atlantic associated with the NAO are accompanied by changes in the intensity and number of storms, their paths, and their weather. During winter, a well-defined storm track connects the North Pacific and North Atlantic basins, with maximum storm activity over the oceans (Hurrell et al., 2003). Generally, positive NAO index winters are associated with a northeastward shift in the Atlantic storm activity with enhanced activity from Newfoundland into northern Europe and a modest decrease in activity to the south. Positive NAO index winters are also typified by more intense and frequent storms in the vicinity of Iceland and the Norwegian Sea.

The winter NAO has a substantial influence on hemispheric temperature. Hurrell (1996) showed that much of a local cooling in the NW Atlantic and the warming across Europe and downstream over Eurasia resulted directly from decadal changes in the North Atlantic atmospheric circulation in the form of the NAO, and that the NAO accounted for 31% of the wintertime interannual variance of Northern Hemisphere extratropical temperatures over the latter half of the 20th century. Moreover, changes in the atmospheric circulation associated with the NAO accounted for much of the hemispheric winter warming through the mid-1990s. However, the warmth of the most recent winters is beyond that which can be explained by changes in the NAO; for example, some recent winters in Central England have been exceptionally warm without a correspondingly exceptional NAO (Figure 1.1).

The NAO controls or modifies three of the main parameters that drive ocean circulation: wind velocity, air/sea heat exchange and evaporation/precipitation. Changes in the NAO are also reflected in sea surface temperature, for example accounting for 40% to 50% of the variability in winter sea surface temperatures in the southern North Sea (Loewe, 1996). Subsurface ocean observations over the North Atlantic indicate fluctuations that are coherent with the low frequency winter NAO index to depths of 400 m (Curry and McCartney, 2001).

The oceanic response to NAO variability is also evident in changes in the distribution and intensity of winter convective activity in the North Atlantic. The intensity of wintertime convective renewal of intermediate and deep waters in the Labrador Sea and the Greenland-Iceland-Norway Seas, for instance, is not only characterized by large interannual variability, but also by inter-decadal variations that appear to be synchronized with variations in the NAO (Dickson et al., 1996). These changes in turn affect the strength and character of the Atlantic thermohaline circulation and the horizontal flow of the upper ocean, thereby altering the oceanic poleward heat transport and the distribution of sea surface temperature.

There are past occurrences of low salinity anomalies that propagate around the sub-polar gyre of the North Atlantic – the most famous example being the Great Salinity Anomaly (Dickson et al., 1988). This formed during the extreme negative index phase of the NAO in the late 1960s, when clockwise flow around anomalously high pressure over Greenland fed record amounts of freshwater from the Arctic Ocean through the Fram Strait into the Nordic Seas. From there some of the fresh water passed through the Denmark Strait into the sub-polar North Atlantic Ocean gyre. There have been other similar events and statistical analyses have revealed that the generation and termination of these propagating salinity modes are closely connected to a pattern of atmospheric variability strongly resembling the NAO.

Wakelin et al. (2003) have shown that winter-mean (December to March) sea levels and the NAO index are significantly correlated over much of the northwest European shelf.

The recent more positive NAO index winters have been associated with increased wave heights over the NE Atlantic and decreased wave heights south of 40° N (Bacon and Carter, 1993; Kushnir et al., 1997). There is a strong link between the NAO and the wave climate to the north and west of the British Isles, but not to the east (Cotton et al., 1999; Woolf et al., 2002, 2003).

2.2.4 Effects of the NAO on non-ocean processes and climate parameters

This section provides a brief description of the effects of the NAO on non-ocean processes and climate parameters; see other sector reports for more details.

Changes in the NAO have been associated with a wide range of effects on the marine ecosystem, including changes in the production of plankton and the distribution of different fish species. For example, the northward shift of phytoplankton and zooplankton in the NE Atlantic over the past 40 years, and recent visits to UK waters by warm-water fish such as sailfin dory (*Zenopsis conchifer*), blue marlin (*Makaira nigricans*) and barracuda (*Sphyraena sphyraena*), have been linked to the general rise in temperature in the Northern Hemisphere along with the additional effect of the NAO, which in recent years has brought warmer conditions to the region (Beaugrand et al., 2002; ICES, 2003).

According to Hurrell et al. (2003), fluctuations in temperature and salinity, vertical mixing, circulation patterns and ice formation induced by variations in the NAO have a demonstrated influence on the marine ecosystem through direct and indirect pathways. Drinkwater et al. (2003) stated that there are three possible pathways by which the NAO affects marine ecosystems. One pathway is the effect of NAO-induced temperature changes on metabolic processes such as feeding and growth. Because the NAO can simultaneously warm ocean temperatures in one part of the Atlantic basin and cool them in another, its impact on a single species can vary geographically. An example is the out-of-phase fluctuations in year-class strength of cod (*Gadus morhua*) between the NE Atlantic and NW Atlantic. More complex pathways may involve several physical and biological steps, for example the intense vertical ocean mixing generated by stronger-than-average westerly winds during a positive NAO index winter. This enhanced mixing delays primary production in the spring and leads to less zooplankton (e.g. Fromentin and Planque, 1996), which in turn results in less food and eventually lower growth rates for fish. Another pathway occurs when a population is repeatedly affected by a particular environmental situation before the ecological change can be perceived (biological inertia), or when the environmental parameter affecting the population is itself modulated over a number of years. For example, spring replenishment of *Calanus finmarchicus* in the North Sea depends on: (1) deep over-wintering stock in the Faroe–Shetland Channel, affected by long-term decline in overflow of Norwegian Sea Deep Water; and (2) transport into the North Sea, depending on north-westerly winds. These winds have declined overall since the 1960s but also vary from year to year without corresponding interannual changes in *C. finmarchicus* abundance in the North Sea (Heath et al., 1999).

3. Progress since *Charting Progress*

The decline in the fleet of Voluntary Observing Ships has impaired the ability to measure marine air temperature both globally and regionally and has increased uncertainties. The National Oceanography Centre analysis used in Section 4.2 is based on these observations. Apart from moored buoys, these ships are the only means of measuring marine air temperature.

There have been some developments in understanding since *Charting Progress* (Defra et al., 2005).

- Stratospheric circulation is now known to have a major indirect influence on regional winter climate over eastern North America, the North Atlantic, and Europe.
- There is some suggestion that conditions in summer 2007 and 2008 were associated with the La Niña then prevailing.
- Extending the record of storminess back to the beginning of the 20th century has shown that storminess at the beginning of the century was similar to that at the end.

Some changes in observational evidence, or record breaking values have occurred.

- Central England Temperature has increased by approximately 1 °C since the beginning of the 20th century. *Charting Progress* reported 0.5 °C; some more very warm years in CET since then have affected trend assessments.
- The warmest year in Central England Temperature since records began in 1659 was 2006.
- Two of the five wettest summers since records began in 1766 occurred in 2007 and 2008.
- Global surface temperature has increased by about 0.75 ± 0.2 °C since the late 19th century, 0.15 °C more than estimated in *Charting Progress*
- All ten warmest years since records began in 1850 have occurred in the 12-year period 1997–2008.

4. Presentation of the evidence

4.1 Global temperature

Northern Hemisphere, Southern Hemisphere and Global average near-surface temperature annual anomalies, from 1861 to 2009, have been compiled by the Hadley Centre and the University of East Anglia's Climate Research Unit from regular measurements of air temperature at land stations and sea surface temperatures measured from ships and buoys (Brohan et al., 2006). See for example, www.metoffice.gov.uk/climatechange/guide/bigpicture/fact2.html .

Global surface temperature has increased by about 0.75 ± 0.2 °C since the late 19th century; the warmth of the past half century is unusual in terms of at least the past 1300 years, and most of the observed increase in global average temperatures since the mid 20th century is very likely to be due to the observed increase in anthropogenic greenhouse gas concentrations (IPCC, 2007).

All ten warmest years since records began in 1850 have occurred in the 12-year period 1997–2008. In some years global warming has been offset by cooling due to factors such as La Niña events and aerosol emissions from volcanoes. For example, the eruption of Mount Pinatubo in June 1991 was followed by a 0.5 °C decrease in mean global annual temperature, and a La Niña event has been a cooling factor in 2008, even though that year was the 10th warmest on record.

4.2 UK temperature

The Central England Temperature (CET) record is the longest continuous record of measured surface air temperatures in the world. It is compiled from records in a roughly triangular area enclosed by Bristol, Manchester and London (Parker et al., 1992); and annual temperature fluctuations in this region are considered to be representative of those in most of the UK. The monthly series began in 1659 and daily records extend back to 1772. Since the beginning of the 20th century, the annual mean CET has increased by about 1 °C. The warmest year since records began in 1659 was in 2006. Despite the large variability in the CET record, nine of the ten warmest years have occurred in the 20-year period 1989–2008 and six of these have occurred in the period 1997–2008.

2003 saw the highest UK temperature ever recorded, in excess of 38 °C at several locations. Annual mean temperatures in Wales, Northern Ireland and Scotland have also increased by about 1 °C since the early 20th century. There is a high correlation between winter UK temperatures and the winter NAO; for example, the cold winter of 1995/96 was associated with the lowest value on record of the NAO index.

CET annual anomalies from 1772 to 2008 are available at www.metoffice.gov.uk/climatechange/science/monitoring/hadcet.html .

Recent trends in temperature throughout the UK were documented fully by Jenkins et al. (2009). Mean temperatures in Scotland and Northern Ireland have risen by about 0.8 °C since 1980, somewhat less than the CET (Jenkins et al., 2009).

Comparison of marine air temperatures (Berry and Kent, 2009) with CET in Figure 1.2 shows the marine temperatures to have a slightly smaller and delayed annual cycle, smoother variation in 2007 but similar if perhaps smaller trend from the 1970s to the decade 1998-2007..

The evolution of annual averages of these quantities over the last four decades is shown in Figure 1.3. As for land air temperature, the recent trend of marine air temperature near Scotland is less than that generally in the region, but variations over several years are strongly correlated; temperatures are lower in the north.

An overview of recent marine air temperature trends for the wider North Atlantic region is given in Figure 1.4, showing larger positive trends with greater probability near the UK than to the north or south.

The Met Office has developed a number of early warning systems to help reduce the effects of natural disasters, such as flooding due to storms and abnormally high sea levels. One such system is the network of Marine Automatic Weather Stations (MAWS) which are deployed mainly on the edge of the UK continental shelf. The network includes eleven moored buoys, nine of which are in open-ocean locations mostly to the west of the British Isles, and two in coastal inshore waters. Figure 1.5 shows air temperature as measured from a selection of these buoys. Additional data have been obtained from oil and gas platforms in the North Sea and from Hilbre (courtesy of NOC). The data are quality controlled and filtered using a running/boxcar 30-day mean. The buoys furthest from land are seen to have a lower annual cycle than those closer to land. In some locations (e.g. Sandettie) year-to-year variability is greater than in others (e.g. K4).

4.3 UK wind

An examination of extreme storms (as detected by rapid 3-hourly pressure changes) during autumn and winter across the British Isles over the past 85 years (Allan et al., 2008) has shown that large-scale natural climate variability plays an important role in modulating these events. Pressure changes were used instead of winds because the results are less sensitive to site moves and instrumentation changes. Severe storms across the British Isles were most prominent in the 1920s and 1990s in autumn, and in the 1920s, 1980s and 1990s in winter. The winter NAO had a significant but historically-varying influence on the incidence of severe storms, in autumn the relationship between storms and the NAO was weaker than in winter. So the severe storms over the UK are often related to strong local gradients of pressure as well as to the large-scale pressure differences over the Atlantic. Similar conclusions were drawn by Alexandersson et al. (2000) and updated in the IPCC Fourth Assessment Report (IPCC, 2007; see Figure 1.6).

Weisse et al. (2005) simulated the storm climate of the NE Atlantic and the North Sea with a regional climate model for the period 1958–2001, driven by the U.S. National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis. It was found that the average number of storms per year increased from 1958 near the exit of the North Atlantic storm track and over the southern North Sea. The average number of storms per year has been decreasing over the NE Atlantic since about 1990–1995.

Summers 2007 and 2008 experienced the jet stream and storm tracks further south than usual, and frequent heavy rains over the UK, perhaps associated with La Niña then prevailing.

Identification of wind speed trends using station records can be difficult because of changes in site exposure and instrumentation. Those included for well-exposed sites in a study of climate trends across Scotland (Barnett et al., 2006) showed conflicting trends for the past 40 years in annual mean wind speed and no trend in gales.

Figure 1.7 shows wind speed as measured from a selection of the MAWS network, oil and gas platforms in the North Sea and Hilbre. The data are quality controlled and filtered using a running/boxcar 30-day mean. Data sources are as for Figure 1.5. Most series show variation with season, at shorter periods and inter-annually, obscuring any trend.

4.4. UK precipitation

Compiled by the Met Office and the University of East Anglia, the monthly time-series of England and Wales total precipitation (Alexander and Jones, 2001) begins in 1766 and is the longest instrumental series of this kind in the world. It is currently based on weighted averages of daily observations from a network of stations in five regions. The England and Wales precipitation annual totals for 1766–2008 are shown at www.metoffice.gov.uk/climatechange/science/monitoring/hadukp.html . They show interannual variability of the order of 10%, no significant overall trend but a decrease from above-average values in the late 1990s to near-average values since then (to 2008).

Recent trends in precipitation across the UK are described in the UKCP09 report (Jenkins et al., 2009). This confirms a tendency towards wetter winters in north and west Scotland; but comments that a previously reported tendency to drier summers in south-east England appears to be lessening (see also Figure 1.8, taken from Folland et al., 2009). Note however, that this comment is based on only a couple of years and interannual variability is high.

The May–July 2007 precipitation across England and Wales was the greatest on record for those months in a series from 1766 (see www.metoffice.gov.uk/climate/uk/interesting/may_july2007/index.html). The UK had its second-wettest summer in 2007 and its fifth-wettest in 2008, in a series from 1914. In 2008 Northern Ireland had its wettest August and its second-wettest summer, just behind summer 1958, also in a series from 1914 (see www.metoffice.gov.uk/climate/uk/2008/summer.html).

5. What the evidence tells us about environmental status

There is most confidence in trends shown by global annual-mean temperature. Thus global surface temperature (assessed using a combination of changes in air temperatures over land and sea surface temperatures) has increased by about 0.75 ± 0.2 °C since the late 19th century; all ten warmest years since records began in 1850 have occurred in the 12-year period 1997–2008.

Regionally, for the UK since the beginning of the 20th century, the annual means of Central England Temperature (CET), and of temperatures in Wales, Northern Ireland and Scotland, have increased by about 1 °C. The warmest year since CET records began in 1659 was in 2006; nine of the ten warmest years occurred in the 20-year period 1989–2008. Marine air temperature around and especially north of Scotland has risen less than CET.

There is significant variability from place to place. For example, some locations show a correlation between winter temperatures and the winter NAO: there is a contrast between the winters of 2006 (NAO index neutral) and 2007 (warmer, NAO index positive) in the Marine Automatic Weather Stations (MAWS) close to land. However, these winter temperatures hardly differed at MAWS further out to sea.

Interannual variability reduces the ability to discern trends. For example, in Figure 1.2, the standard deviation for any month within a decade is of comparable size to the difference between the two decades 1970–1979 and 1998–2007.

Although winds are well measured, their variability on short time and space scales makes it difficult to form representative statistics. Storminess and NAO are indicators of different aspects of wind strength. Both show an overall decline in the first half of the 20th century and a rise from the 1960s to 1990s restoring early-20th century values. However, they do not correlate exactly; severe storms over the UK are often related to strong local gradients of pressure as well as to large-scale pressure differences (as NAO) over the Atlantic. The relationship between storms and the NAO is weaker in autumn than in winter.

Recent trends in precipitation show a tendency towards wetter winters in north and west Scotland. Summers 2007 and 2008 experienced the jet stream and storm tracks further south than usual, and frequent heavy rains over the UK, perhaps associated with La Niña then prevailing.

The summary table (Table 1.1) includes an assessment of trend but not status (‘traffic-light’) because (1) no accepted criteria apply for weather and climate giving significant risk of adverse effects; and (2) the UK (government), or even the EU, cannot itself take measures to improve the status.

Table 1.1 Summary assessment of trends.

Parameter	**CP2 Region**	**Key factors and impacts**	**What the evidence shows**	**Trend**	**Confidence in assessment**	**Forward look**
Weather and Climate	All: 1-8	(Global) climate, location. Affects sea level, waves, salinity, temperature, circulation; biodiversity, species range	Variable interannually	Warming; unclear for wind, rain	High	Continued warming

Weather is subject to a wide range of natural variability on time-scales ranging from hours to interannual periods. Climate change governs the risk that should be attached to weather. Since pre-industrial times, climate change has been most clearly apparent in a mean temperature rise of the order of 1 ºC, which gives comparable change in shelf-sea temperatures. There are changes to the character of storms on interannual to decadal time-scales, but longer-term or future climate-related trends are not clear. Seasonal ranges are much greater than changes to date, and interannual variability somewhat greater. However, larger and faster temperature rises in future are likely and will make adaptation (natural or managed) more difficult.

The UK Climate Projections 2009 report (UKCP09) provides probabilistic projections for future UK climate under three possible greenhouse gas emissions scenarios (denoted low, medium and high, see UKCP09 report at http://ukclimateprojections.defra.gov.uk/ for details). Probabilistic projections account for uncertainties arising from the representation of climate processes and the effects of natural internal variability of the climate system. Effects of an expected gradual weakening of the Atlantic Ocean circulation over time are included. Projections have been produced for UK regions and for surrounding marine regions (see http://ukclimateprojections.defra.gov.uk/).

Headline results from UKCP09 for the 21st century are as follows.

- All areas of the UK are projected to get warmer, and the warming is projected to be greater in summer than in winter.
- There is projected to be little change in the amount of precipitation that falls annually, but it is likely that more will fall in winter, with drier summers, for much of the UK.

Figure 1.9 shows projections of mean air temperature changes, relative to 1961–1990, for UK marine regions under the 'high' emissions scenario, for 30-year periods centred on 2020, 2050 and 2080. The three levels of confidence shown (10%, 50%, 90%) can be translated respectively as: not likely to be less than, central estimate and not likely to be greater than, respectively. The figure shows sustained warming, greater in the south and east. Similar all-year means for precipitation show few changes with time, but season- and month-specific projections for marine and land areas, providing detail to the headline result above, can be generated using the UKCP09 User Interface (see http://ukclimateprojections.defra.gov.uk/).

6. Forward look and need for further work

The main focus of future research into understanding UK climate on seasonal and decadal timescales is likely to be as follows.

- What are the factors that determine wintertime NAO variability on seasonal timescales and its decadal trends? Certain things are known to have an effect, for example the quasi-biennial oscillation in the stratosphere and ENSO. It is thought that North Atlantic sea surface temperature also plays a role, but this is currently hard to reproduce in climate models; this difficulty may be related to the spatial and/or temporal resolution of the simulations.
- What are the origins of decadal variability of the NAO? To what extent have anthropogenic greenhouse gas emissions had an influence? To what extent is it predictable?
- What affects year-to-year variability in UK summer climate? How do the teleconnections between the tropics and Europe affect this? What is the role of land surface feedbacks?

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Figure captions

Figure 1.1. North Atlantic Oscillation (NAO) index, 1867-2009, based on the normalized pressure difference between Ponta Delgada (Azores) and Stykkisholmur (Iceland). Figure courtesy of the Met Office.

Figure 1.2. Monthly mean air temperatures for (a) UK coastal waters (7°W-3°E, 50°N-60°N) from the National Oceanography Centre analysis and (b) for the Central England Temperature. Shaded regions give the mean ± 1 standard deviation for 1970–1979 (red) and 1998–2007 (green). The dashed lines represent the minimum/maximum values and the black line represents the annual cycle from 2007. Figure courtesy of the National Oceanography Centre.

Figure 1.3. Time series of yearly mean marine air temperature estimated from the National Oceanography Centre air temperature analysis for UK shelf waters (7°W-3°E, 50°N-60°N, black), a 2° × 2° grid box in the North Sea (1°W-1°E, 56°N-58°N, red), a 2° × 2° box to the north east of Scotland (1°W-1°E, 60°N-62°N, green) and the Central England Temperature (blue). Figure courtesy of the National Oceanography Centre.

Figure 1.4. Colours show the 26-year linear trend in air temperatures estimated over the period 1982–2007 (°C/decade) from the National Oceanography Centre air temperature analysis. Contours are r-squared values and show where there is confidence in the trends; larger numbers indicate greater confidence. Figure courtesy of the National Oceanography Centre.

Figure 1.5. Air temperature (°C) measured by UK moored buoys (a) K4 at 55° 24'N, 12° 12'W; (b) K7 at 60° 36'N, 4° 54'W; (c) Aberporth at 52° 24'N, 4° 42'W; (d) Seven Stones Light Vessel at 50° 06'N, 6° 06'W; (e) Hilbre Island at 53° 23'N, 3°14' W; (f) Sandettie at 51° 06'N, 1° 48'E; (g) Leman Bank at 53° 03'N 2° 14'E; and (h) Alwyn at 60° 48'N ,1° 42'W. Data for all platforms other than Hilbre are courtesy of the Met Office, and come from moored automatic weather stations, and oil and gas platforms. Data for Hilbre are courtesy of National Oceanography Centre.

Figure 1.6. Storm index for the British Isles, North Sea and Norwegian Sea, 1881 to 2004. Blue circles are 95th percentiles and red crosses 99th percentiles of standardized geostrophic winds averaged over ten sets of triangles of stations. The smoothed curves are a decadal filter (updated from Alexandersson et al., 2000). Reproduced from IPCC (2007: figure 3.41 page 313).

Figure 1.7. Wind speed (m/s) at UK moored buoys (a) K4 at 55° 24'N, 12° 12'W; (b) K7 at 60° 36'N, 4° 54'W; (c) Aberporth at 52° 24'N, 4° 42'W; (d) Seven Stones Light Vessel at 50° 06'N, 6° 06'W; (e) Hilbre Island at 53° 23'N, 3°14'W; (f) Sandettie at 51° 06'N, 1° 48'E; (g) Leman Bank at 53° 03'N 2° 14'E; and (h) Alwyn at 60° 48'N ,1° 42'W. Data for all platforms other than Hilbre are courtesy of the Met Office, and come from moored automatic weather stations, and oil and gas platforms. Data for Hilbre are courtesy of National Oceanography Centre.

Figure 1.8. The Summer North Atlantic Oscillation and July-August England and Wales rainfall, 1850–2008. The rainfall data have been reversed in sign and both series are standardised over 1850–2008. The smooth lines are low pass filtered for periods >25 years. Figure courtesy of the Met Office.

Figure 1.9. Projections for mean air temperature changes in future 30-year periods in UK marine areas (°C relative to 1961–1990) assuming a ‘high’ emissions scenario (see http://ukclimateprojections.defra.gov.uk/). Periods are centred on: top: 2020; middle: 2050; bottom: 2080.

Confidence intervals: left: not likely to be less than; middle: central estimate; right: not likely to exceed.
Source: UKCP09, http://ukclimateprojections.defra.gov.uk/