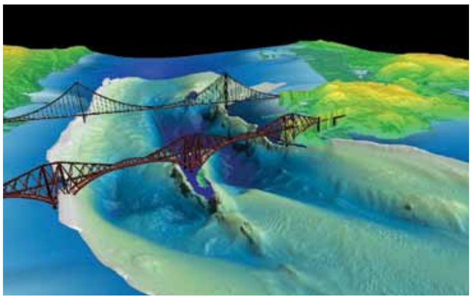
Charting Progress 2

Feeder Report: Ocean Processes



UKMMAS
United Kingdom Marine Monitoring & Assessment Strategy

Charting Progress 2

Feeder Report: Ocean Processes

Preface

Charting Progress 2 seeks to show the extent to which the UK Government and the Devolved Administrations are making progress towards their vision of achieving clean, healthy, safe, productive and biologically diverse oceans and seas as set out in *Safeguarding our Seas*, published in 2002. It builds on *Charting Progress*, the first assessment of the UK Seas, published in 2005, and its delivery is the responsibility of the United Kingdom Marine Monitoring and Assessment Strategy (UKMMAS) community which was set up in response to a recommendation in *Charting Progress* to provide a more coordinated approach to the assessment and monitoring of the state of the UK marine environment. UKMMAS created four evidence groups (the Healthy and Biologically Diverse Seas Evidence Group – HBDSEG; the Clean and Safe Seas Evidence Group – CSSEG; the Productive Seas Evidence Group – PSEG; the Ocean Processes Evidence Group – OPEG) to collect the evidence needed to assess progress towards achieving the vision. Each evidence group has a broad membership across the academic and research communities as well as experts in government agencies and non-governmental organisations and was tasked to produce a 'Feeder Report' assessing all the evidence available under its remit which could be used as source material for the evidence chapters in the main *Charting Progress 2* report.

This Feeder Report forms the OPEG contribution to *Charting Progress 2* and provides a context for the clean, healthy, safe, productive and biologically diverse aspects in the other Feeder Reports. Key contributors are listed at Pages 255 and 256.

The authors of this report are responsible for all the information, including all data, technical information and graphic material, contained within this report, including the referencing, correct use and accuracy of such information.

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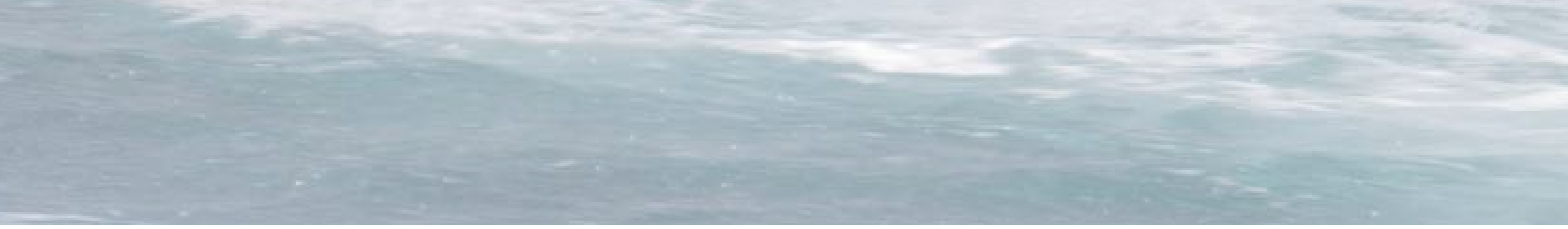


Executive Summary

The state of the physical environment sets the context for the overall UK vision of ‘clean, healthy, safe, productive and biologically diverse oceans and seas’. Weather, climate and ocean processes form the context for the marine ecosystem, all marine activities and management. Knowledge and understanding of the physical marine environment are needed for planning, for safe operations at sea and to sustain a healthy and productive ecosystem.

Some aspects of the physical environment can be managed directly on scales up to a few kilometres. On larger scales, there is strong dependence on weather and climate. NE Atlantic conditions largely control salinity, sea level, tidal elevations, currents and waves in UK seas. Climate change is an important factor.

Developments in monitoring programmes and networking are improving data availability. For example, more Argo profiling floats enable better forecasts of North Atlantic state, the RAPID array monitors the North Atlantic Meridional Overturning Circulation (AMOC) that generates the UK’s maritime climate, and a programme to measure seawater pH and carbon dioxide (CO_2) concentrations has been started in view of concern about ocean acidification. The National Centre for Ocean Forecasting provides operational forecasting of currents, storm surges, waves, temperature, salinity and ecosystem variables, for example primary production. Model predictions aid and benefit from improved scientific understanding, such as the significance of local weather for shelf-sea temperatures. Ensembles of scenarios enable a fuller account of future climate impacts.

Variability is a feature of the marine physical environment. The largest changes in temperature and monthly-averaged wave height are between winter and summer. Salinity near rivers depends on recent outflows, circulation depends on winds in the previous few hours or days, suspended matter depends on recent waves and currents. Changes from year to year typically exceed changes from any trend over the previous three decades.

This Feeder Report covers weather and climate, sea temperature and salinity, CO_2 and pH (for acidity), circulation, sea level, waves, suspended particulate matter and morphology. The main emphasis of the report is on trends and variability. Some of the main findings are as follows.

- Annual mean Central England Temperature has risen by about 1 °C since the beginning of the 20th Century; likewise annual mean air temperatures in Wales, Northern Ireland and Scotland. Over the 21st century, all areas of the UK are predicted to get warmer.
- Annual sea-surface temperature averaged around the UK coastline has risen by about 0.5 °C to 1 °C for the period 1871 to 2000; most coastal sites show an upward trend. Much of the warming has been since the mid-1980s.
- In future, shelf-sea temperatures are likely to follow the atmospheric climate quite closely.

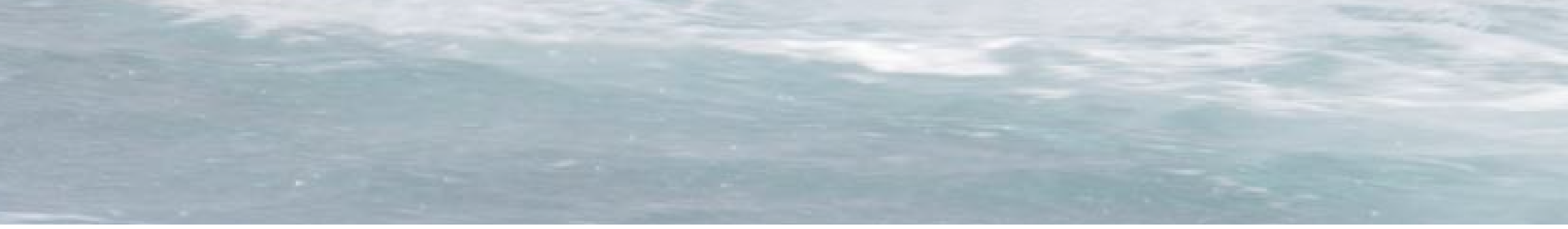
- The range of salinity variation is effectively small except in regions affected by river or estuarine inputs. Seasonal and inter-annual variability exceed any trend.
- The North Atlantic appeared to reduce its net uptake of CO_2 by more than 50% from the mid-1990s to 2005. However, this may be part of a natural cycle rather than a one-way trend. Calculations based upon the IPCC (Intergovernmental Panel on Climate Change) 'business as usual' scenario indicate that by around 2100 the average pH of the surface ocean will have decreased by 0.3, i.e. a doubling of the acid (active hydrogen ion) content.
- Baseline measurements of pH, against which to judge changes in UK waters, are not available.
- The AMOC is very variable on time-scales of weeks to months. Climate models suggest that AMOC is very likely to decrease over the next century, but not 'shut down' completely.
- In UK shelf seas, residual flow or circulation (forced by tides, wind and differences in density) can be very variable, on various time-scales. Transports of water in one storm can be significant relative to a year's integrated transport.
- Sea level around the UK coast rose on average by about 1.4 mm/y during the 20th Century, but with periods of faster or slower rise, for example, 3 to 4 mm/y in the 1990s.
- Global sea level is projected to rise in the 21st century by 0.18 to 0.59 m, plus an uncertain amount arising from dynamic instability of ice sheets. Predictions for the UK are comparable.
- Long-term changes in extreme sea levels appear to behave similarly to mean levels.
- Mean winter wave height in the NE Atlantic increased significantly between the 1960s and the early 1990s; subsequent trends are not clear and may depend on region.
- Suspended Particulate Matter concentrations and therefore turbidity for UK waters show much variability but no significant recent trend.
- There is extensive coastal erosion around the UK and decrease of the intertidal area, at least in part caused by the presence of 'hard' coastal defences. This in turn is causing loss of land and properties and loss of habitat, particularly saltmarsh and mud flats, which are also bird feeding grounds.

There are summary reports for the eight CP2 Regions. However, many controls (weather, water depth, distance from the open Atlantic) on ocean process variables cut across regions. The spatial scales of weather, sea level and temperature climate are larger than the CP2 Regions.

For the future, estimates of the marine physical environment in reasonable detail are likely to depend on models (in effect interpolating and predicting from available data). This applies to temperature, salinity, currents, day-to-day surface elevations and waves, in time and space. Models will also provide the means to see how drivers (ocean acidification, climate change, etc.) and changes in pressures (e.g. fishing, pollution) may interact to modify ecosystem responses.

Future needs for data emphasise sustaining for now the present intensity of measurements, building up monitoring of pCO_2 and pH, and the need for long consistent time series. Research is needed to understand shorter-term variability, enabling more confident estimates of longer-term trends, and to estimate (by experiments with tested models) what future density and frequency of data provide the best (cost/benefit) value.

SECTION 1
INTRODUCTION



Introduction

The UK vision of clean, healthy, safe, productive and biologically diverse oceans and seas depends above all on the state of the physical environment. Variables such as ocean temperature, salinity, circulation, degree of acidification, sea level, strength of waves, turbidity and morphology, in turn set the context for the different components of the vision. For example, storms and currents affect habitats and offshore operations; acidification affects plankton physiology, especially calcification; sedimentary processes affect the distribution of hazardous material. Thus most ocean process variables are affected by climate and mediate how future climate change will affect the marine environment in many ways.

In this report prepared by the Ocean Processes Evidence Group, we assess the physical state of the UK seas and so provide a context for the clean, healthy, safe, productive and biologically diverse aspects in the other Feeder Reports.

In 2005, *Charting Progress* (Defra et al., 2005) reported evidence that climate change was affecting the marine ecosystem. In the physical environment it identified rising air and sea temperatures, increasing winter wave heights (to the mid-1990s), more frequent winter storms since the mid-20th century, and rising sea level as key evidence.

Since *Charting Progress* we have made considerable progress in our ability to assess the state of ocean process variables. This report builds on the findings of *Charting Progress* and addresses the state of ocean process variables in terms of the eight CP2 Regions (see Figure 1.1). Although the conclusions in this assessment generally reinforce those from 2005, recent awareness of ocean acidification, and concerns about the ability of our seas to continue to take up carbon dioxide from the atmosphere, means we have added this issue as an explicit topic.

We have based our assessment on a combination of direct measurements from ongoing and new monitoring programmes, understanding of processes, and models.

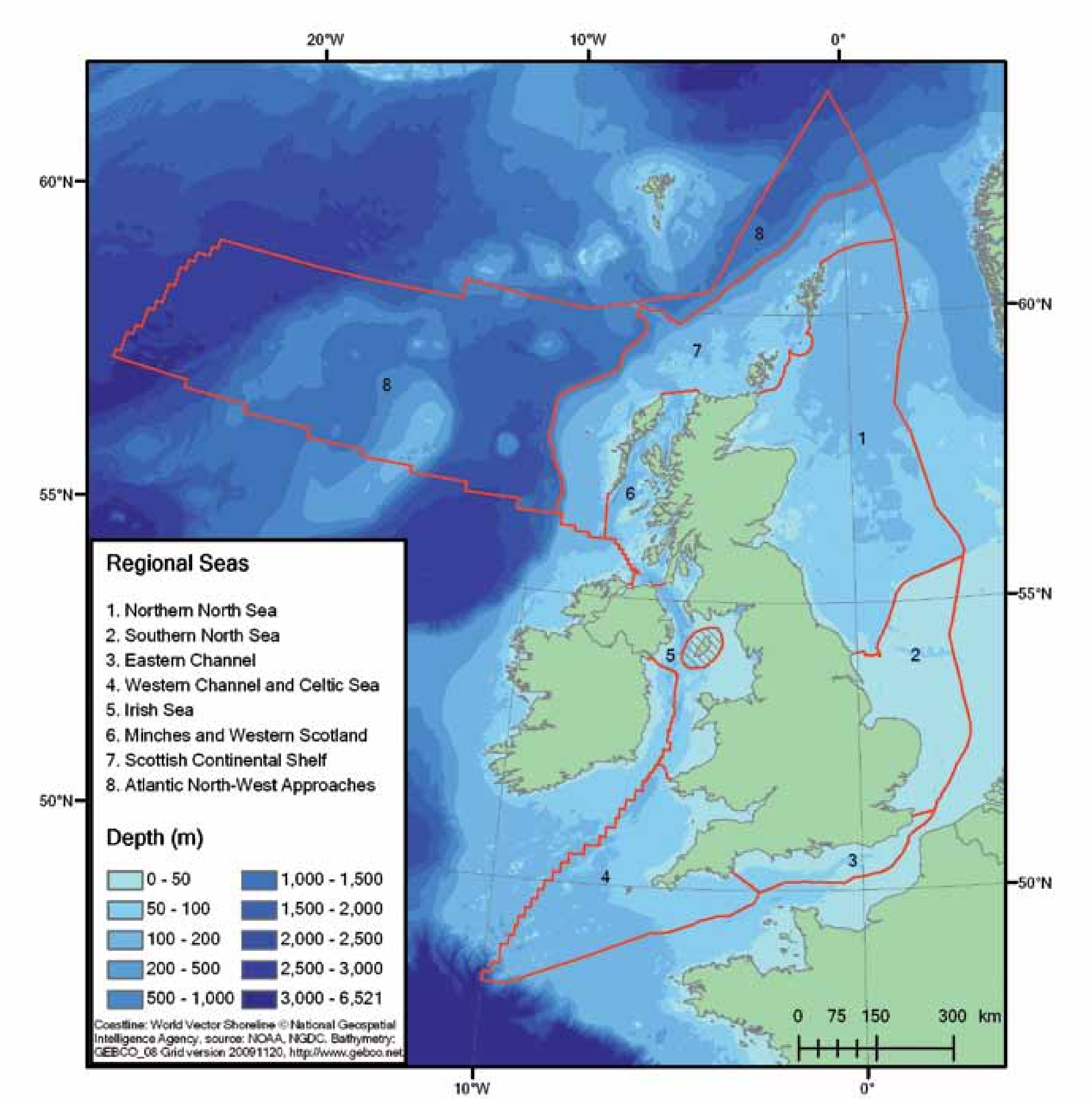
This combination is very powerful. The variables that define ocean processes – such as currents, storm surges, waves, temperature and salinity – are typically not distributed according to local inputs by humans but follow patterns that depend on physical laws. Therefore, we do not need to measure them at every point in order to assess the overall state. Rather we can obtain enough measurements to keep the forecast models on track, and then use the models to assess the state in places where there are few or no measurements. This ability has improved since *Charting Progress*.

Since we have no clear reference point, baseline or criterion against which we can sensibly assess the ideal state of the physical environment, we focus here on the present state and trends.

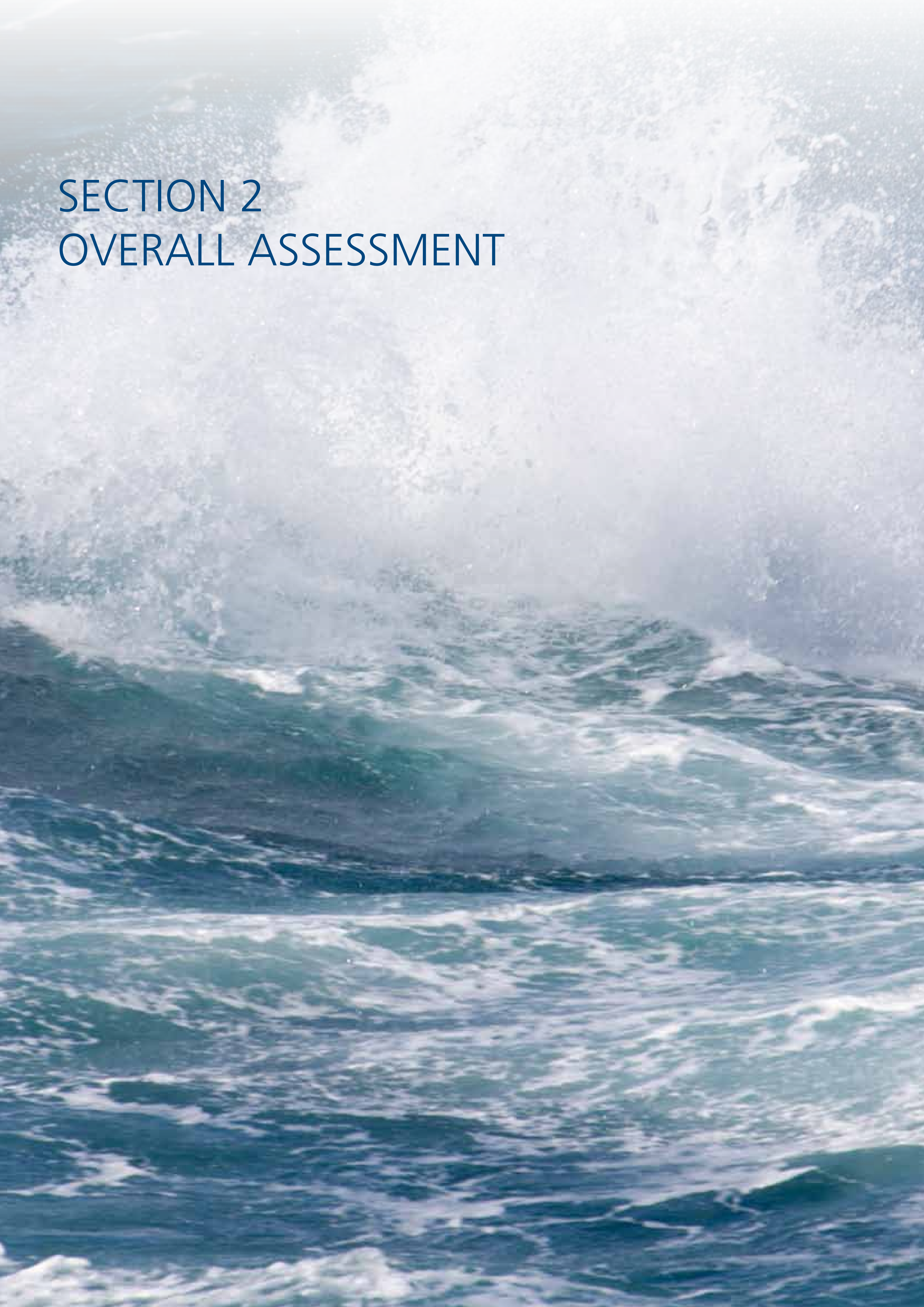
There are two levels at which we affect the physical environment of the UK seas. Locally, and directly, design and control of construction and activities can influence temperature, currents, waves and suspended matter. For example, offshore wind farms can affect winds; tidal energy barrages or breakwaters can change currents, the height of the sea surface, waves and suspended matter; coastal developments, defences and dredging can all affect suspended particulate matter and coastal power stations can raise the temperature of the cooling water they release back to the sea. Such activities are subject to environmental impact assessments and/or licensing which require such changes to be considered. Less directly, and more broadly, greenhouse gas emissions will influence future temperatures, salinity, pH, sea level, and possibly winds and waves. At either level, we are restricted as to how much we can control.

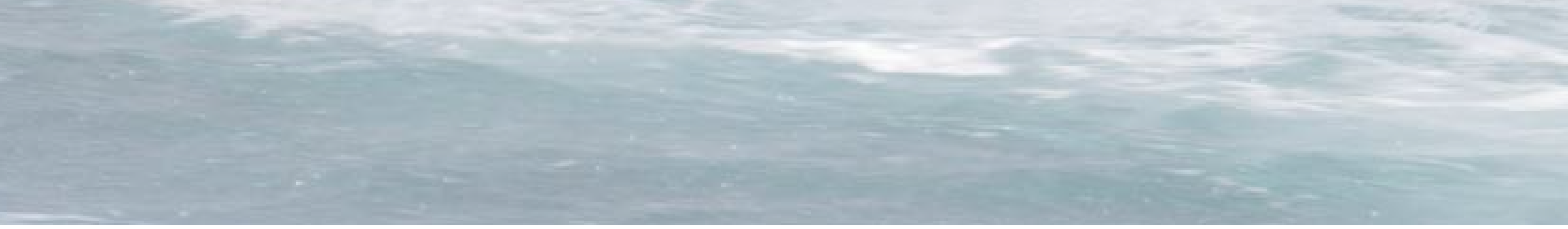
Our confidence in the estimated state and variability or trends is generally high. We found representative data on appropriate scales for all variables except where affected locally by shoals, proximity to land or river outflows. Morphology, rainfall, salinity and circulation are most susceptible to variability on small spatial scales.

Figure 1.1 Charting Progress 2 *Regional Sea boundaries.*



SECTION 2
OVERALL ASSESSMENT





The overall assessment of Ocean Processes in UK waters reported here follows the summary assessment in Table 2.1, with an overview of the respective ocean process variables, a summary for each CP2 Region and an outlook for further work to improve assessments.

2.1 Weather and climate

Atmospheric weather and climate have important effects on the ocean, influencing its temperature, salinity and circulation patterns on short and long timescales, respectively. For this assessment we have studied variability and trends in these factors using direct observations from the UK and world-wide.

There have been significant changes over the past few decades. The global surface air temperature has risen by about 0.75 °C since the late 19th century, 0.15 °C more than estimated in *Charting Progress* (some more warm years since then have affected trend assessments). The ten warmest years since global records began in 1850 all occurred between 1997 and 2008. The Central England Temperature has risen by about 1 °C since the beginning of the 20th century, as have annual mean air temperatures over Wales, Northern Ireland and Scotland. 2006 was the warmest year in central England since records began in the 17th century. Most of this rise was very probably caused by increases in human greenhouse gas emissions.

The average number of winter storms recorded at UK stations has increased significantly over the past 50 years. However, this has largely balanced a decline in the first half of the 20th century. Winters are continuing to become wetter in northern and western Scotland. Two out of the five wettest UK summers since records began in 1766 were in 2007 and 2008.

2.2 Sea temperature, salinity and circulation

Ocean temperature, salinity and circulation affect marine ecosystems in many ways. Some species are sensitive to temperature and/or salinity; circulation and currents distribute salt, deep-ocean heat and pollutants; currents affect habitats; many species are carried by the flow during their life cycle. Temperature and salinity control water density, which drives its motion in tandem with tides and winds. In return, circulation patterns and currents influence the temperature and salinity of the UK seas. From above, the atmosphere provides warming and cooling and changes the amount of freshwater arriving into the sea, through the balance of precipitation and evaporation as well as via rivers. For the shelf seas, the physical properties of the water column are controlled by a balance between mixing by tides and winds and buoyancy changes through warming, cooling and changes in salinity.

We have assessed variability and trends in these factors using time-series that span several decades. Temperature and salinity data come from: volunteer observing ships, drifting and moored buoys, repeated cross-sections measured from ships, bottom trawl surveys, coastal stations, and satellite radiometers. There are also some important recent developments. Over the past ten years the international Argo programme has established a global array of 3000 free-drifting profiling floats, measuring temperature and salinity between the surface and 2000 m depth; these now provide essential monitoring data in deeper waters west of the British Isles. The Natural Environment Research Council (NERC) and The Department for Environment, Food and Rural Affairs (Defra) have supported FerryBoxes on some ferries (see photo), and

Table 2.1 Assessment summary for the state of physical ocean process variables, the main influencing factors and their significance for the UK seas. Major changes result mainly from the global consequences of increasing greenhouse gas emissions to the atmosphere

Trend in variable assessed	*Status in UK atmosphere and seas*	*Influencing factors and significance for UK seas*
Air temperature Upward trend	**Rising in all regions** UK annual mean temperature has risen by about 1 °C since the beginning of the 20th century. 2006 was the warmest year in central England since records began in the 17th century	**Influencing factors** Global climate change mostly resulting from anthropogenic greenhouse gas emissions **Significance** Raises sea temperature
Sea temperature Upward trend	**Rising in all regions** Sea-surface temperature has risen by between 0.5 and 1 °C from 1870 to 2007. Warming since the mid-1980s has been more pronounced in Regions 2, 5 and 6 (Southern North Sea, Irish Sea, Minches and Western Scotland)	**Influencing factors** Air temperature **Significance** Reduces the ability of the oceans to take up CO_2, affects certain species, e.g. forcing them to move or adapt, and contributes to rising sea level. Shifts in plankton populations on which most marine animals feed are associated with temperature rise
Sea level Upward trend	**Rising in all regions** Mean sea level around the UK coast rose by about 1.4 mm per year during the 20th century	**Influencing factors** Temperature (the greater effect to date) and melting land-based ice (potentially more important in future) **Significance** Intertidal habitats and groundwater regimes are affected, and the flooding risk for vulnerable coastal populations will increase, notably in Region 2 (Southern North Sea), if upward trends continue
Carbon dioxide and ocean acidification Upward trend	**Acidification in all regions** Oceans are acidifying (pH decreasing) as CO_2 is absorbed. In UK waters we have no baseline measurements of pH against which changes can be judged, and it will be some time before we can make accurate judgements about the rate of acidification relative to natural annual and interannual cycles of pH	**Influencing factors** CO_2 which is present naturally and released from anthropogenic sources (e.g. combustion of fossil fuel). Various climatic factors influence its concentration in the sea **Significance** There are potential threats to marine species and ecosystems if acidification continues
Circulation, suspended particulate matter, turbidity, salinity and waves No significant trend	**Variable** These processes vary on daily to interannual timescales but show no significant trend over the past decade, except for a slight salinity decrease in Region 2 (Southern North Sea) and a slight increase in salinity in the northern Regions 1, 7 and 8	**Influencing factors** *Circulation:* tides and weather, especially winds *Salinity:* rainfall near the surface; river outflows locally; adjacent Atlantic salinity **Significance** *Suspended particles:* can reduce light availability and inhibit plant growth *Waves:* the main cause of damage to offshore and coastal structures

long-term series in the western English Channel, the Isle of Man and Liverpool Bay.

2.2.1 Temperature

Globally, sea surface temperatures rose by about 0.3 °C from around 1910 to 1940, remained steady until the 1970s and have then risen again by about another 0.4 °C. Since the mid-1980s, Atlantic surface waters adjacent to the UK have warmed by between 0.5 and 1 °C. Superimposed on this background trend are seasonal cycles of many degrees, variations between regions, and interannual-to-decadal variability (for any season) of 0.5 to 2 °C.

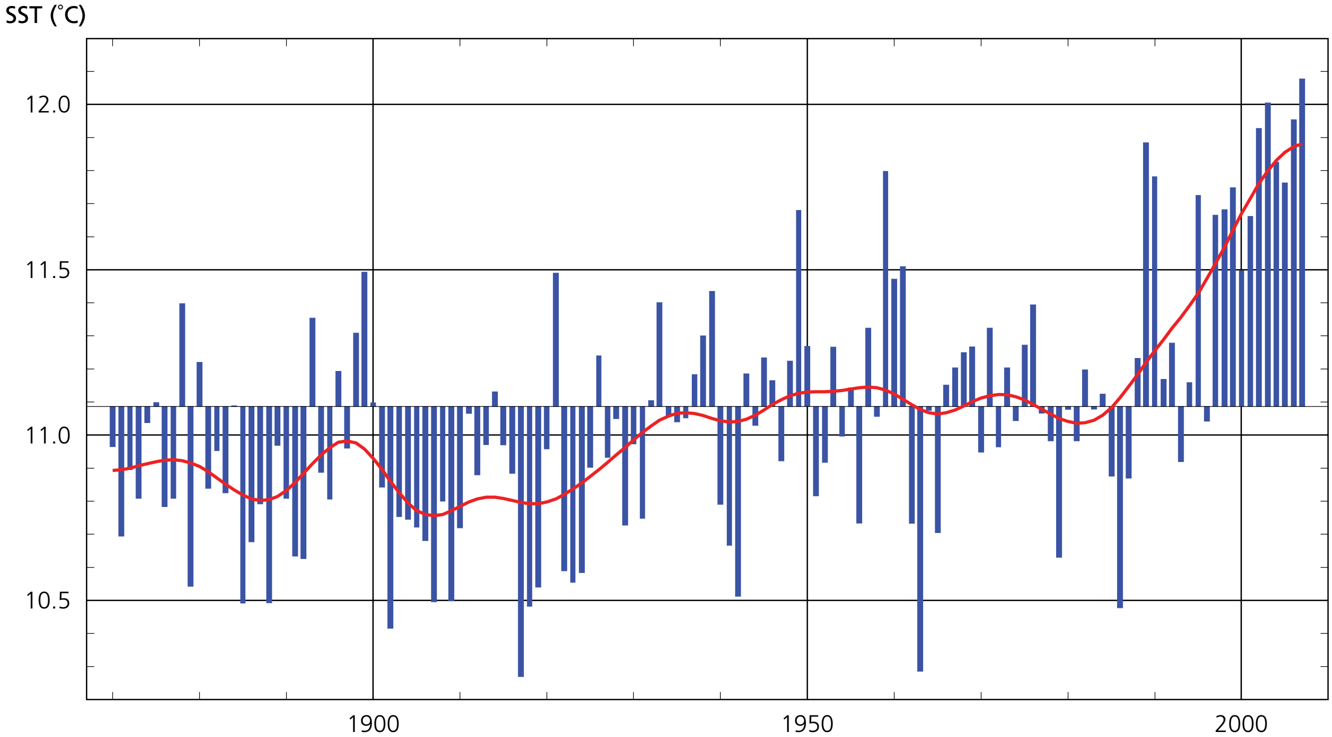
In shallower UK shelf seas, mixing of water masses and especially local weather largely control the temperature, on timescales of a day (for 1 m water depth) to a few months (for 100 m water depth). There is also some influence from adjacent Atlantic water where it moves onto the shelf. The annual sea surface temperature, averaged around the UK coastline, has increased by about 0.5 to 1 °C for the period 1870 to 2007 (Figure 2.1). Much of the warming took place in the 1920s and 1930s and again since the mid-1980s; this later warming was especially pronounced in the Southern North Sea, Irish Sea and the Minches and Western Scotland. Spatial and interannual temperature variability in UK waters is of the order of 0.5 °C; but can be up to 2 to 3 °C in shallow areas for an extreme month.

2.2.2 Salinity

Salinity is influenced primarily by Atlantic water, slightly by rainfall and evaporation, and locally by the influx of fresher water from rivers via estuaries; values are usually between 34 and 35.6 in salinity units. Atlantic waters adjacent to the UK have experienced an increase in salinity of 0.05 to 0.1 units since the late 1970s and this in turn has caused a salinity rise in the nearby UK shelf waters. The picture is rendered more complex by spatial and interannual-to-decadal variability, of up to 0.1 in salinity. Irish Sea salinities are especially variable; they are typically between 34 and 35 in the west but sometimes as low as 31 approaching the English coast where freshwater inputs are relatively important. Typically salinity is most variable, with potential impacts on biota, near the head of an estuary where the fresh-salty water transition may move according to river flow and stage in tidal cycles.

FerryBox system as installed on the RV Cefas Endeavour*. This equipment provides continuous measurements of variables such as temperature and salinity*

Figure 2.1 Annual average sea surface temperature (SST) for the UK seas, between 1870 and 2007. The 1961–1990 average was 11.09 °C. The red line smoothes out fluctuations shorter than 5 to 10 years to illustrate the longer-term trend. Courtesy of the Met Office.



2.2.3 Circulation

North-East Atlantic temperature and salinity are controlled by the large-scale circulation (Figure 2.2) and history of these waters. The Atlantic Meridional Overturning Circulation (AMOC) brings warm surface water past the west of the UK, strongly influencing our climate by warming the prevailing westerly airflow. Instantaneous currents in UK shelf seas comprise tidal flows, wind-driven flows and flows driven by differences in density that arise from seasonal heating and salinity differences. 'Residual' flow, after averaging out oscillatory tidal flow, is mainly driven by winds and by density differences in many areas. Tides, winds and density all change on a range of timescales, so that observed and residual flows can be very variable. On the shelf, transport of water in a single storm can be significant relative to a year's total.

We have assessed the long-term circulation in the adjacent North Atlantic using tracks of drifters and Argo floats, and in shallower UK waters using distributions of tracers, drifter tracks or numerical hydrodynamic models. We have also used data from current-meter measurements in a few long-term mooring arrays and from submarine cables. For components with timescales longer than a day, we inferred circulation from ship-based temperature and salinity measurements. High Frequency radar gives spatial coverage for surface currents, although the range is limited to the order of 50 to 100 km. A recent development is the NERC-funded RAPID programme which maintains an array of moored

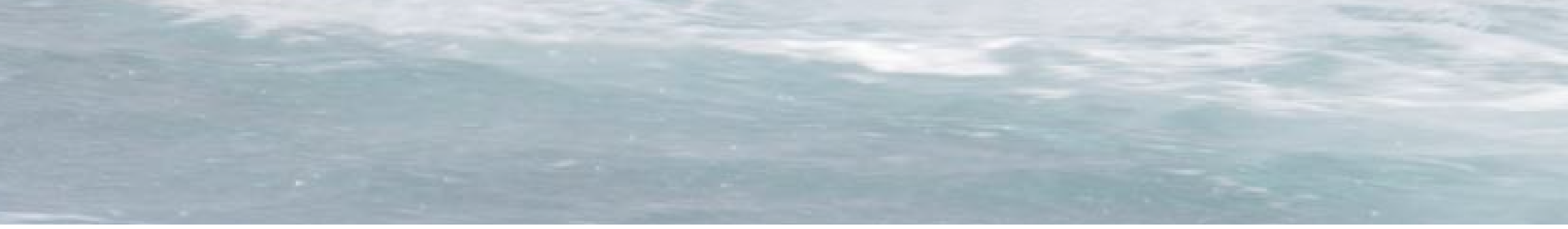
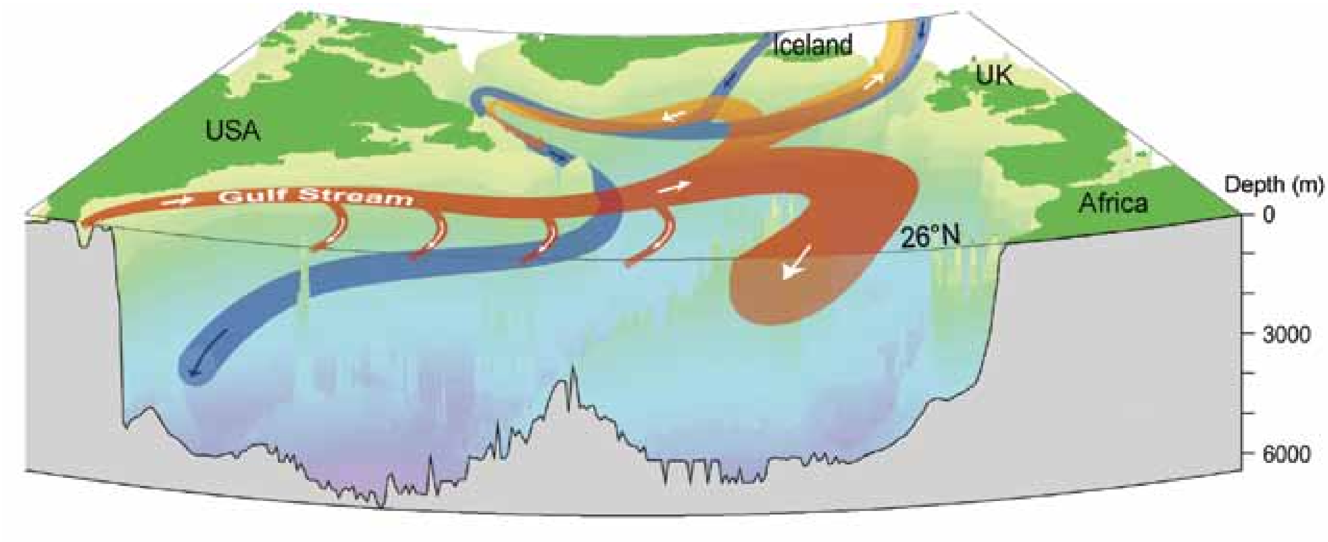


Figure 2.2 Schematic of the North Atlantic ocean circulation showing the northward transport of relatively warm surface water (red/orange) and the southward return of cooler, subsurface water (blue). The Gulf Stream is a component to the overall circulation. Note the partial recirculation of northward-flowing water by the sub-tropical and sub-polar gyres before water enters the far North Atlantic. Courtesy of NOC after Church (2007).



sensors to study the sub-surface temperature and salinity distribution, and hence monitor transport of the AMOC, across a section of the Atlantic Ocean at 26° N where it is strongest.

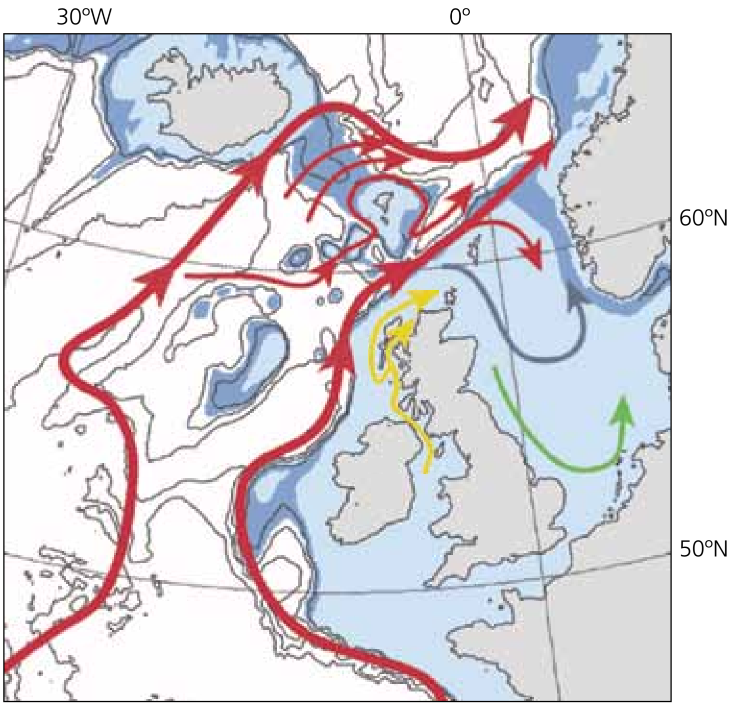
Five ship-based cross-sections of the Atlantic near 24° N suggest that the AMOC declined in strength from 1957 to 2004. However, continuous measurements starting in 2004 show this to be within the range of variability on timescales of weeks to months, so that we cannot be sure of an overall trend. Deep outflows of cold water from Arctic seas are likewise too variable to infer any trend.

Future monitoring of the Atlantic circulation in RAPID extends to 2014; this will help to clarify variability and the statistical confidence in any trend. However, changes in circulation at 26° N have proved hard to relate to patterns of sea surface temperature (Figure 2.3), or to circulation at higher latitudes, where AMOC correlation with surface heat fluxes is suggested by models. Other measurements, especially at higher latitudes, may help us to understand how changes in the AMOC are relayed from place to place and possibly to establish proxies for easier monitoring.

2.3 Carbon dioxide and acidification

The oceans play an important role in reducing the contribution of carbon dioxide (CO_2) to climate change, by taking up more CO_2 than they release, which substantially reduces the rate of increase in the atmosphere. However it also makes the oceans more acidic and potentially reduces their capacity to take up CO_2 in the future. Continental shelf seas play a key role in this global CO_2 uptake. Changing the pH of seawater alters the balance of and rate of conversion between different nitrogen compounds, changing their availability to

Figure 2.3 Schematic of circulation of surface waters in the North-East Atlantic. Red arrows represent the flow of warm, salty Atlantic waters along the continental slope and further west, while the yellow, blue and green arrows represent the flow of coastal waters. The yellow arrow indicates the path of the Scottish Coastal Current, while the blue arrow indicates the inflow of mixed coastal/oceanic water past Fair Isle (the Fair Isle Current) and the green arrow indicates average anti-clockwise flow in the southern North Sea. Courtesy of S. Hughes, Marine Scotland, © Crown copyright 2010.

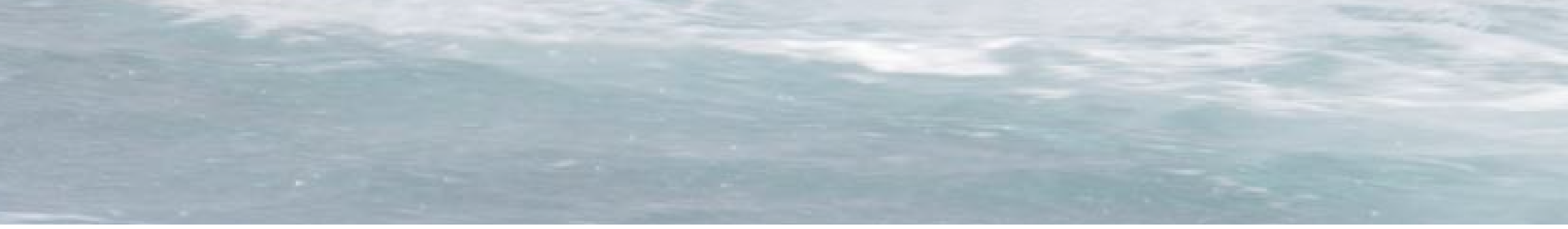


support the growth of phytoplankton and hence eutrophication. Biogeochemical and ecosystem processes affected include planktonic calcification, carbon and nutrient assimilation, primary production and physiology; many marine animals have planktonic larval stages that are likewise vulnerable. Organisms such as bivalves and tube worms may have difficulty forming shells in lower-pH waters. Changes in pH also affect the availability of trace metals, which may be necessary for plankton growth, or may in some cases be toxic. We assessed the state of CO_2 uptake and acidification in UK waters using models of the sea, inverse modelling of atmospheric concentrations and validation with evidence from direct measurements.

We found that the north-west European continental shelf is a net absorber of atmospheric CO_2, but that its capacity to do so is highly variable. More widely, the North Atlantic apparently reduced its net uptake of CO_2 by more than 50% from the mid-1990s to 2005. However, this may be part of a natural cycle rather than a one-way trend.

Since the industrial revolution, ocean acidity has already increased by a third (or decreased by 0.1 in pH units).

Because there are currently no baseline measurements of pH against which changes in UK waters can be judged, it will be some time before we can make accurate judgements about the rate of acidification relative to natural annual and interannual cycles of pH. We also need a better understanding of the physical, chemical and biological processes controlling the ocean's ability to absorb CO_2.



2.4 Sea level

Growing populations and urbanisation of the coastal zone means that increasing numbers of people are vulnerable to extreme rises in sea level, particularly in south-eastern parts of the UK. Sea level changes affect inter-tidal habitats and groundwater status. Rising sea levels imply more flooding and more coastal erosion by waves, for any given storm scenario.

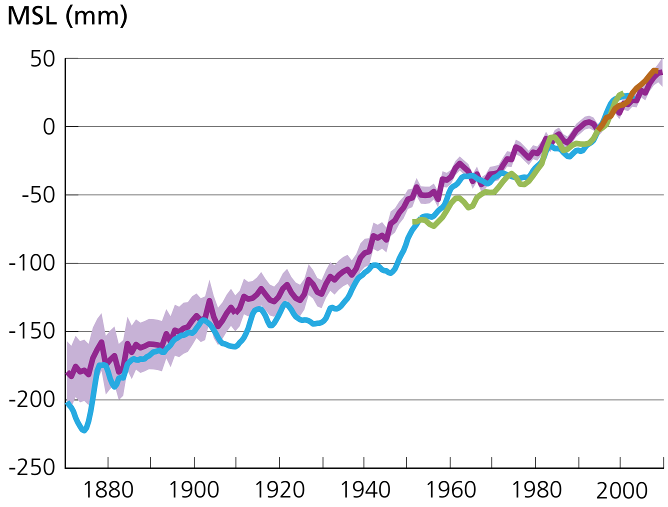
For this assessment we used data from global and UK-wide networks of tide gauges, satellites, and climate modelling. Most findings are available in the scientific literature and have been included in the periodic assessments published by the Intergovernmental Panel on Climate Change (IPCC).

Global sea level rose by about 1.7 mm per year during the 20th century (Figure 2.4); the few long European records suggest this rate of rise was slightly faster than in the 19th century. The rate of rise around the UK coast, adjusted for land movements, was slightly less at about 1.4 mm per year during the 20th century. However the rise was not steady. For example, in the 1990s sea level rose by 3 to 4 mm per year.

Oceanic tides around the UK generally show some local short-term variations in height and timing, but no long-term trends. However, there is a long-term increase in mean tidal range at Newlyn (south-west Cornwall), notable for its long well-maintained record, open-sea location and lack of harbour works. Extreme sea levels (mean + tide + storm surge) are rising at about the same rate as mean sea level.

Erosion at Hunstanton cliffs, Norfolk. Rising sea levels are affecting a large proportion of the coast in this region

Figure 2.4 Global mean sea level estimated by different methods of averaging coastal tide gauge data (purple, green and blue lines – all held by the Permanent Service for Marine Sea Level). The pale purple envelope shows the estimated uncertainties of the purple line. The brown line shows altimeter data, which are independent of tide gauge data. Source: Adapted from Church et al. (2010).



The most significant missing piece of this puzzle is a fuller understanding of the connection between the causes of sea level rise and the effects. To address this, scientists are attempting to set up a coherent global monitoring system for sea level (altimetry, space gravity, tide gauges) and for the factors that cause changes in sea level (mass balance of ice sheets and glaciers; temperature and salinity of the ocean; water in rivers, lakes, soils and the rocks below). This will give us greater confidence in model predictions of future change, which should enable more effective coastal planning and management.

2.5 Waves, suspended particles and turbidity

Waves affect transport, fishing, offshore industry and coastal communities; they can cause coastal erosion and structural damage, which contribute to flood risk. They influence the stratification of surface layers and the rate at which gases pass between the atmosphere and the ocean surface. In shallow waters, waves cause strong currents within a few centimetres of the seabed, affecting habitats and suspending sediment.

In turn, suspended particulate matter (SPM) influences nearshore and benthic habitats; it affects marine communities including plankton, benthic invertebrates and fish, by carrying pollutants and blocking sunlight, so inhibiting photosynthesis. SPM also includes plankton and so forms part of the marine ecosystem. Hence studying SPM can help us understand the transportation of pollutants and nutrients, primary production and its fate – how much falls to the seabed or contributes to the water-column food web – and perhaps also eutrophication. SPM also affects bathing water quality. Its transport, for example longshore drift, is a factor in coastal erosion and morphology. SPM is driven directly by seabed currents from tides, wind and waves, and so varies greatly with water depth. It also depends on sediment availability, which can be affected by dredging and land use, and varies locally with rainfall and flooding around the coast.

For waves, this assessment uses data from satellite altimetry, wave sensors on moored buoys and lightships, offshore and many nearshore sites. We have also used modelling for wave prediction, forecasts and state estimation, which is well-developed.

In the west (especially the north-west) and the Irish Sea, winter wave heights correlate significantly with the North Atlantic Oscillation Index, which is a measure of the strength of westerly winds at UK latitudes. They increased through the 1970s and 1980s west of the UK and in the North Sea from the relatively calm conditions experienced during the 1960s. However, recent trends are not clear, with some measurement sets appearing to show a decrease in winter wave heights. Year-to-year variability is such that there is no clear longer-term trend and no clear change since *Charting Progress* was published in 2005.

In very shallow waters, for example near coasts, trends in wave heights are less marked because the water depth limits the height of the waves as they break. However, as rising sea levels increase nearshore depths, larger waves may approach the shore, enhance erosion and steepen intertidal profiles.

For SPM, we used data from traditional assessment methodologies such as measuring the depth over which a white disk can be seen suspended in the water. However, more sophisticated optical techniques such as back scatter from light beams are increasingly available for particle size as well as concentration. This has increased our understanding of SPM dynamics and processes in shelf seas, especially the tidal stirring of sediments. Remote sensing measurements of ocean colour provide time series for studying variability of SPM, phytoplankton pigments and coloured dissolved material. However, these techniques can be hampered by clouds and by insufficient understanding of optics in turbid coastal and shelf waters.

There is much ongoing research on SPM and turbidity in coastal regions of the UK and Europe but we still need to understand more about nutrient binding and the breakdown of particulate matter. The data currently available show that SPM concentrations, and therefore turbidity for UK waters, are very variable depending on currents, biological influence on sediment properties and seabed characteristics. However, we have no evidence for any changes in the general state of SPM around the UK since *Charting Progress*.

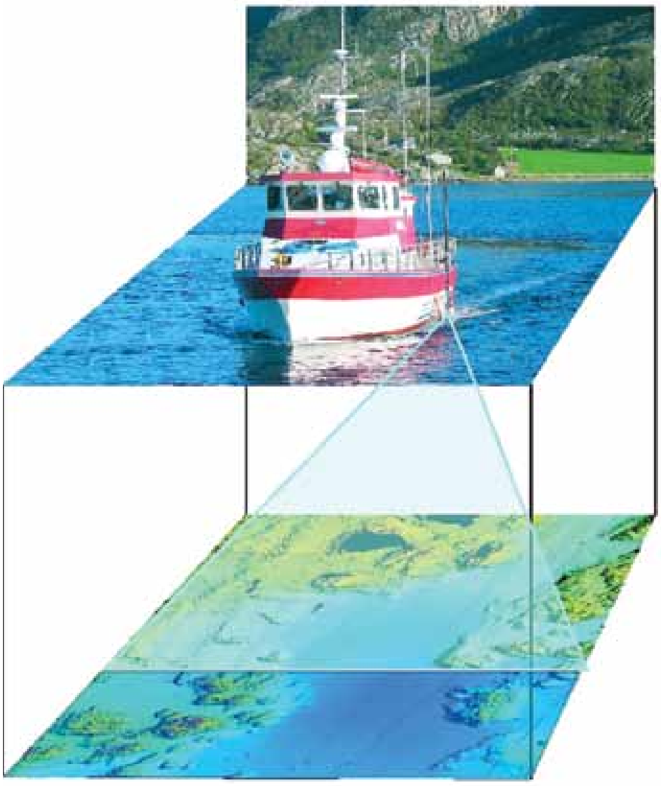
2.6 Sedimentary processes and morphology

The morphology and sedimentary processes of the seabed play a critical role in the distribution of benthic habitats, which form an integral part of much of ocean life. For this assessment we have brought together data from many sources, including research programmes and commercial surveys.

In areas of relatively rapid coastal erosion, rates of change are being monitored. Offshore, there are several means of mapping the seabed. Multibeam Echosounder Systems (MBES; Figure 2.5) provide a new approach, and MBES data collection programmes have expanded dramatically since *Charting Progress*. We now have new measurements from all regions using MBES, although as of 2008 MBES data cover only about 15% of the UK seabed.

As yet we have little information from very shallow waters, where surveying is slow (the rate of coverage is proportional to the water depth) and therefore cost has limited progress. However, the coastal zone is so important in relation to erosion, flooding, habitats, and commercial uses, that this is a key area for future work.

Figure 2.5 Schematic illustration demonstrating the principles of data collection using Multibeam Echosounder Systems. Courtesy of the Geological Survey of Norway, NGU.



In offshore areas, the rate of change of the seabed is generally low; rapid changes are restricted to shallow areas where wave action is strong or human activities take place (e.g. trawling, aggregate extraction and dredging). Erosion (excluding hard-rock coasts) is occurring along 17% of the total UK coastline (30% of England's coastline; 23% Wales; 20% Northern Ireland; 12% Scotland). Almost two-thirds of the intertidal profiles in England and Wales have steepened over the past 100 years, as rising sea levels have taken waves closer to the base of hard defences or erodible cliffs. Steepening of the intertidal profile is particularly prevalent on coasts defended against erosion (this represents 46% of England's coastline; 28% Wales; 20% Northern Ireland and 7% Scotland).

To underpin future marine planning and to support commercial exploitation and legislative drivers such as environmental monitoring and conservation, we now need more high-quality bathymetric data and to match this with analysis of the geology and habitats, so forming coherent maps and models. We should optimise use of the several existing UK programmes that collect MBES data for a wide range of different uses (unlike Ireland, for example, which has a single integrated marine mapping programme). Better integration of Government-funded surveys is being achieved through: the Civil Hydrography Annual Seminar (CHAS) meetings organised by the Maritime and Coastguard Agency (MCA); a Memorandum of Understanding between several public sector organisations to share data; and several initiatives to collaborate in the collection and interpretation of data (e.g. Channel Coastal Observatory and MCA; NERC research centres and others). Adding commercial data, and further collaboration between programmes building on the Civil Hydrography Programme, would help in developing marine renewable energy and meeting the challenges of the EU Marine Strategy Framework Directive.

2.7 Regional seas statements

This section summarises the state of ocean process variables in terms of the eight CP2 Regions (see Figure 1.1 on Page 3).

2.7.1 Northern North Sea (Region 1)

Modified Atlantic water flows into Region 1 via the Fair Isle current between Orkney and Shetland, and around the north and east of Shetland. Thus salinity is near to open Atlantic values (above 35) except close to river outflows. Winter temperatures, typically 6 to 9 °C minimum, increase to the north as water from the Atlantic has less time to cool and water depths increase (from about 50 to 150 m, south to north; heat taken out of shallower water in the south causes temperature to fall further in winter). Summer temperatures are typically 12 to 14 °C near the surface. The depth is sufficient to support summer stratification (tidal currents being generally moderate) except close to the coast; water below about 50 m depth warms much more slowly in summer, to 7 to 10 °C, with a maximum 9 to 11 °C typically in October. Exceptions are in strong tidal currents around islands, and famously in Pentland Firth where water is vigorously mixed all year. In common with most UK waters, sea temperatures have been rising; changes in plankton composition, northwards movement of species and shifts in benthic-invertebrate intertidal species distribution have been attributed to rising temperatures (as detailed in the respective topic chapters). On account of the stratification, the region is believed to have a net uptake of CO_2 from the atmosphere (by phytoplankton which then sink and respire below the warmer surface layer). Much of the inflow turns eastwards, roughly following depth contours away from Scotland towards Scandinavia. The North Sea is most exposed to waves from the north; average wave heights decrease southwards and Region 1 is relatively sheltered from prevailing westerly winds. Resulting turbidity is moderate, except that some parts of the coast (especially Yorkshire) are susceptible to erosion. In common with the UK in general, sea level is rising; the presence of seawalls (for example) in some locations has led to 'coastal squeeze' of intertidal sediment habitats.

2.7.2 Southern North Sea (Region 2)

The Southern North Sea is shallow, mostly less than 50 m in depth, and furthest from inflows and influence of Atlantic water (most of that from the north turns east rather than continuing south to Region 2; there is some inflow from the Channel, i.e. Region 3). Tidal currents are strong in most of the region (off Norfolk and further south) and correspondingly the waters are mixed all year (except in the northern part). Temperature minima in winter are typically 4 to 8 °C; they depend strongly on the weather in any one year, and on depth (shallow waters get colder because heat is lost from less water). Likewise the typical summer maxima 16 to 19 °C depend on the weather and strongly on depth (shallow waters get warmer because less water is heated). The trend of temperature rise in UK waters is fully manifested here. A sharp boundary 'front' extends eastwards from Flamborough Head (Yorkshire) with mixed waters to the south and summer-stratified waters to the north. Salinity mostly exceeds 34; near freshwater inputs (notably from the Humber, Wash, and Thames) it may be as low as 30 (more extensively around continental river outflows, but these rarely extend to UK waters). In the absence of stratification, the south of Region 2 is believed to have a net flux of CO_2 to the atmosphere. Overall circulation is anti-clockwise but weak, the net result of tidal, wind- and density-driven components. Tidal amplitudes are large, and wind-driven surges (arriving from the north) occasionally build up to cause large changes of sea level and extra circulation (transport of water and its contents). Sea level is rising, faster relative to land than in the UK as a whole because the land sinks in this region. Thus the soft coasts of Region 2 suffer rapid erosion in many places, and the extensive sedimentary habitats (heavily impacted by reclamation and hard structures) are a consequent concern.

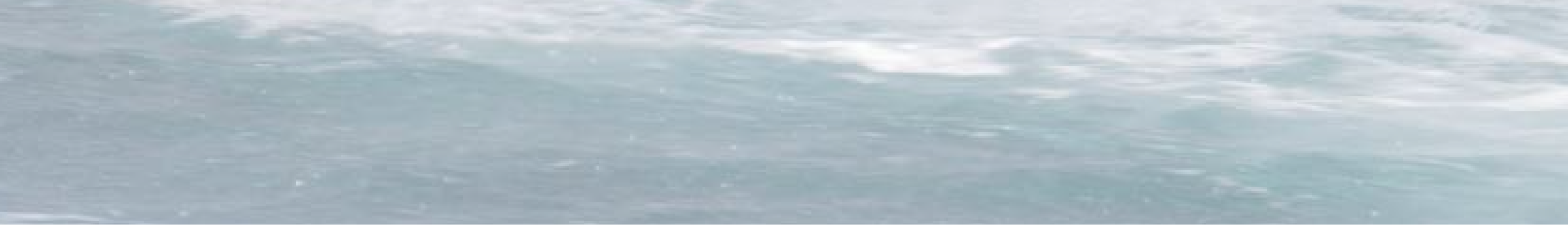
However, the region is relatively sheltered from prevailing westerly winds and average wave heights are relatively small. Turbidity (with strong tidal currents) is enough to delay the spring growth of phytoplankton in many areas.

2.7.3 Eastern Channel (Region 3)

About half of Region 3 has depths of less than 50 m but the central Channel deepens westwards to 100 m. There is some influence of Atlantic water with a net eastward flow (albeit tending to be nearer the south side of the Channel). Tidal currents are strong enough to mix the water throughout the depth all year. Thus minimum winter temperatures, typically 5 to 8 °C, are strongly dependent on the weather in any one year and on depth (shallow waters get colder because heat is lost from less water). Summer maximum temperatures (similarly controlled) are typically 16 to 19 °C. The trend of temperature rise in UK waters is fully manifested here. Salinity mostly exceeds 34; UK river outputs are moderate and do not depress salinity much below the adjacent Atlantic value, about 35.5. Rising sea levels are here compounded by subsidence of the land (as in the Southern North Sea). The Channel is rather specifically exposed to waves from the west-south-west; although wave heights are usually moderate relative to UK waters generally, storms aligned to give strong west-south-westerly winds across the Celtic Sea and western Channel occasionally cause severe wave conditions. The combination of sea level, waves and 'soft' coasts in places implies vulnerability to coastal flooding and erosion of beach areas. (Hence there are sea-defence works with their own effects.) Turbidity is high.

2.7.4 Western Channel and Celtic Sea (Region 4)

Depths in Region 4 are mostly between 50 and 150 m (shallower near coasts); they increase rapidly at the edge of the continental shelf to more than 4000 m (just beyond the edge of the region). The shelf is very wide, with very high tides and hence strong tidal currents. (The Avonmouth mean spring tidal range 12.3 m is only exceeded globally in the Bay of Fundy (eastern Canada) and Umgava Bay (north Labrador, Canada).) However, the net inflow of Atlantic water is weak relative to the large area of the Celtic Sea. There are sharp boundaries ('fronts') between summer-stratified waters (in the outer Celtic Sea) and mixed waters: the fronts are across the western Channel (Brittany to south Devon), Bristol Channel (north Cornwall to Pembrokeshire) and St George's Channel into the Irish Sea. Sea temperatures are strongly related to the weather in any one year and to water depth (shallow waters have a wider range because heat is lost or gained by less water). The climate being strongly maritime, typical winter minima are 8 to 11 °C and summer maxima 14 to 18 °C (but 11 to 16 °C below summer stratification; the maximum here is reached typically in October when the heat of surface waters is fully mixed down). Temperatures are rising. Salinities are typically greater than 34.5 (the adjacent Atlantic value is about 35.5) except in the Bristol Channel and where river outflows reduce salinity locally. There is a tendency for eastward flow through the English Channel (tending to be nearer the south side) and for weak anti-clockwise circulation around the eastern and northern Celtic Sea from off Brittany to south of Ireland. Sea level is rising at rates typical or faster than for the UK as a whole. The near-resonance that gives high tides in the Bristol Channel also makes this area susceptible to wind-forced surges and occasional flooding of



low-lying areas (e.g. north Somerset). The region is very exposed to the Atlantic in the west, resulting in large average wave heights. Turbidity is high in the Bristol Channel (helped by tidal currents up to 2 m/s) but moderate in deeper waters.

2.7.5 Irish Sea (Region 5)

The Irish Sea is enclosed by land except for St. George's Channel in the south and the North Channel. Depths in the east (Cardigan Bay and east of Anglesey – Isle of Man – southwest Scotland) are mostly less than 50 m. However, depths increase towards a western channel (running from St. George's Channel west of the Isle of Man to the North Channel) with an axis mostly deeper than 100 m. Overall mean flow is northwards and equivalent to the volume of the Irish Sea passing through in about one year. This northward through-flow tends to be on the eastern side; there can be southward flows near to Ireland. High tides (extreme range up to 10 m in Liverpool Bay) and consequently strong currents give mixing in general except for (i) an area of summer stratification between the Isle of Man and Ireland with associated anti-clockwise surface circulation (ii) fresher surface waters at times in the east where river outflows (via estuaries) are relatively important. As elsewhere, temperatures depend strongly on the weather in any one year and on water depth (shallow waters have a wider range because heat is lost or gained by less water). Typical winter minima are 4 to 8 °C and summer maxima 14 to 18 °C (but below summer stratification the maximum 13 to 15 °C is typically in October when the heat of surface waters is fully mixed down). Salinity is typically between 34 and 35 in the west but river outflows depress values in the east and the North Channel; sometimes as low as 31 approaching the English coast; on average salinities are less in late winter. Sea level is rising in common with the UK as a whole. In common with the Bristol Channel, the large tidal range in the eastern Irish Sea is accompanied by susceptibility to wind-forced surges (up to 2 m) and occasional flooding of low-lying areas (e.g. Towyn, Fylde). Waves tend to be short and steep rather than high, but combine with strong tidal currents in extensive shallow areas to give high sediment mobility, coastal erosion (e.g. north of Liverpool) and turbidity.

2.7.6 Minches and Western Scotland (Region 6)

Depths in Region 6 are varied, generally less than 100 m in the south but up to nearly 200 m in the North Channel and in a channel through the northern sector (Sea of the Hebrides and the Minch). The climate is maritime with prevailing westerly winds. Tidal currents vary, being very strong locally between and around islands. As a result, stratification is variable, and also influenced by fresher water from the Irish Sea; this forms the Scottish Coastal Current flowing northwards through the region. Typically, there is summer stratification in deep waters away from islands and north of the Islay front (west of Islay to Ireland). There is some influence of (modified) Atlantic water arriving from the west via Region 7. Resulting typical winter minimum temperatures are 6 to 8 °C and summer maxima 13 to 15 °C (11 to 13 °C below where stratified); there has been a rise of more than 1 °C since 1981 (in Tiree Passage). Salinity is typically between 34 and 35; there are lower values near freshwater outflows from rivers (typically via sea lochs), but the majority contributor to lower-than-Atlantic values is outflow from the Clyde and Irish Sea (Region 5). Mean sea-level rise (relative to the coast) is slower in this region due to land uplift. The south of the region is exposed to waves from the Atlantic, but locally islands give shelter and the Outer Hebrides shelter the

northern sector. Strong currents can give high turbidity in places; however, the predominance of hard rock limits coastal erosion and the supply of particulate material.

2.7.7 Scottish Continental Shelf (Region 7)

Typical depths in Region 7 are between 100 and 150 m, shoaling towards coasts and increasing rapidly at the edge of the continental shelf (the boundary with Region 8, where depths are more than 2000 m in Rockall Trough at the south-west end and 2000 m in the Norwegian Sea at the north-east end). Region 7 is exposed to Atlantic influence: weather (these latitudes experience the strongest westerly winds), waves and water (significant flows onto the shelf and then northwards/north-eastwards and into Region 1). There is some influence of fresher water from Region 5 around the Outer Hebrides. Tidal currents are generally moderate except locally between and around islands; wind-driven flows can be comparable; there is a poleward flow of relatively warm, saline Atlantic water along the upper continental shelf which is apt to broaden onto the shelf in winter. All these individual contributions are typically 0.1 to 0.2 m/s. Except for shallow areas near coasts, there is summer stratification. Temperature minima in winter are typically 9 to 10 °C at the shelf edge but 6 to 9 °C elsewhere; they depend on the weather in any one year, on depth (shallow waters get colder because heat is lost from less water) and on travel time (i.e. cooling time) for any Atlantic water arriving from the shelf edge. Summer maxima are typically 12 to 14 °C for surface water, lower below. Temperatures are rising but are more influenced by wider Atlantic variations than in other UK shelf areas. Salinity typically exceeds 35 except locally as influenced by (moderate) freshwater outflows from rivers; Atlantic variability is more significant than in other UK shelf areas but still a minor factor in the Fair Isle current exiting the region between Orkney and Shetland. As in Region 6, sea level rise (relative to the coast) is slower due to land uplift. The predominance of hard rock and limited length of coast reduces the impact of sea-level rise, limits coastal erosion and limits supply of particulate material; turbidity is moderate.

2.7.8 Atlantic North-West Approaches (Region 8)

Region 8 differs from Regions 1 to 7 in having no coastline (except Rockall). Depths range from 200 m at the edge of the continental shelf (less over Rockall Bank) to about 3000 m in the Iceland Basin west of Rockall. Region 8 is fully exposed to Atlantic influence: weather (strong westerly winds prevail), waves (the highest around the UK) and water. There is overall passage of Atlantic water northwards through Rockall Trough, with much variability; eddies have been found over seamounts and there can be clockwise circulation over Rockall Bank. A poleward current along the upper continental slope in eastern Rockall Trough is augmented along the west Shetland slope (Faroe–Shetland Channel) by some re-directed water from Rockall Trough and by recirculating Atlantic water that circuited the Faroe Isands clockwise. There is summer stratification except locally over the shallowest part of Rockall Bank. Surface (0 to 50 m) temperatures in Region 8 typically have a winter minimum of 9 to 10 °C (but as low as 6 °C on Rockall Bank) and summer maximum of 12 to 14 °C; at depths of 200 to 500 m temperatures of 9 to 10 °C prevail for most of the year. Typical temperatures at 2000 m are 3 to 4 °C; however, Norwegian Sea and Faroe–Shetland Channel bottom waters are below 0 °C, even at 1000 m. Temperatures are rising but also vary with the origin of waters arriving in the region, as does salinity. Upper-level salinity

is 35.3 to 35.4 in Rockall Trough and decreases slowly to the north-east (still exceeding 35.3 on the West Shetland slope); salinity decreases downwards to about 34.9 at 1000 m in the Faroe–Shetland Channel (in Rockall Trough, minimum salinity is deeper). Sea-level rise is not relevant in the absence of any significant coastline. Waves have impact primarily at the surface and not on the seabed (only a relatively small area is less than 100 m deep); turbidity is low.

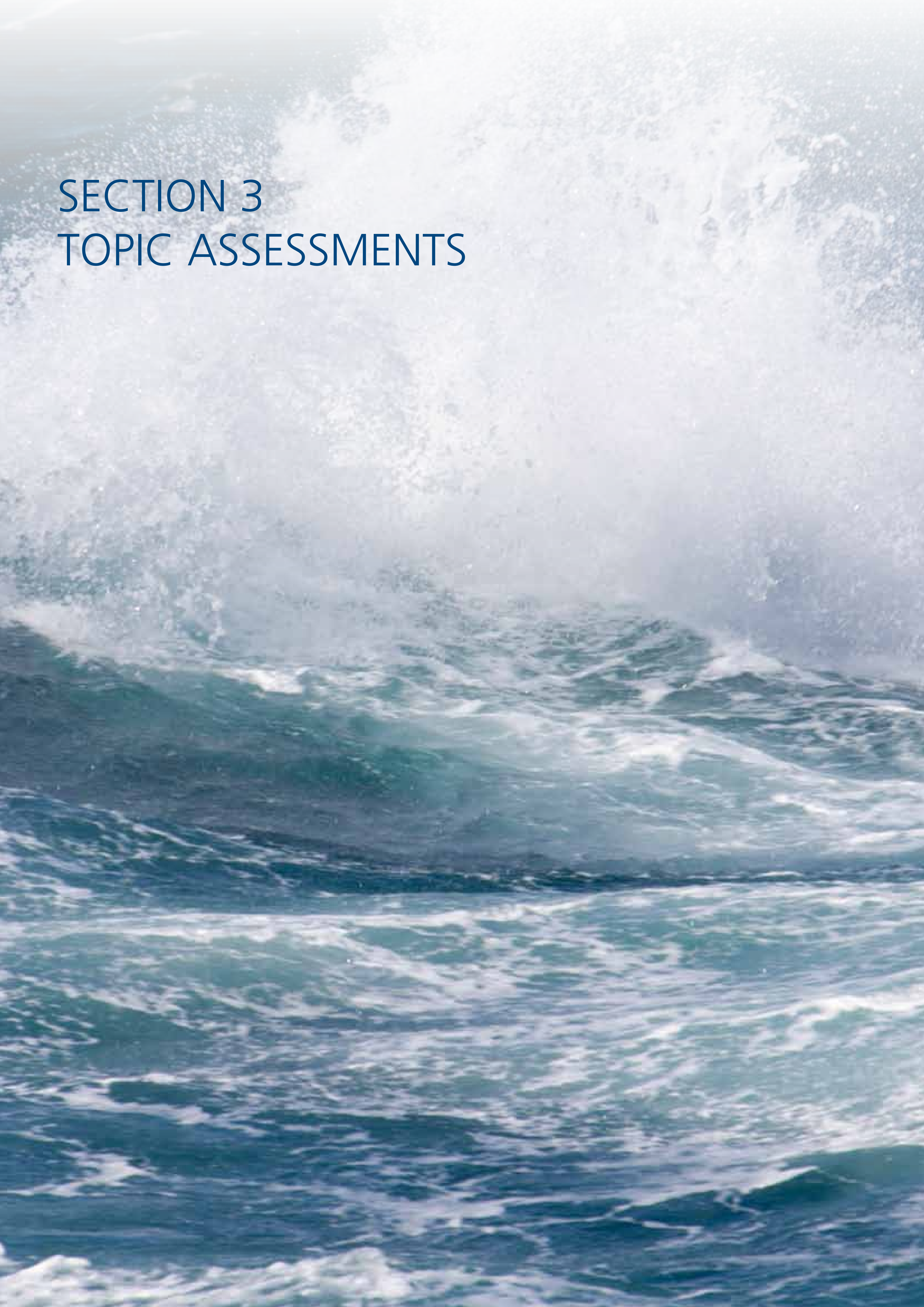
2.8 Further work

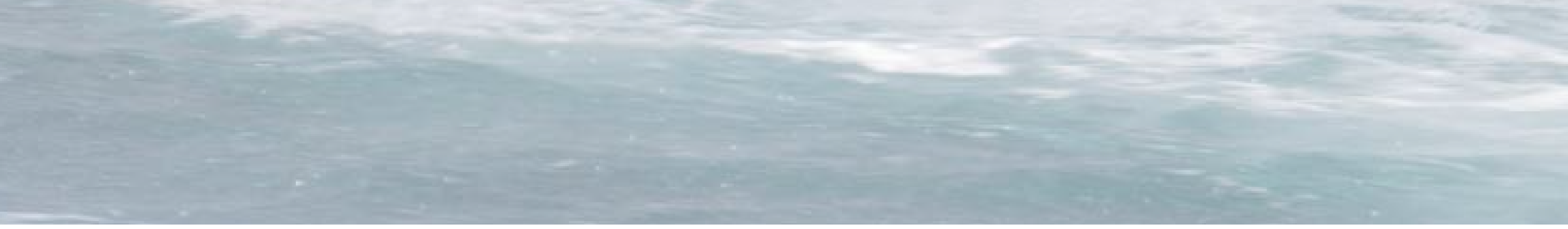
For the immediate future, we should sustain measurements of Ocean Process variables at least at their present intensity. However, we could significantly reduce the uncertainties in future assessments by increasing the quality and quantity of these observations, notably for sub-surface temperature and salinity. Moreover, the accuracy of reported variability and trends in several variables is limited by the spatial density of observations. Uncertainty in monthly mean air temperature estimates over the Atlantic near the UK increased many-fold from 1970/74 to 2004/08 owing to fewer Voluntary Observing Ships, implying reduced confidence in marine air temperature trends. In UK shelf seas, salinity, current and wave measurements are sparse and are inadequate for sampling of local variations.

Better prediction of short-term variability in circulation will require both model validation and the development of new observational networks. For currents, temperature and salinity, model experiments could help design measurement arrays: i.e. the density, frequency and allowable time-delay in observed data sets (assimilated in forecasting models) that provide the best cost/benefit value both for making predictions, and for assessing the current state of UK waters.

Long-term, decadal-scale trends in variables such as temperature, precipitation, salinity, circulation, waves, and suspended particulate matter and its dependent biogeochemistry, are often obscured by larger short-term variability from year to year, season to season and from one weather event to the next. To separate out the longer-term trends and make a better assessment of the contribution of human-induced climate change, we will need long-term yet frequent measurements, as in UK coastal observatories, and/or understanding and models that enable shorter-term variations to be estimated from their known causes. Data buoys and ships of opportunity (FerryBoxes) now demonstrate much improved temporal and spatial coverage in a cost-effective manner.

SECTION 3
TOPIC ASSESSMENTS





3.1 Weather and Climate

3.1.1 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 risen 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 3.1.4.2).
- 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 3.1.3).
- 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 3.1.4.4).
- Global surface temperature (assessed using a combination of changes in air temperatures over land and sea surface temperatures) has risen 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 3.1.4.1).
- 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 UK (section 3.1.5).

iv. What has driven change?

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

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.

3.1.2 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.

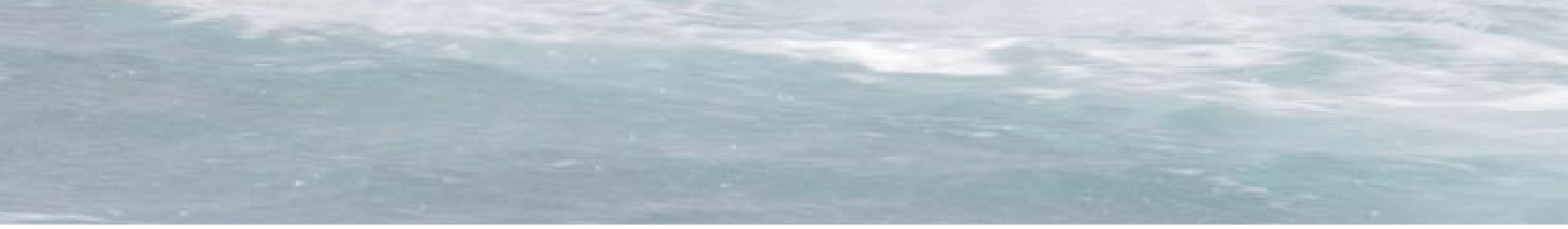
The three main weather parameters that drive ocean circulation are wind speed and direction, air/sea heat exchange and evaporation/precipitation. They affect the strength and character of the Atlantic thermohaline circulation, thereby altering the distribution of sea surface temperature and salinity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

3.1.2.1 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.

3.1.2.2 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).

3.1.2.2.1 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 3.1.2.2.3 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.

3.1.2.2.2 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 3.1). 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 earlier periods of comparable values over the past 500 years.

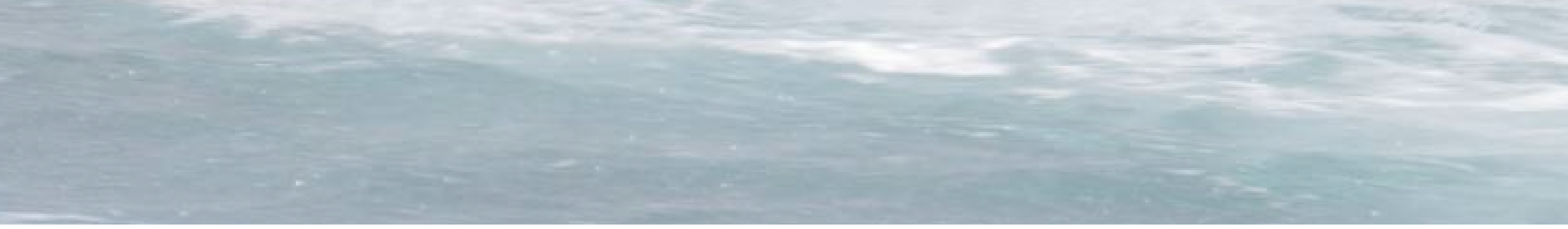
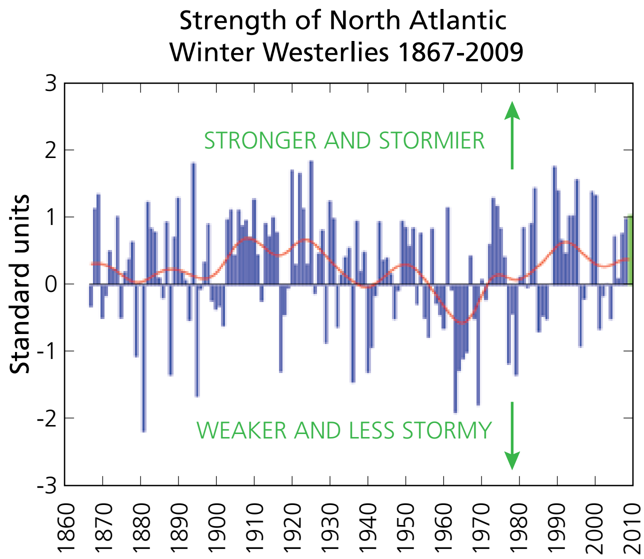


Figure 3.1 North Atlantic Oscillation (NAO) index, 1867-2009, based on the normalized pressure difference between Ponta Delgada (Azores) and Stykkisholmur (Iceland). Figure courtesy of the Met Office.



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.

3.1.2.2.3 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. The relevant topic assessment sections of Section 3 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 3.1.2.2.4), 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 3.1).

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).

3.1.2.2.4 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 topic assessment sections 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).

3.1.3 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 3.1.4.2 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 risen 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 risen 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.

3.1.4 Presentation of the evidence

3.1.4.1 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 risen 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, 2007a).

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.

3.1.4.2 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 risen 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 risen 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 3.2 shows the marine temperatures to have a slightly smaller and delayed annual cycle, smoother variation in 2007, but a similar if perhaps smaller trend from the 1970s to the decade 1998–2007.

The evolution of annual averages of these quantities over the past four decades is shown in Figure 3.3. 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 3.4, showing larger positive trends with greater probability near the UK than to the north or south.

Figure 3.2 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 NOC.

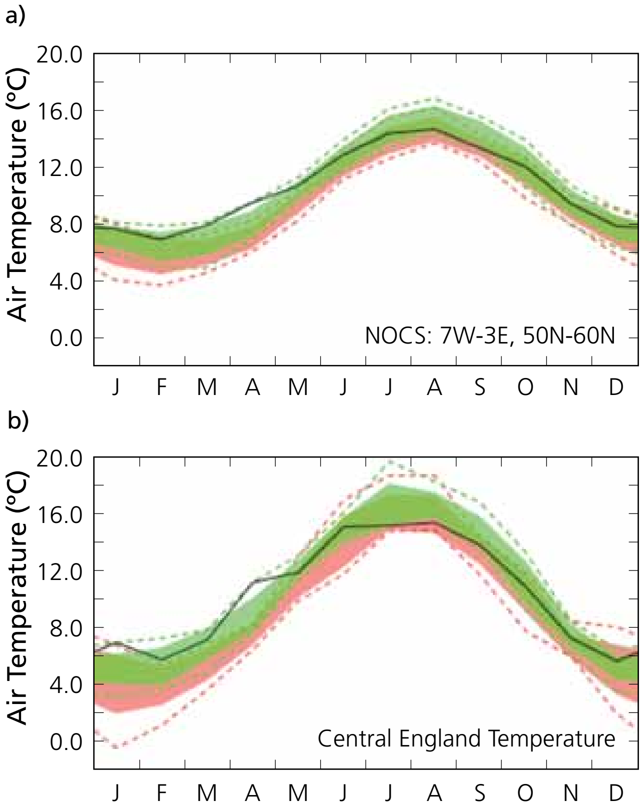


Figure 3.3 Time series of yearly mean marine air temperature estimated from the National Oceanography Centre air temperature analysis for UK shelf waters (7°W-3°E, 50°N-60°N, black), a 2° × 2° grid box in the North Sea (1°W-1°E, 56°N-58°N, red), a 2° × 2° box to the north east of Scotland (1°W-1°E, 60°N-62°N, green) and the Central England Temperature (blue). Figure courtesy of the NOC.

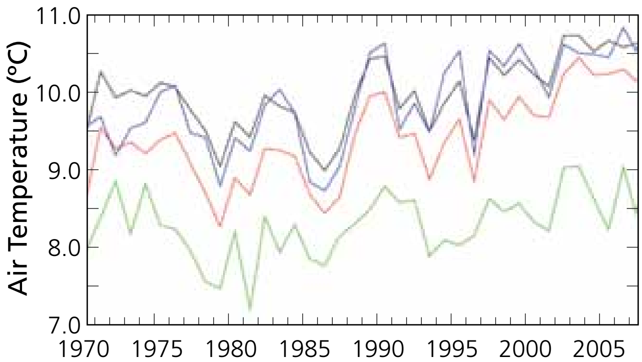
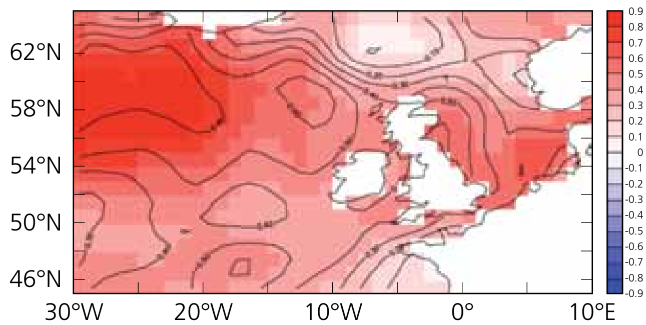


Figure 3.4 Colours show the 26-year linear trend in air temperatures estimated over the period 1982–2007 (°C/decade) from the National Oceanography Centre air temperature analysis. Contours are r-squared values and show where there is confidence in the trends; larger numbers indicate greater confidence. Figure courtesy of the NOC.



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 3.5 shows air temperature as measured from a selection of these buoys.

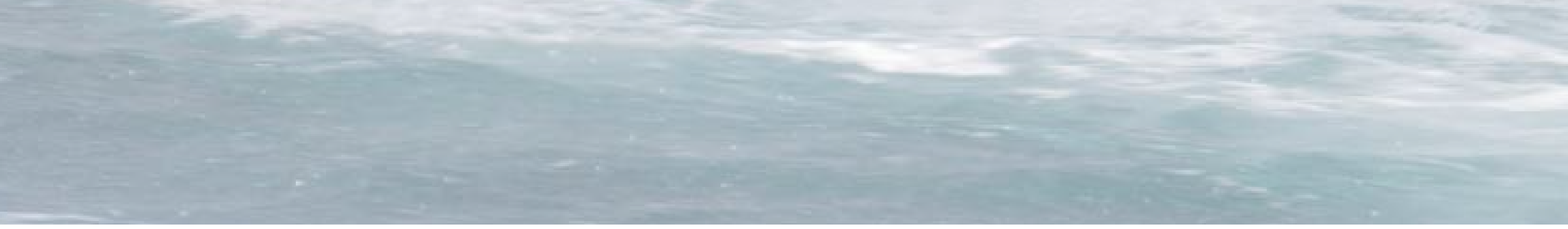
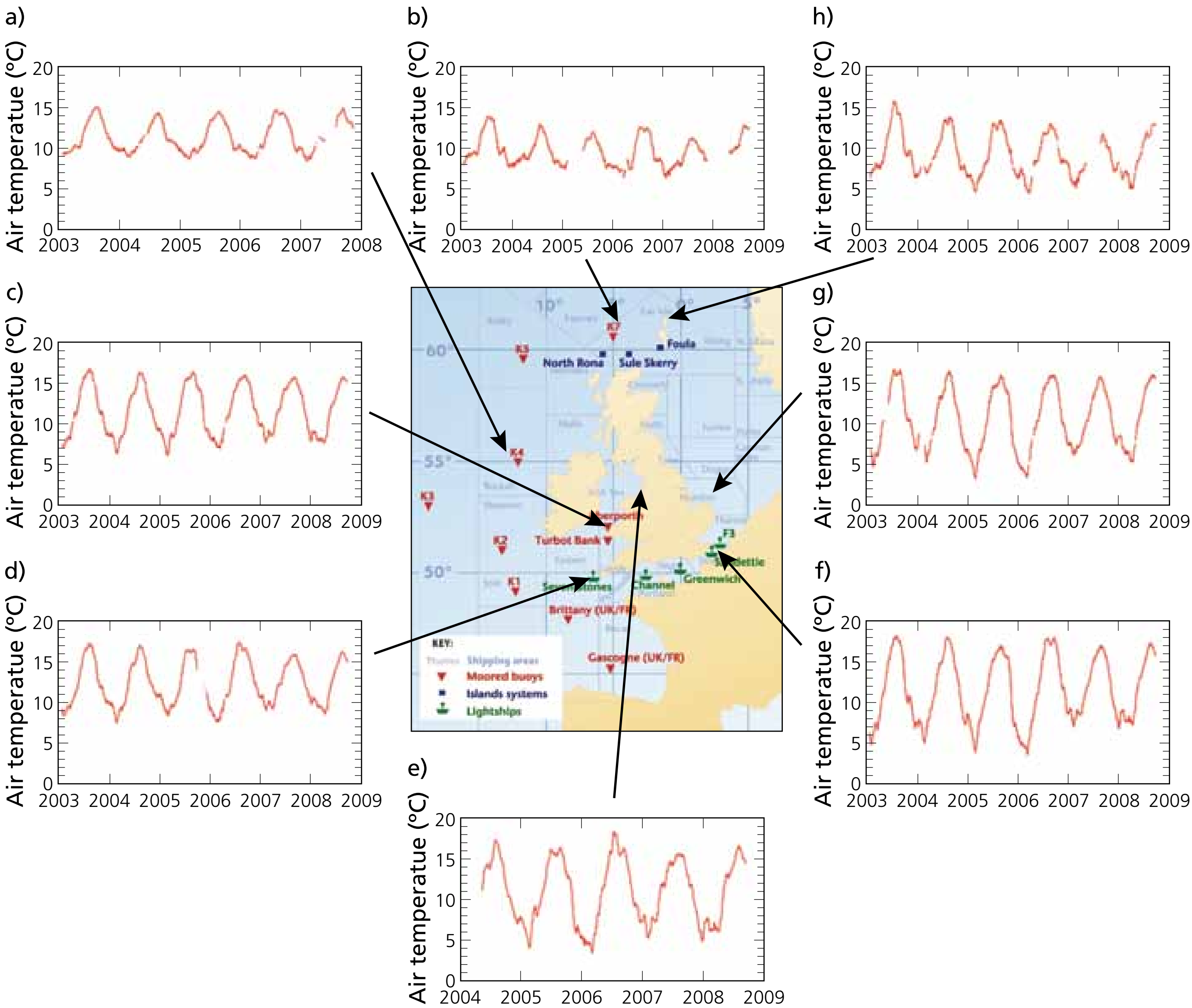


Figure 3.5 Air temperature (°C) measured by UK moored buoys (a) K4 at 55° 24'N, 12° 12'W; (b) K7 at 60° 36'N, 4° 54'W; (c) Aberporth at 52° 24'N, 4° 42'W; (d) Seven Stones Light Vessel at 50° 06'N, 6° 06'W; (e) Hilbre Island at 53° 23'N, 3°14' W; (f) Sandettie at 51° 06'N, 1° 48'E; (g) Leman Bank at 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 NOC.



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).

3.1.4.3 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., 2009) 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, 2007a; see Figure 3.6).

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.

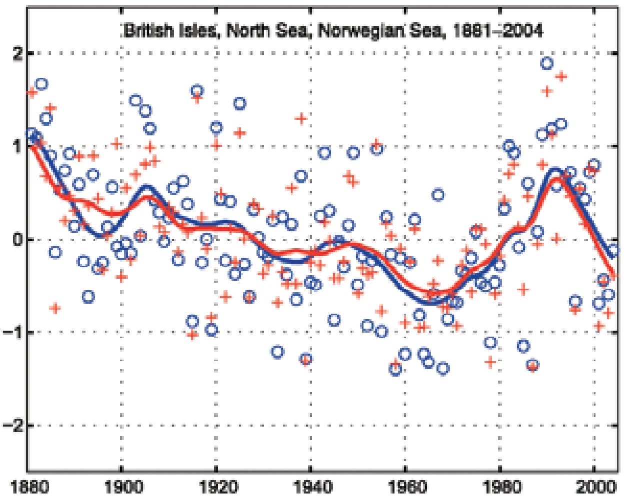
Identification of wind speed trends using station records can be difficult because of changes in site exposure and instrumentation. Those included for well-exposed sites in a study of climate trends across Scotland (Barnett et al., 2006) showed conflicting trends for the past 40 years in annual mean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

Figure 3.7 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. Most series show variation with season, at shorter periods and inter-annually, obscuring any trend.

3.1.4.4 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

Figure 3.6 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).



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 3.8, 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).

3.1.5 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 risen 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 risen 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 3.2, the standard deviation for any month within a

Figure 3.7 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 NOC.

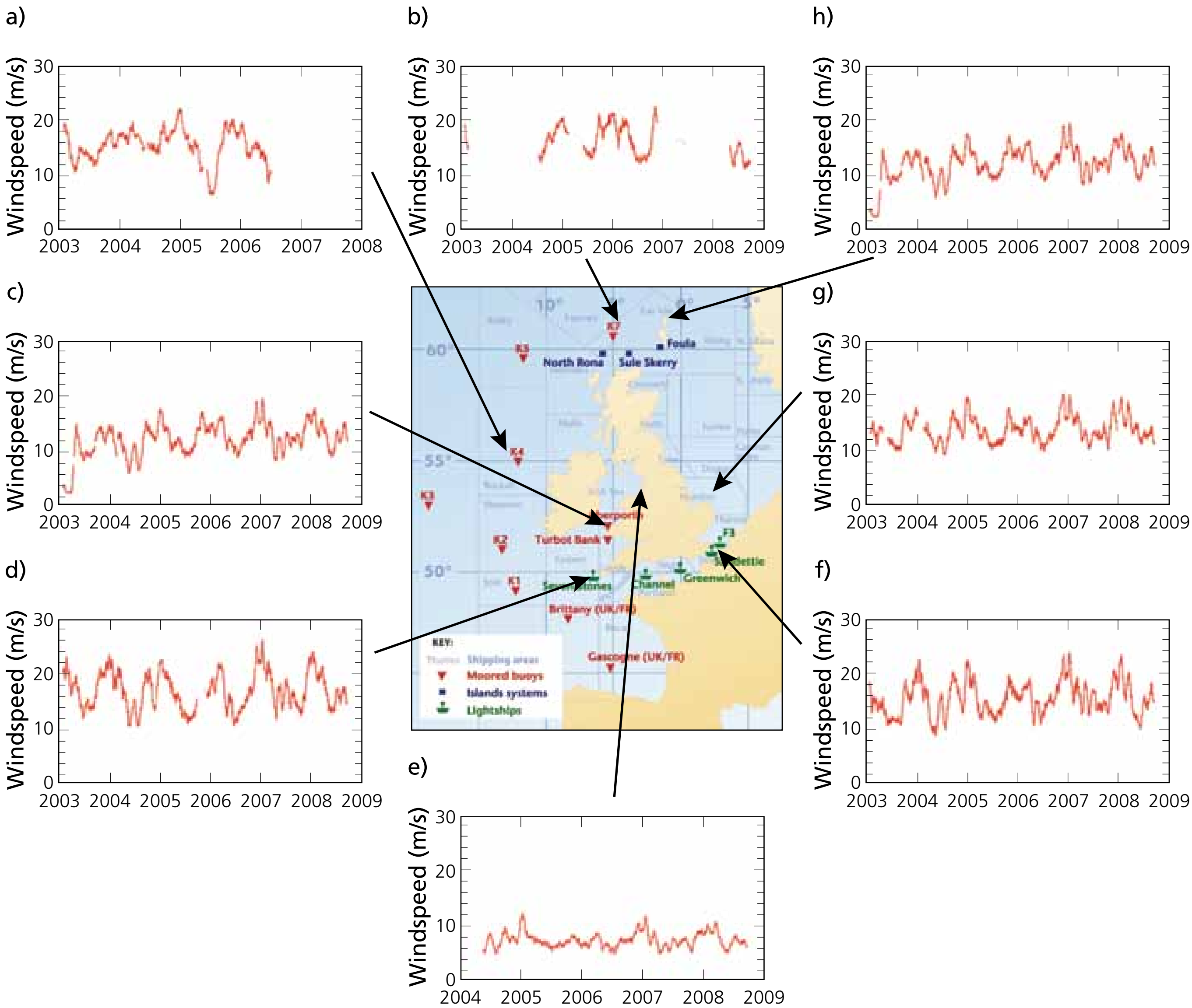
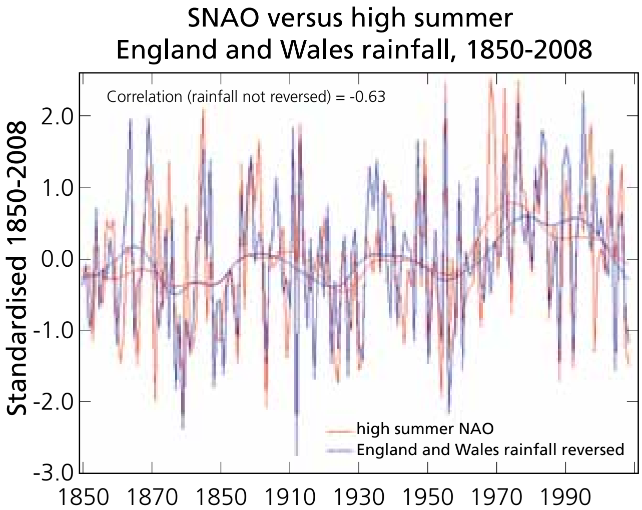


Figure 3.8 The Summer North Atlantic Oscillation and July-August England and Wales rainfall, 1850–2008. The rainfall data have been reversed in sign and both series are standardised over 1850–2008. The smooth lines are low pass filtered for periods >25 years. Source: Folland et al. (2009).



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 3.1) 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.

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 °C, 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

Table 3.1 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

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 3.9 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, greatest 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/).

3.1.6 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?

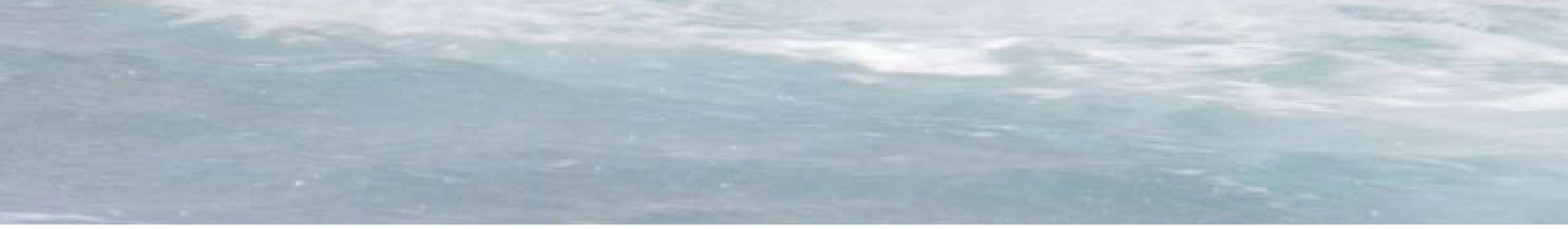
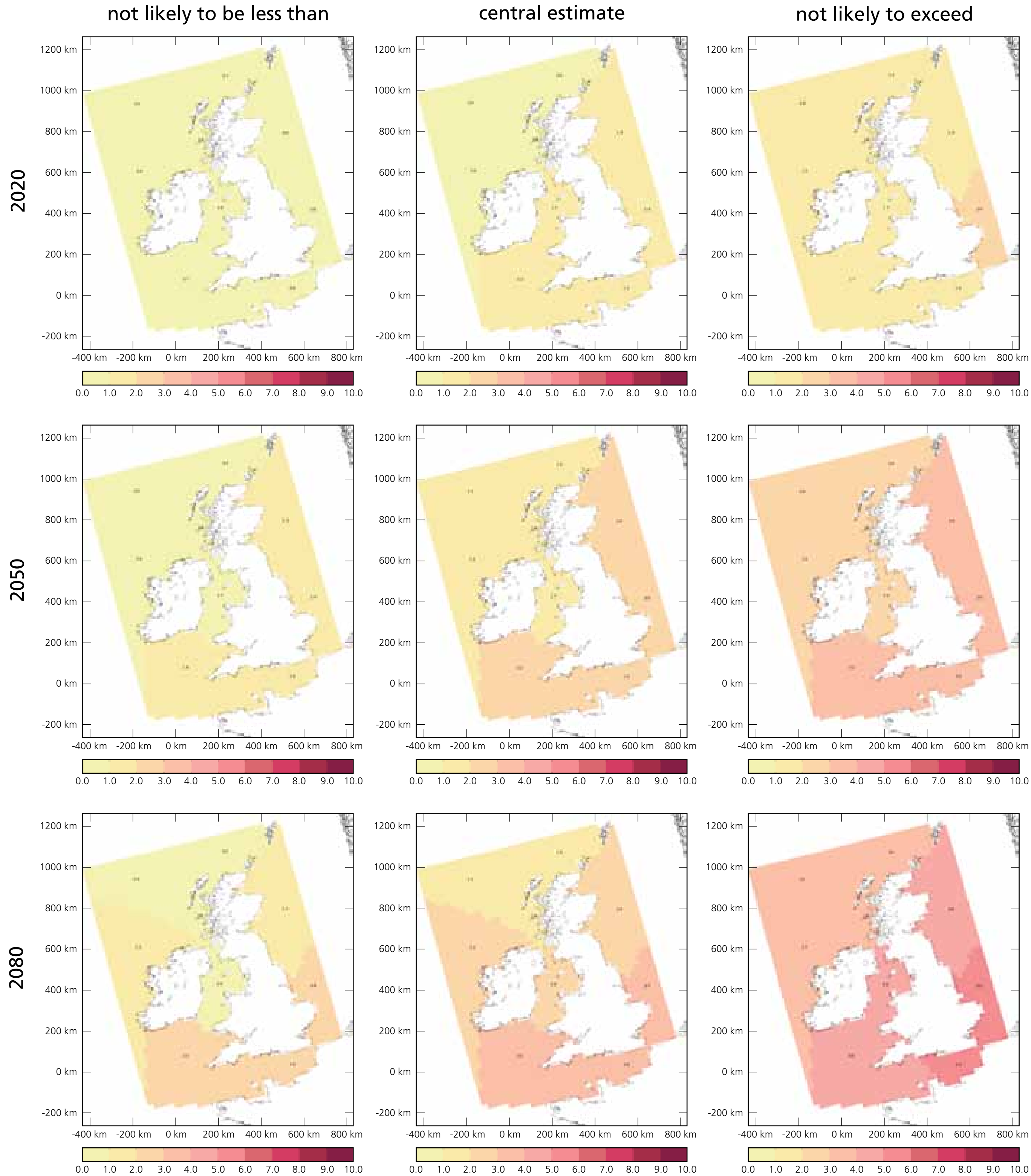


Figure 3.9 Projections for mean air temperature changes in future 30-year periods in UK marine areas (°C relative to 1961–1990) assuming a 'high' emissions scenario (see http://ukclimateprojections.defra.gov.uk/). Source: UKCP09, http://ukclimateprojections.defra.gov.uk/. © UK Climate Projections, 2009.



3.2 Temperature and Salinity

3.2.1 Key points

i. Introduction

Marine temperatures are important to the UK maritime climate and to the marine ecosystem. Some species are sensitive to salinity and may be affected by changes. Adjacent Atlantic temperature and salinity are controlled by the large-scale circulation and history of these waters (ultimately coupled with atmospheric weather and climate). Shelf-sea temperature is controlled primarily by mixing and local weather, with some influence of Atlantic water near where it moves onto the shelf. Temperature has a strong seasonal cycle, larger in shallow water; summer maxima decrease from south to north. Summer stratification (i.e. warmer water near the surface from about May to October) occurs in large areas of UK shelf seas, typically in depths exceeding about 50 m; below, cold bottom water warms only slowly. The water column remains vertically mixed where the depth is relatively shallow and/or tidal currents are large. Salinity is influenced primarily by Atlantic water salinity, and locally by fresher-water inflows from rivers via estuaries; values are usually between 34 and adjacent upper oceanic values 35.3 to 35.6 (measured in parts per thousand); (Sections 3.2.2, 3.2.4.2).

ii. How has the assessment been undertaken?

Variability and trends have been assessed on the basis of many time series spanning several decades. There is no clear reference point or criterion to assess status.

Data come from many sources: Volunteer Observing Ships, drifting and moored buoys, repeated sections, Bottom Trawl surveys, coastal stations, and satellite radiometers. Recent developments include: more profiling floats (the international Argo programme) providing data essential for year-round monitoring in deep waters west of the UK, RAPID monitoring the North Atlantic overturning circulation, FerryBox instrumentation on some ferries, (changed) support for some long-term series (western Channel, Isle of Man, Liverpool Bay) (Section 3.2.2).

iii. Current and likely future status of temperature and salinity

- Global temperature trends are: warming over the past century; fastest warming of surface waters – sea surface temperature (SST) rose by about 0.3 °C from 1910 to 1940, remained steady until the 1970s and has since continued to rise by about another 0.4 °C. Global and North Atlantic warming trends apply to Atlantic waters adjacent to the UK. The warming is especially evident near the surface and since the mid-1980s has been of the order of 0.5 to 1 °C. However, a global and Atlantic decrease in salinity at UK latitudes is not seen in Atlantic waters adjacent to the UK; with salinity here increasing by 0.05 to 0.1 since the late 1970s 'Great Salinity Anomaly' minimum. On top of these overall trends is spatial and interannual-to-decadal variability of the order of 0.5 to 2 °C in temperature and 0.05 to 0.1 in salinity (Sections 3.2.4.1, 3.2.4.2).
- Annual SST averaged around the UK coastline has risen by about 0.5 to 1 °C for the period 1871 to 2000. Much of the warming occurred in the period 1920 to 1940 and again since the mid-1980s; the latter was common with UK shelf waters SST, being especially pronounced in the southern North Sea, Irish Sea and Tiree Passage (Sections 3.2.4.2, 3.2.4.3).

- Salinity trends vary (tending to increase where influenced most by Atlantic water).
- Spatial and interannual temperature variability in UK waters is of the order of 0.5 °C; up to 2 to 3 °C in shallow areas for an extreme month. Winter temperatures tend to be higher when westerly winds prevail. Likewise, shorter-term salinity variability exceeds the multi-decadal trend. Irish Sea salinities are especially variable; freshwater inputs are relatively important (Section 3.2.4.3).
- In future, climate change may bring reduced flow of warm Atlantic water past the west of the UK. However, shelf-sea temperatures are likely to follow the atmospheric climate quite closely. Modelled future scenarios suggest most warming in the south and east, especially in autumn, and a general increase in the number of stratified days. Confidence in these predictions is low to moderate (Section 3.2.5).
- Future salinities over the shelf will reflect a combination of adjacent oceanic values (hitherto with small variability of the order of 0.1) and freshwater inputs: from rivers and net rainfall minus evaporation. Modelled future scenarios suggest lower salinity (by roughly 0.2) in UK waters at the end of the 21st century; confidence in this prediction is low (Section 3.2.5).

iv. What has driven change?

Temperature and salinity changes in the Atlantic are controlled by the large-scale circulation coupled with atmospheric weather and climate. In shallower UK shelf seas, changes in local weather and climate (influenced by Atlantic waters) are the main factor affecting temperature; salinity is locally reduced by variable outflows from rivers.

v. What are the uncertainties?

Interannual variability exceeds longer-term trends over periods of decades, making trends difficult to determine. The spatial resolution of salinity measurements is sparse relative to local variations near river outflows. For the future, climate scenarios for temperature are uncertain, for rainfall even more uncertain; these uncertainties increase at the regional level.

vi. Forward look

Operational models assimilate regularly-measured data to provide day-to-day estimates of the ocean state and forecasts of its evolution. This entails maintaining the present intensity of measurements to constrain model forecasts close to 'truth'. Argo has proved particularly valuable below the surface of the deep ocean; there is no equivalent in UK shelf seas. There is scope for model experiments to estimate what density, frequency and allowable time-delay in observed data provide the best (cost/benefit) value for predictions, forecasts and state-estimation.

3.2.2 Introduction

Heat and salt in the seas are critical to climate; controlled by temperature and salinity differences, the seas store and transport large amounts of heat.

Globally, ocean temperatures vary from about -2 °C, in deep polar waters and where ice forms, to over 30 °C in some tropical waters and marginal seas in hot arid regions (e.g. Red Sea, South Australian gulfs). Surface waters are generally warmer towards the tropics, and towards the western side of sub-tropical oceans as a result of circulation. In the North Atlantic, this is exemplified by the Gulf Stream from which warm surface waters extend north-eastwards, some eventually flowing past the

UK to the Norwegian Sea (after cooling). Except in polar regions, surface waters are generally warmer than deep water below the main 'thermocline' (where the temperature changes rapidly with depth); the main thermocline is several hundred to a thousand metres deep in the NE Atlantic. In the sub-tropics and towards polar seas, the top 50 m or so, above a seasonal thermocline, are warmer in summer than water below; in autumn, surface cooling and mixing deepens the seasonal thermocline, usually down to the main thermocline by the end of winter. The Atlantic adjacent to the UK has typical temperatures as shown in Table 3.2.

In the shallower shelf seas around the UK, temperature changes near the deeper Atlantic can reflect the movement of Atlantic Water onto the shelf. This influence of Atlantic Water on temperature is greatest at the shelf edge and decreases onto the shelf. Some influence of Atlantic Water properties appears in MCCIP (2008) plots of temperature since 1970; the north-western North Sea (at the seabed), the core Atlantic Water at the western shelf edge of the Norwegian Trench, and the Fair Isle Current (between Orkney and Shetland) show similar variations on 5- to 10-year timescales.

For the majority of the north-west European shelf seas, not reached by Atlantic Water within a few months, the main factors controlling temperature are mixing (by currents) and weather: local and regional; solar heating and heat exchange with the atmosphere (Sharples et al., 2006). This is because the timescale for adjustment of temperature in O(100 m) water to the atmosphere is a few months (only). Hence the Atlantic influence is primarily via the atmosphere (i.e. prevailing westerly winds). In winter, a positive North Atlantic Oscillation (NAO) Index (see Section 3.1: Weather and Climate) usually corresponds with higher air temperatures and stronger wind speeds, thereby affecting atmosphere-ocean heat exchange. Loewe (1996) found that the NAO Index accounts for 40% to 50% of the winter SST variability in the southern North Sea. Spring and summer heating causes water in the top 30 to 50 m to be warmer than below, unless tidal currents are strong enough to mix through the total depth all year (which typically occurs in depths of less than 50 m). Typical shelf sea temperatures are as shown in Table 3.3.

Locally, cooling water from power stations may have a significant effect. A modern power station may discharge heat of order of 3 GW in cooling water, comparable with solar heating over 10 km^2. (The marine effect is minimized if the discharged water is hot, on the surface and losing heat rapidly to the atmosphere.)

Salinity may be defined as the mass of dissolved material per mass of seawater (solution), expressed in parts per thousand. According to depth, NE Atlantic salinities are typically in the range 34.9 to 36 (about 35.2 to 35.6 in upper waters adjacent to the UK). Individual water types may show changes of the order of 0.1 on time scales of years to decades. Values of the order of 35 (as distinct from 30 or 40) have been established on time scales of millennia and longer.

In UK shelf seas, salinities are typically 34 to 35, slightly less than in the adjacent Atlantic. Influences are the salinity of Atlantic Water (predominant; unlike temperature), exchanges of water with the atmosphere (slight) and freshwater from land and rivers (locally important). Areas on the continental shelf which are most influenced by inflowing oceanic waters were typically fresher in the mid- to late 1970s, related to the passage of the 'Great Salinity Anomaly'. The atmosphere is a net source of

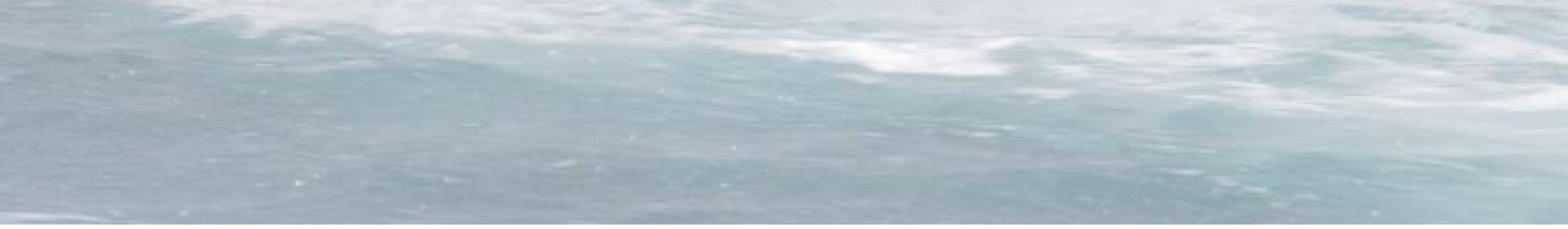


Table 3.2 Typical temperatures (°C) of Atlantic Ocean waters near the UK.

Depth, m	*SW of UK, winter*	*SW of UK, summer*	*NW of UK, winter*	*NW of UK, summer*
0–50	10–12	16–18	9–10	12–14
200–500	10–12	10–12	9–10	9–10
2000	3–4	3–4	3–4 (< 0 in Nordic)	3–4 (< 0 in Nordic)

Table 3.3 Typical temperatures (°C) of UK shelf seas.

	Celtic Sea winter	*Celtic Sea summer*	*S. North Sea winter*	*S. North Sea summer*	*N. North Sea winter*	*N. North Sea summer*
Surface	9–11	16–18	4–8	16–19	6–9	12–14
Bottom	9–11	10–14	4–8	16–19	6–9	6–10

freshwater where rainfall exceeds evaporation; in fact over many UK shelf-sea areas rainfall minus evaporation is within ± 200 mm/y. Indeed, ± 200 mm/y freshwater input (variability) corresponds to changes in salinity of less than 1% (0.3), if (as typically) the depth exceeds 20 m and water flows through in periods of a year or less. Inputs of freshwater from land and rivers are moderate in global terms, but exceed the net atmospheric input in most UK shelf-sea areas except to the west and north of Scotland (Regions 6 and 7; because most of Scotland drains eastwards; however, Regions 6 and 7 are affected by fresher water from the Clyde and Irish Sea – Region 5 – where river inputs are relatively important). Salinity near river outflows depends strongly on the mixing between river and sea water in estuaries, and on river flow strength. Outflow salinities are typically between 30 and 35, as most UK estuaries are well mixed and the volume change between high and low water is large relative to river flow during one tidal cycle. Salinities may be lower in a surface layer if mixing is weak (as favoured by small tidal range, neap tides, deep estuarine and coastal waters).

Changes in sea temperature cause sea level changes (q.v. Section 3.5: Sea Level); warming causes sea-level rise through thermal expansion.

Heat storage and transport in the ocean are important because the specific heat and density of water are large (relative to the atmosphere). Meridional (tropics to poles) transport of energy is required for the Earth system to be in global radiative balance; some 30% to 50% of this energy transport is via ocean currents at mid-latitudes and an even larger proportion at lower latitudes (Bryden and Imawaki, 2001). Ocean circulation (transporting heat) is determined primarily by forcing due to momentum, heat and water fluxes to and from the atmosphere; the distributions of temperature and salinity in the ocean establish its density structure and density differences drive currents. Mixing due to wind and tidal energy input also controls the density structure and enables meridional overturning circulation (e.g. warm poleward flow above deeper equatorward flow in the North Atlantic). The density structure also affects the smaller-scale dynamics of fronts and eddies – 'ocean weather' – which, together with the Antarctic

Circumpolar Current and western boundary currents like the Gulf Stream, are the most energetic open-ocean flows. Near coasts, fresher waters from rivers often result in (1) estuarine circulation having net surface outflow and bottom inflow, (2) along-shore coastal currents, and (3) density stratification (which varies according to wind conditions) with fresher water on top (as it is less dense). Fresher water exiting the Irish Sea, and local river outflows, drive the Scottish Coastal Current northwards around western Scotland.

Descriptions of monitoring networks that regularly measure sea temperature and salinity are given by the UK Directory of the Marine-observing Systems (www.ukdmos.org). These monitoring networks are extensive and include: Argo profiling floats; Volunteer Observing Ships (VOS); drifting and moored buoys which are the primary source of Hadley Centre SST data HadISST utilised here; sections (the 'extended Ellett line') across Rockall Trough and to Iceland; sections across the Faroe-Shetland Channel; Marine Automatic Weather Stations (MAWS, on moored buoys and lightships around the UK); several ferry routes; several locations of maintained offshore mooring locations and sections or grids surveyed on the continental shelf; many coastal time series. Ships can measure surface temperature and salinity while underway; satellite radiometers give a measure of sea-surface (skin) temperature. Stratification and bottom temperature and salinity are not so widely measured; although the annual ICES International Bottom Trawl Survey specifically measures bottom temperature and salinity.

Daily analyses of SSTs for the global ocean are produced by Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA; Stark et al., 2007), with resolution 1/20° (approx. 5 km). OSTIA uses satellite data provided by the GHRSST project, together with *in situ* observations to determine SST. An example is given in Figure 3.10 showing seasonal distributions for the North Atlantic. Notable features are (1) cold surface waters extending from the Nordic Seas around Greenland to the Labrador Sea and US east coast, (2) warm water in the Gulf Stream and its extension across the North Atlantic to Iceland, UK and Norway, and (3) large seasonal range in the Baltic, Mediterranean and Black Seas. Figure 3.11 shows seasonality and some interannual variability in the spatially averaged SSTs shown in Figure 3.10.

Salinity and temperature play important roles in the functioning of marine ecosystems. Some examples follow. Stratification in the upper water column can be important to primary production; in some cases prompting a spring phytoplankton bloom. The salinity of water overlying the seabed affects nitrogen release from sediments and thus its availability for primary production. Many organisms or life stages are adapted to specific salinity ranges, especially in saline pools, lagoons and estuaries; salinity fluctuations can cause sub-lethal stress or even death. Sea temperature affects the geographic distribution of marine biota and can cause changes in biodiversity, with effects on species composition, reproduction, plankton and fish populations. Hátún et al. (2009) attributed bio-geographical shifts in the NE Atlantic to exchanges of sub-arctic and sub-tropical water masses. Edwards et al. (2001) showed that there has been a steady increase in phytoplankton biomass in the North Sea since the mid-1980s; a peak in 1989 corresponded with anomalously warm SSTs. Beaugrand et al. (2002) found rising sea temperatures to be a factor in the northward extension (by more than 10° latitude) of warm-water copepods (small planktonic crustaceans). There has been a similar retreat of colder-

Figure 3.10 Surface temperatures from the OSTIA analysis for January, April, July and October 2007. © Crown Copyright 2007, published by the Met Office.

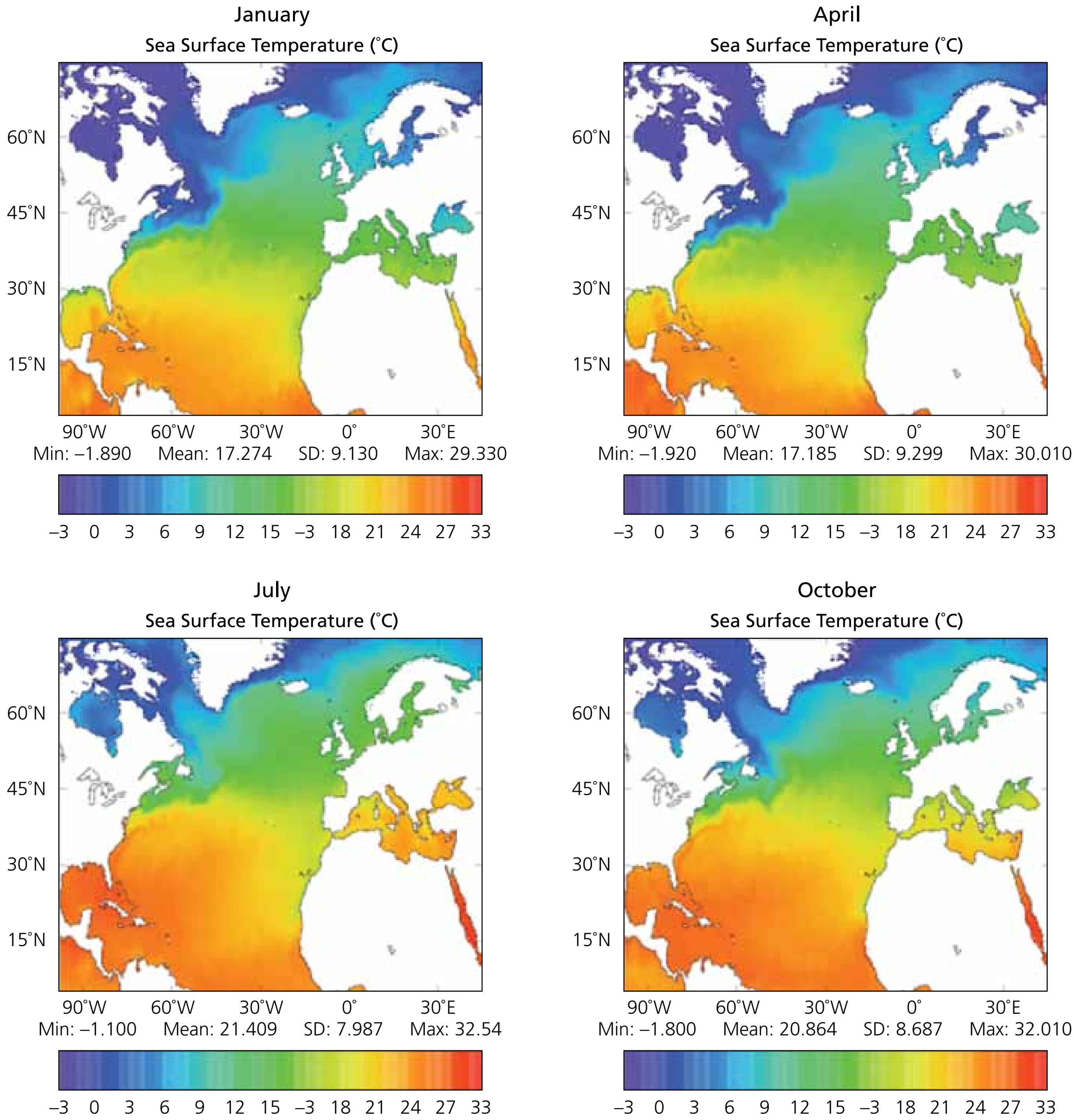
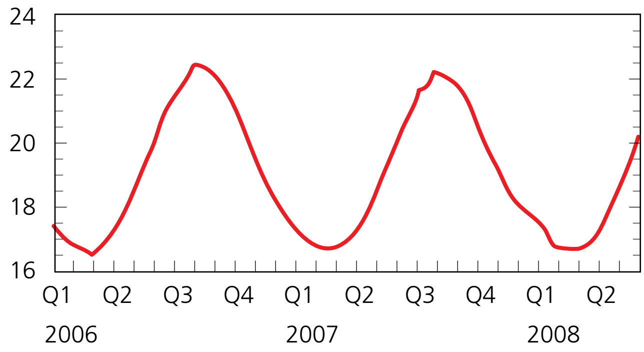


Figure 3.11 The spatially averaged surface temperature for the North Atlantic region (as given by the region shown in Figure 3.10). Courtesy of the Met Office.



water plankton to the north (a mean poleward movement of 200 to 250 km per decade (see those sections of the HBDSEG Feeder Report on Plankton and Fish where such changes are discussed further).

3.2.3 Progress since *Charting Progress*

The IPCC Fourth Assessment Report (Meehl et al., 2007) reinforced the concept that global temperatures are rising with climate change.

In general, the array of temperature and salinity measurements around the UK has been maintained and in some respects enhanced. Changes in the array include:

- more Argo profiling floats (in deep oceans globally; specifically in the North Atlantic); these have greatly improved monitoring of temperature and salinity down to 1500 m
- RAPID monitoring of the North Atlantic Meridional Overturning Circulation
- a few changes in the MAWS (Marine Automatic Weather Station) array
- increased use of ferry routes with installation of FerryBox or similar equipment on ships
- support for the Western Channel locations E1 and L4 as sustained observations
- some changes in the arrangements for monitoring around the Isle of Man with closure of the Port Erin Marine Laboratory (the longest time series are continuing). Launch of NCOF (the National Centre for Ocean Forecasting) in 2005 formalised Met Office collaboration with the UK academic community; it allows efficient input of world-class science to operational marine model forecast products for UK waters and beyond (some products have been available for more than a decade). Important products from model forecasts include temperature and salinity through the water column, supplementing the measurements which are fewer at depth than near the surface.

3.2.4 Presentation of the evidence

3.2.4.1 Global and North Atlantic sea temperature and salinity

Globally, the ocean is warming as shown by the heat content having increased significantly since the late 1950s. All oceans, including the Atlantic, show a net warming (Levitus et al., 2000; Bindoff and Willebrand et al., 2007: fig. 5.1). More than half of the increase in heat content has occurred in the upper 300 m of the ocean, equivalent to a rate of warming of about 0.04 °C per decade (IPCC, 2001); in the upper 700 m, the rise was about 0.1 °C in the period 1961 to 2003 (Meehl et al., 2007). Global SSTs for the past 100 years show two distinct warming periods: the first from about 1910 to 1940 with a warming of about 0.3 °C, and the second starting during the 1970s with warming of another 0.4 °C (Trenberth and Jones et al., 2007: fig. 3.4). However, there is significant variability on decadal or shorter time scales (e.g. relative cooling in the mid-1980s and high values in the period 1997 to 1998). Thus the global trends illustrated in Figure 3.12 comprise warming over the past century, additional variability on all time scales, and fastest warming of surface waters.

Ocean salinity is changing on gyre and basin scales (Bindoff and Willebrand et al., 2007). Where evaporation is fast, near-surface salinity is increasing in almost all ocean basins. At high latitudes, surface waters are freshening consistent with greater rain- or snowfall; more freshwater from land and rivers, ice melting, advection and changes in circulation may also contribute.

Atlantic salinity increased during the period 1955 to 1998 in the area defined by 15° to 42° N but decreased in the area defined by 42° to 72° N (Bindoff and Willebrand et al., 2007: figs 5.5–5.7). These trends accord with the global trends (increasing salinity of more saline waters and freshening of less saline waters). However, the North Atlantic experienced further variability, with freshening during the Great Salinity Anomaly in the 1970s and a further minimum in the 1990s. Since the 1990s minimum, the upper ocean west and north of the UK is again more saline, reflecting the proportions of inflowing sub-tropical (saline) and sub-polar (fresher) water (Holliday, 2003a; Meehl et al., 2007; MCCIP, 2008; Ivchenko et al., 2009).

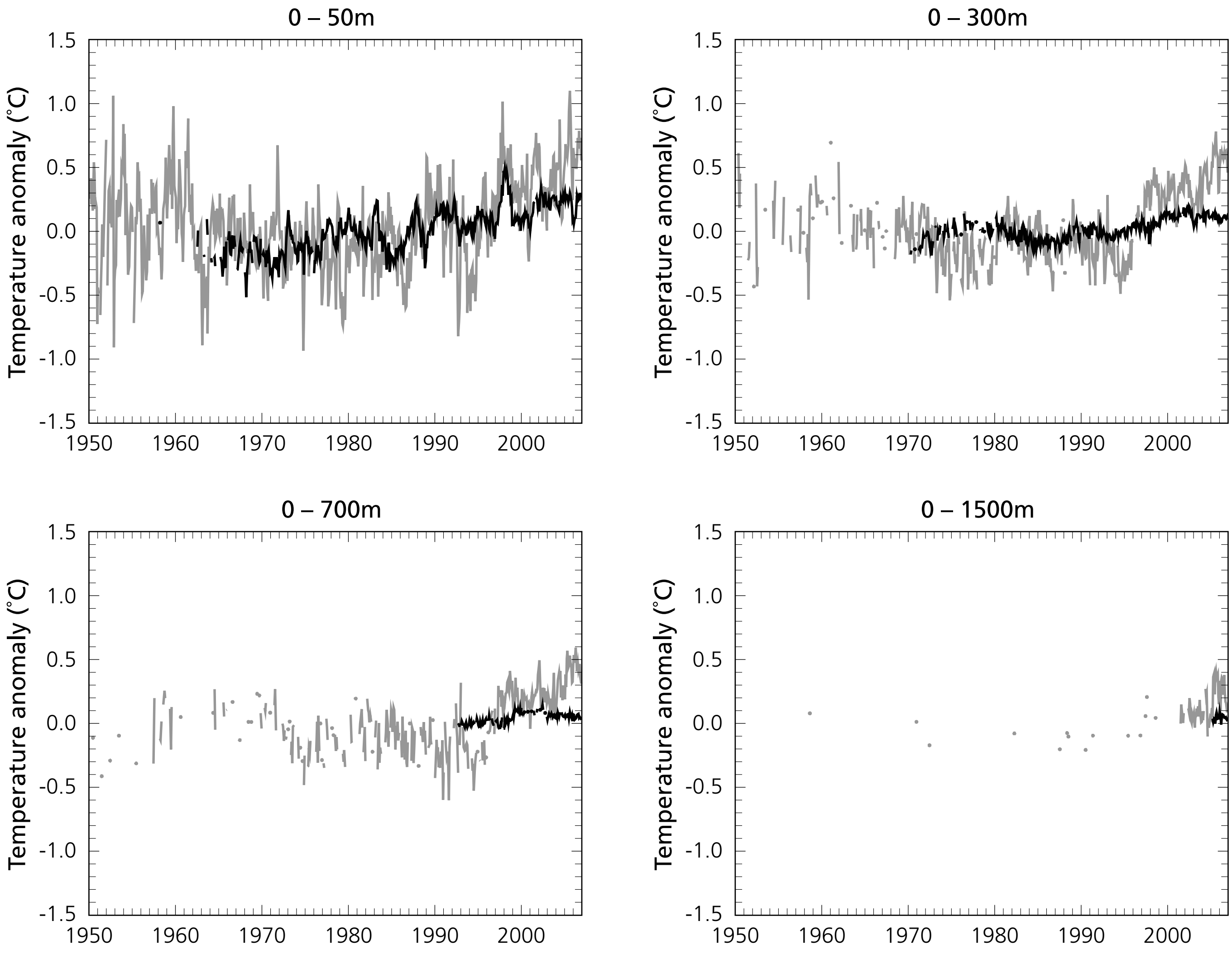
NE Atlantic temperature trends are compared with global trends in Figure 3.12; the region appears to have warmed relatively rapidly from an anomalously cool start in the period from 1993. (Here and in many places following, seasonality is 'removed'; an overall mean for each month is subtracted month by month from the time series to produce a monthly anomaly time series). North-Atlantic SST has risen faster than the global average over the past 25 years (and especially since 1993), perhaps due in part to the Atlantic Multi-decadal Oscillation (MCCIP, 2008): this is a natural mode of variability; North Atlantic SST is the dominant feature; successive peaks and troughs are at intervals of roughly 65 years (Knight et al., 2005). The greater variability in surface waters is to be expected (less thermal capacity in the 0 to 50 m depth range than in 0 to 300 m or deeper). Trends also vary spatially in the NE Atlantic.

With sufficient Argo tracked floats (from 2001), temperature in the NE Atlantic can be monitored to 1500 m depth; Figure 3.12 shows the correspondingly improved availability of data at depth. Ivchenko et al. (2006, 2009) analysed Argo temperature data to monitor changes in oceanic heat content in the North Atlantic as a function of depth and latitude band (Figures 3.13 and 3.14). Figure 3.13 (40°–50° N and 50°–60° N) shows warming on which is superimposed 'quasi seasonal' variations. Figure 3.14 (40°–60° N, 0°–30° W) shows warming overall but relative cooling from mid-2005 to the beginning of 2007 (the end of the analysis period); this may just be 'normal' interannual variability.

Operational analyses (and forecasts) of ocean temperature and salinity fields at 1° (latitude by longitude) and 1/9° resolution are produced routinely by the Met Office's Forecasting Ocean Atmosphere Model (FOAM; Martin et al., 2007). The analyses assimilate observed data; for subsurface structure the model relies heavily on the availability of Argo profiles.

The temperature anomaly fields (Figure 3.15a) show cooling from 2005 to 2007 in some areas at all three levels in the NE Atlantic. The cooling is most pronounced at the 1000 m level (influenced by the Labrador Sea water mass) west of Ireland. This cooling pattern

Figure 3.12 Sub surface ocean temperature time series. The plots show anomalies averaged over the globe (black) and the NE Atlantic (44°N–66°N, 30°W–10°E; grey), and between the surface and 50, 300, 700 and 1500 m. The ocean profiles were initially averaged onto a 2° by 2° lat/long grid and anomalies were derived by subtracting a climatology calculated from the data for 1956–2004. Time series points are plotted only in months when at least 10% of the ocean grid cells were sampled. The data source was the EN3 dataset (available from www.metoffice.gov.uk/hadobs), while processing followed the methodology of Palmer et al. (2007). Courtesy of the Met Office.



reinforces the findings from the Ivchenko et al. (2006) analysis and suggests that cooling from 2005 continued at least until early 2007. The corresponding salinity anomaly fields (Figure 3.15b) suggest freshening between 2005 and 2007, particularly marked in the north of the analysis area and at the deepest level, 1000 m.

Despite 2005-2007 cooling, warming (since the mid-1980s and before) is found in all shelf-sea regions around the NE Atlantic (Hughes et al., 2008). Synthesis of the 30-year data set from the Ellett Line (Rockall Trough) with other sustained ocean observations from the North Atlantic and Nordic Seas shows the spread of warm water throughout the region. Time lags along the

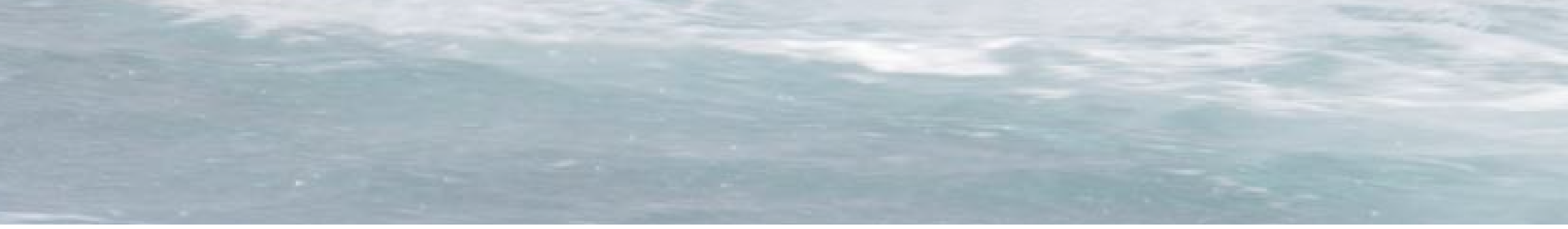


Figure 3.13 Changes in heat content in the upper 1500 m of the water column, for the full-width of the North Atlantic at (a) 40°–50°N and (b) 50°–60°N. The plots show monthly (blue), 7-point filter (red) and 5-month moving averages (smoother blue). Year numbers indicate the start of each year. The temperature rises suggested by the linear fits are about 0.2 °C. Courtesy of V. Ivchenko, NOC.

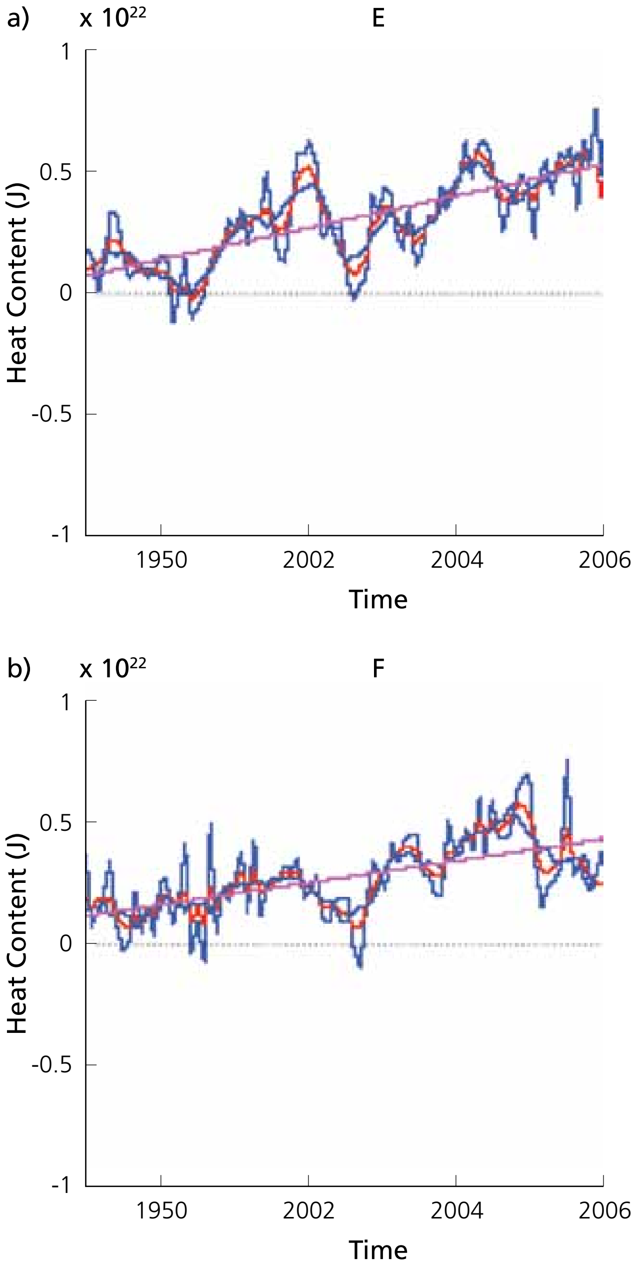
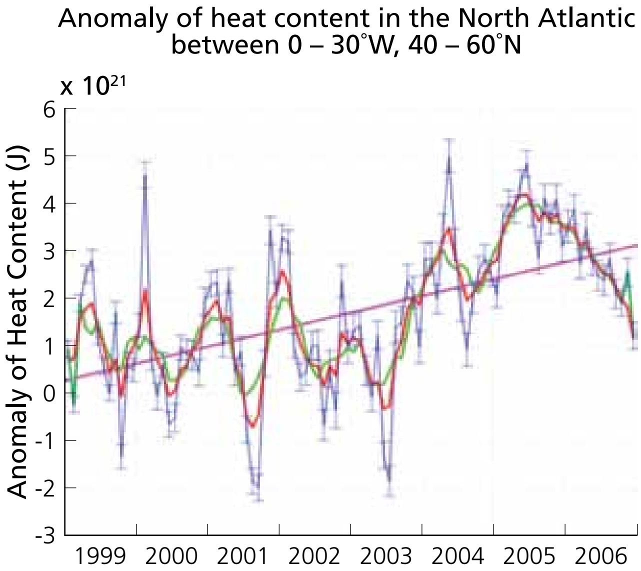


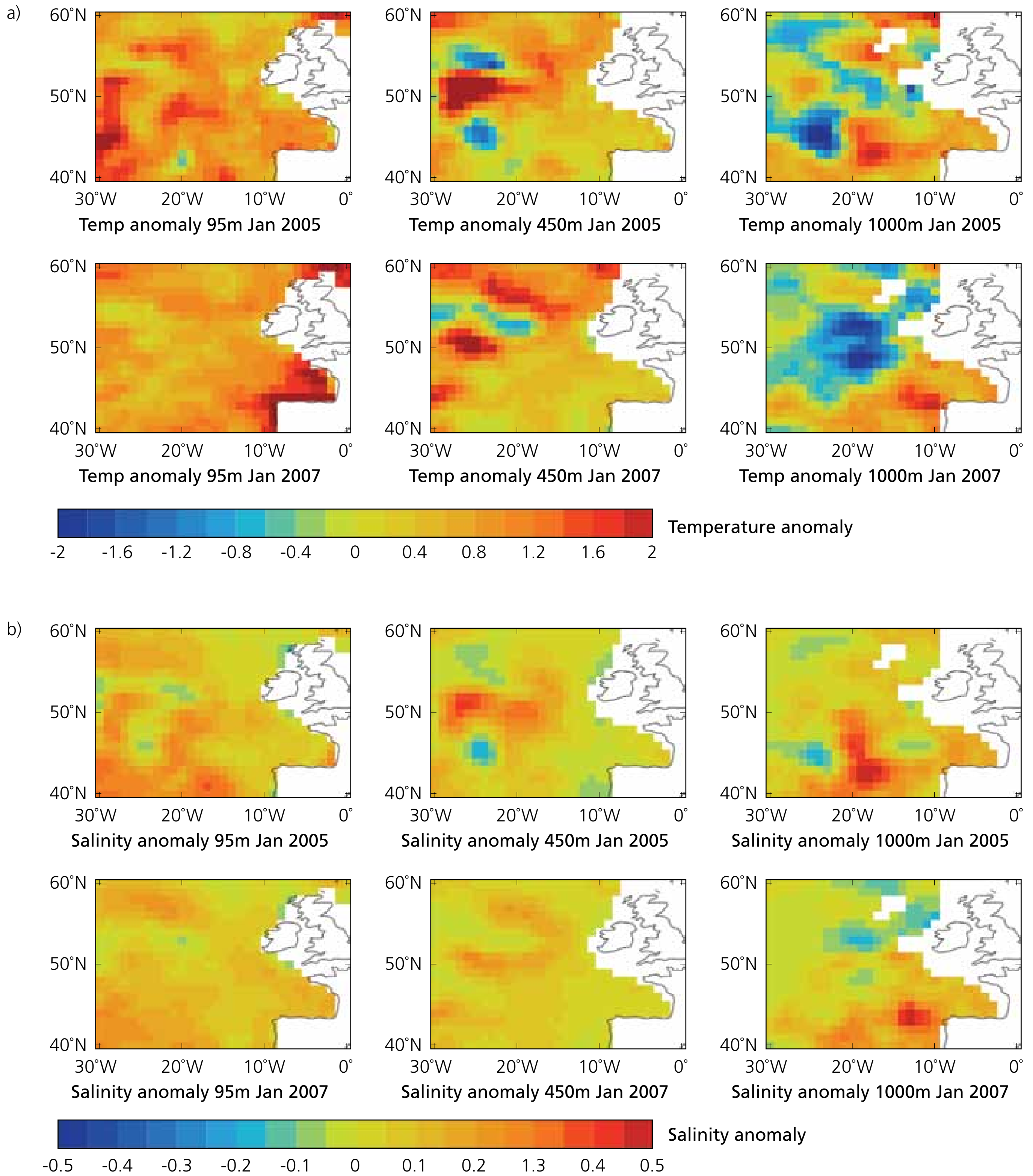
Figure 3.14 Changes in heat content in the upper 1500 m of the water column in the NE Atlantic for the region defined by 40–60°N, 0–30°W. Year numbers indicate the start of each year. The plot shows the monthly (blue), 7-point filter (red) and 5-month moving average (green). The temperature rise suggested by the linear fit is about 0.13 °C. After Ivchenko et al. (2006). Courtesy of V. Ivchenko, NOC.



spreading pathway can be explained by the net advective speed of the Atlantic inflow; the time lag from the Ellett Line in the northeast subpolar gyre to Fram Strait is 3 to 4 years. The data show that interannual to decadal-scale patterns of variability have a large-scale coherence (Holliday et al., 2008). Warming since 1983, in the North Atlantic adjacent to the UK is also illustrated in Figure 3.16 (sub-surface) and Figure 3.17 (SST), along with spatial variability in the trends.

The SST trends in Figure 3.17 may be compared with marine air temperature trends in Figure 3.18. There are broad similarities (overall positive, similar magnitudes, greater towards the west / west-north-west and in the southern North Sea). A marine effect on westerly air flow

Figure 3.15 (a) Temperature and (b) salinity anomaly fields (departures from the Levitus climatology), 40°–60°N, 30°W–0°E, January 2005 and January 2007. Winter dates were chosen to ensure that near surface fields were meaningful and unaffected by seasonal stratification. 1° resolution output is shown. Gaps are due to intersection of the analysis level with bottom topography. Courtesy of the Met Office.



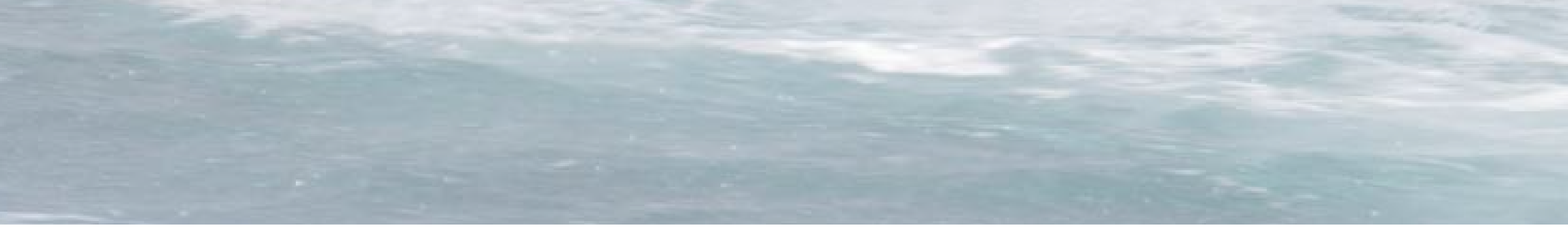


Figure 3.16 Sub surface ocean temperature. Linear trends (°C/decade) in annual UK/North Atlantic anomalies for 1983–2006 averaged between the surface and (a) 300 m and (b) 700 m depth. The ocean profiles were initially averaged onto a 1.25° by 1.25° lat/long grid and anomalies were derived by subtracting a climatology calculated from the data for 1983–2006. Trends are plotted only where at least 50% of the years were sampled. The data source was the EN3 dataset (available from www.metoffice.gov.uk/hadobs), while processing followed the methodology of Palmer et al. (2007). Courtesy of the Met Office.

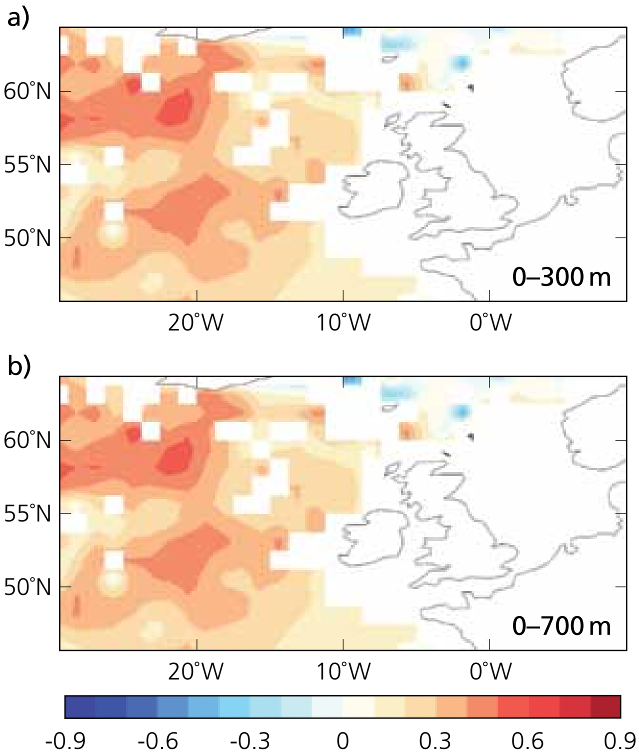


Figure 3.17 Sea surface temperature. Linear trends (°C/decade) in annual UK/North Atlantic anomalies for 1983 2007. The SST analysis is on a 1° by 1° lat/long grid and anomalies were derived by subtracting a climatology for 1961–1990. The data source was the HadISST1 dataset (available from www.metoffice.gov.uk/hadobs). Courtesy of the Met Office.

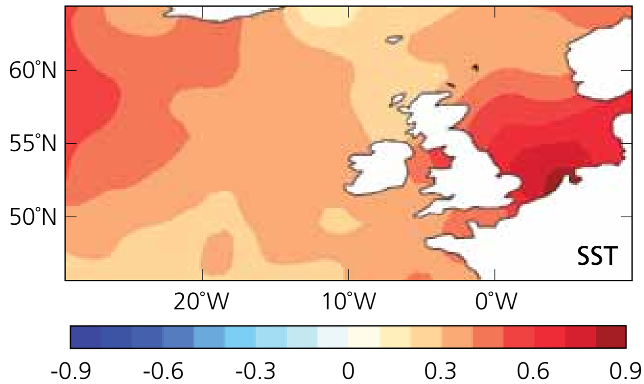
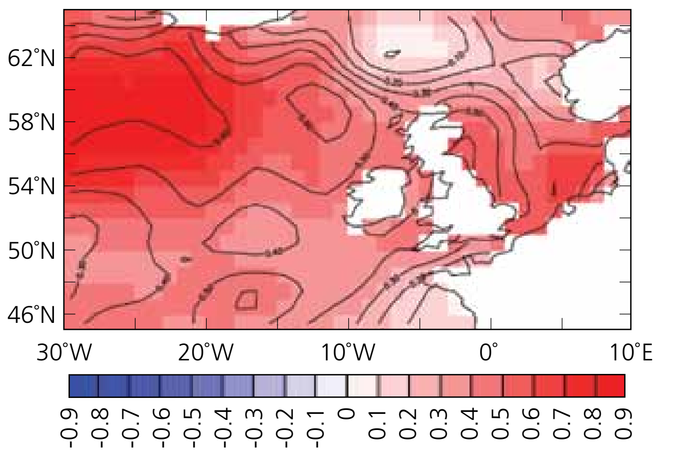


Figure 3.18 Air temperature. Linear trend in air temperatures estimated over the period 1982–2007 (°C/decade) from the NOC (Berry and Kent, 2009) air temperature analysis. Contours are r-squared values and show where there is confidence in the trends. Courtesy of NOC.



is suggested by the eastward displacement of air temperature trend patterns (north of Scotland, German Bight) relative to the SST trend patterns.

Satellite data (Figure 3.19) confirm that SSTs in the North Atlantic adjacent to the UK were typically higher in the period 2003 to 2007 than the 1985–2001 average. They also show that spatial and interannual variability of the order of 1 to 2 °C is superimposed on any such trend.

Spatial variability of salinity is not available to match these maps of SST. However, long time-series of temperature and salinity are available in Rockall Trough and the Faroe-Shetland Channel for North Atlantic waters adjacent to the UK.

In Rockall Trough, *Charting Progress* (Defra et al., 2005) reported that temperatures were relatively low in the early 1990s but rose by the late 1990s to reach values similar to those in the 1960s. Temperature in Rockall Trough has continued to rise (Figure 3.20a). After relatively low temperatures in the early 1990s (relatively lowest in May 1994), the average temperature of the top 800 m in Rockall Trough has risen continually since the mid-1990s. A dip in temperature in the period 2000 to 2001, as reported in *Charting Progress*, was followed by rises in the period 2003 to 2006. The temperature anomaly, calculated relative to 1975–2000 long-term mean, peaked at 0.8 °C in 2008. The persistently warm conditions are similar to those found in all regions around the NE Atlantic.

Rockall Trough salinity is shown in Figure 3.20b. Salinity of the top 800 m of the Ellett Line increased through the late 1990s and into the 2000s. After a dip in the period 2000 to 2001, salinity increased to a peak in 2003, with a salinity anomaly 0.08 above the 1975–2000 long-term mean. Since 2003 salinity has remained roughly constant. A slight dip during the period 2004 to 2006 results from fresher water on the west side of the section, between the Anton Dohrn Seamount and Rockall Bank (11°–13° W). The apparent overall increasing trend contrasts with decreasing salinity in the North Atlantic generally at this latitude (Bindoff and Willebrand et al., 2007). Holliday (2003b) attributed Rockall Trough salinity variations to varying amounts of relatively fresh North Atlantic Current water mixing with saline Eastern North Atlantic Water entering the southern Rockall Trough. Temperature continued to rise in the period 2003 to 2007 while salinity decreased, so the density of the upper layer decreased, giving greater stratification with possible implications for deep mixing, the overturning thermohaline circulation, upwelling of nutrients and biological production.

In the Faroe-Shetland Channel, surface waters have generally warmed over the past two decades, with highest temperatures in 2003 and a slight decrease to 2007 (Figure 3.21a). Faroe-Shetland Channel salinity (Figure 3.21b) shows interannual and some shorter-period variability, fluctuations on timescales of about five years and some overall decrease to a minimum in the late 1970s (the time of passage of the Great Salinity Anomaly) have since been followed by some increase. The magnitude of the shorter-period fluctuations (~ five years or less) exceeds that of the longer-period changes over the duration of the 58-year time series. Since the reporting period of *Charting Progress* there was a maximum in 2003 followed by an overall decline ~ 0.05 to 2007, with superimposed fluctuations of the order of 0.05, but higher values again in 2008 and 2009.

Overall, it is concluded that global and North Atlantic warming trends, especially since the mid-1980s, apply to Atlantic waters adjacent to the UK. The warming is especially clear near the surface, of the order of 0.5 to 1 °C since the

Figure 3.19 Annual-average SST anomaly from Earth Observation data, 2003–2007, from the mean of monthly anomalies relative to the 1985–2001 climatology; from the NOAA Pathfinder v5 dataset. Courtesy of P. Miller, Plymouth Marine Laboratory (PML).

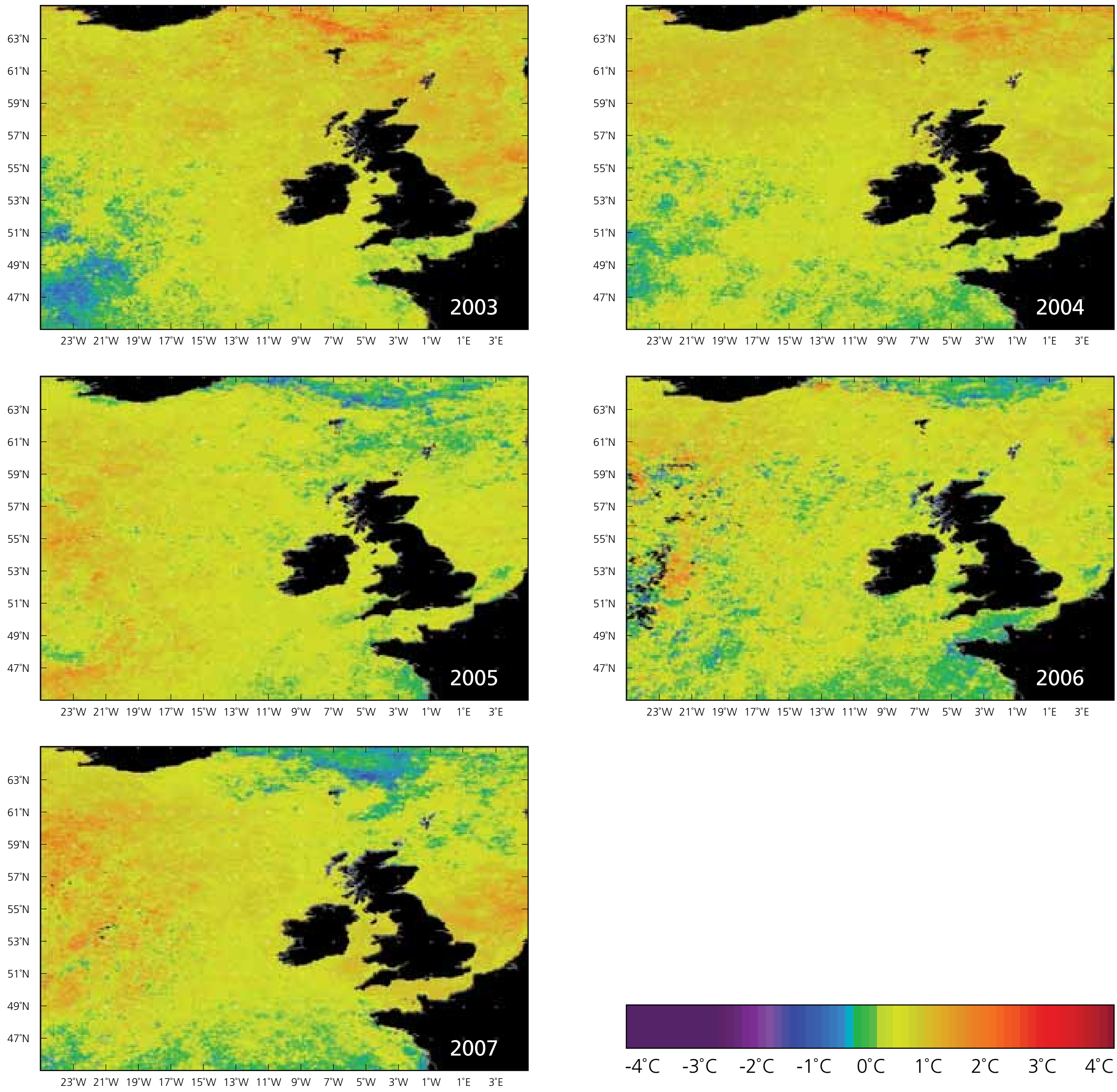


Figure 3.20 Annual-mean temperature and salinity in Rockall Trough within the upper 0 to 800 m, with a 3-point running mean overlaid. Courtesy of J. Read and N.P. Holliday, NOC.

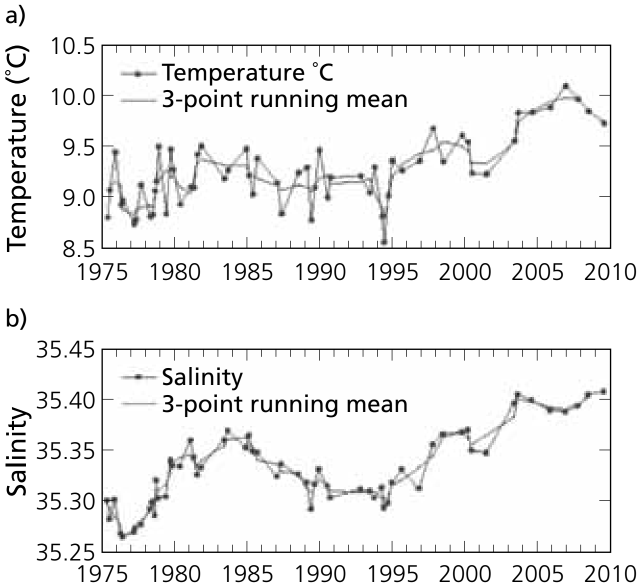
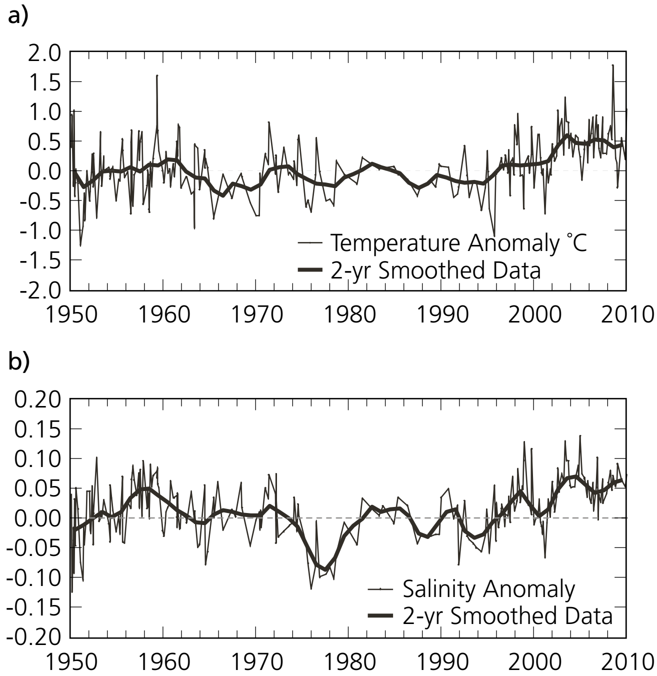


Figure 3.21 Temperature and salinity anomalies in the Atlantic Water forming the slope current along the Faroe-Shetland Channel. Courtesy of S. Hughes, Marine Scotland.



mid-1980s. However, the global and Atlantic decrease in salinity at UK latitudes (1955–1998; Bindoff and Willebrand et al., 2007) is not seen in Atlantic waters adjacent to the UK; indeed, salinity here has increased by 0.05 to 0.1 since the late 1970s Great Salinity Anomaly minimum. On top of these overall trends is spatial and interannual-to-decadal variability of similar magnitude (i.e. of the order of 0.5 to 2 °C in temperature and 0.05 to 0.1 in salinity).

3.2.4.2 Sea temperature and salinity in UK waters

This section outlines the control of shelf-sea temperature primarily by mixing and local weather, with some influence of Atlantic water near where it moves onto the shelf. Typical salinities of 34 to 35, slightly less than in the adjacent Atlantic, are influenced primarily by Atlantic water salinity, slightly by exchanges of water with the atmosphere and significantly, locally, by freshwater from land and rivers (with values of 30 or less in estuaries).

SST for UK waters is shown as annual averages for the period 1870 to 2007 in Figure 3.22. There is interannual, decadal and longer-term variability. Most striking is the rise after 1987 (about 0.2 to 0.6 °C per decade) with sustained high values from 1997. This is supported by independent local time series shown later, and appears to be a coherent change in the North Sea, English Channel and Irish Sea. MCCIP (2008) reported that marine (air and) SST have been rising at a similar rate to land air

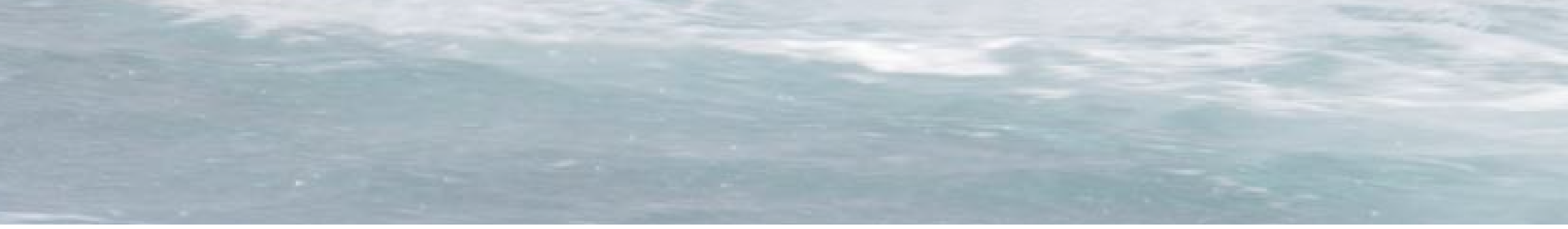


Figure 3.22 Annual average SSTs for UK Territorial Waters for the period 1870–2007, from HadISST (Rayner et al. 2003). Blue bars show deviations of the annual average from the 1961–1990 average. The red line shows annual averages after smoothing with a 21 point binomial filter. Courtesy of the Met Office.

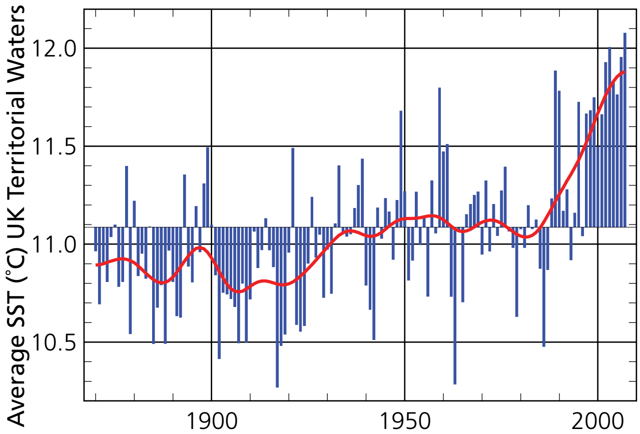
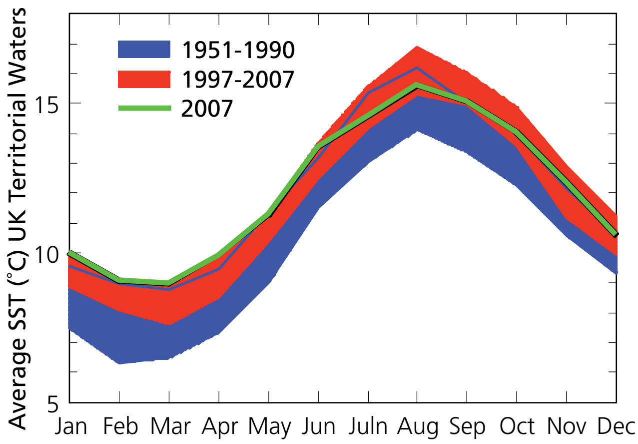


Figure 3.23 Seasonal cycle of monthly average SSTs in UK waters for 2007 (°C, green). The blue shaded area shows the range of monthly average SSTs from the 1961–1990 period (the coldest January in 1961–1990 was about 7.5 °C, the warmest was about 9.5 °C). The red shaded area shows the range of monthly average SSTs for the 1997–2007 period (the coldest January was about 8.8 °C, the warmest was about 10 °C). Data from HadISST (Rayner et al., 2003). Courtesy of the Met Office.



temperature, but with strong regional variations. 2007 has been the warmest year in UK coastal waters (up to 2007) since records began in 1870; seven of the ten warmest years occurred in the decade to 2007.

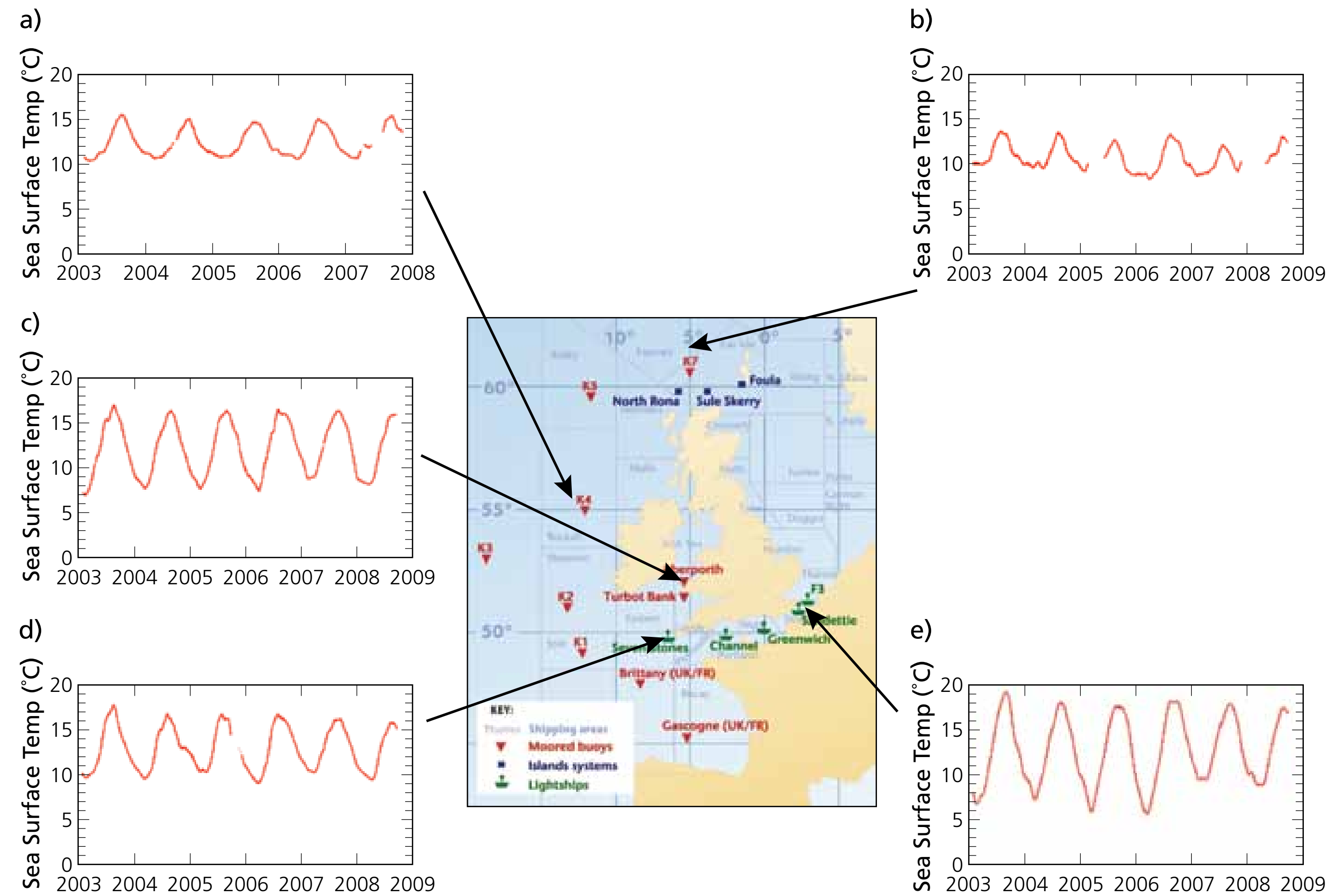
The seasonal cycle of SST in UK waters (Figure 3.23) shows an average range of about 8 °C (late-winter minimum to late-summer maximum) and higher temperatures throughout the year in the period 1997 to 2007 relative to the period 1961 to 1990. Analyses by Evans et al. (2004) for UK coastal waters confirmed a rise in temperature over a 40-year period (1960s to 1990s); they also found (1) faster rises in mid-summer and mid-winter than at other times of year, and (2) an earlier rise in spring and an earlier autumn: a 2-week shift in (air and) sea temperatures.

Spatial variability in SST (seasonal cycle and annual mean) is illustrated by data from Met Office MAWS buoys and Light Vessels (www.ukdmos.org). Figure 3.24 shows larger seasonal variation in shallow water, summer maxima decreasing from south to north, and interannual variability sufficient to obscure any trend in the period 2003 to 2008 (Figures 3.17 and 3.22 show trends on longer timescales).

Distributions of SST are shown with fine resolution by satellite remote sensing (e.g. Figures 3.10 and 3.19) and by operational numerical models.

Satellite remote sensing (Figure 3.19) shows almost all areas and years 2003 to 2007 as having positive annual SST anomalies relative to 1985–2001 climatology. 2003 and 2004 patterns are similar: raised SST (+1 to 2 °C) in

Figure 3.24. SST data from the Met Office Marine Automated Weather Stations. The data are quality controlled and filtered using a running/boxcar 30-day mean. (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; and (e) Sandettie at 51°06'N, 1°48'E. Courtesy of the Met Office.



the North Sea, Scottish Shelf and Atlantic North-West Approaches; slightly raised SST (<+0.5 °C) in the English Channel and Irish Sea. August 2003 (Figure 3.25) was the time of the European summer heat-wave; temperatures in the North Sea were then 4 °C higher than the 1985–2001 average. 2005 and 2006 (Figure 3.19) were cooler but still above average (0 to +1 °C). In March 2006 parts of the English Channel were 3 °C lower than average (Figure 3.25, at the end of a winter with low NAO Index). September 2006 to May 2007 (spanning a winter with high NAO Index) were up to 2 °C higher than average for a majority of UK waters. 2007 (Figure 3.19) indicates a new pattern of raised SST (1 to 2 °C) in the southern North Sea, Channel, Irish Sea and Atlantic North-West Approaches, with less anomaly in the northern North Sea and Scottish Continental Shelf. MCCIP (2008) reported likewise that warming has been faster in the English Channel and southern North Sea than within Scottish continental shelf waters. Overall, however, these figures emphasise spatial and temporal variability: interannual variability of the order of 1 to 2 °C and extremes of 2 to 3 °C in any one year.

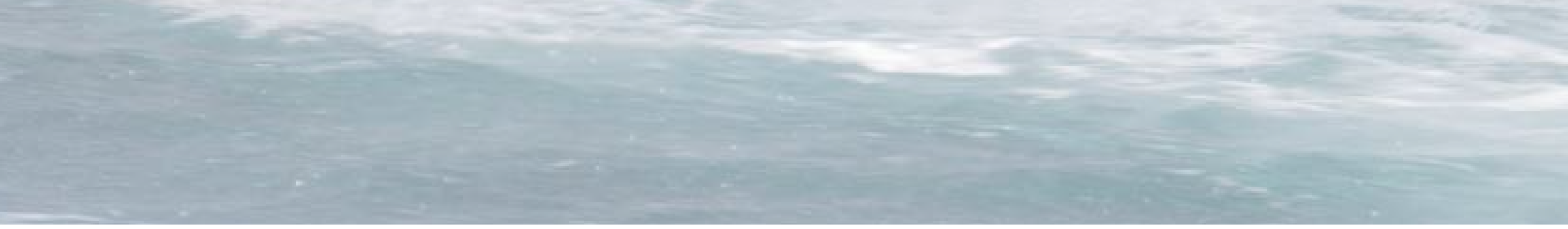
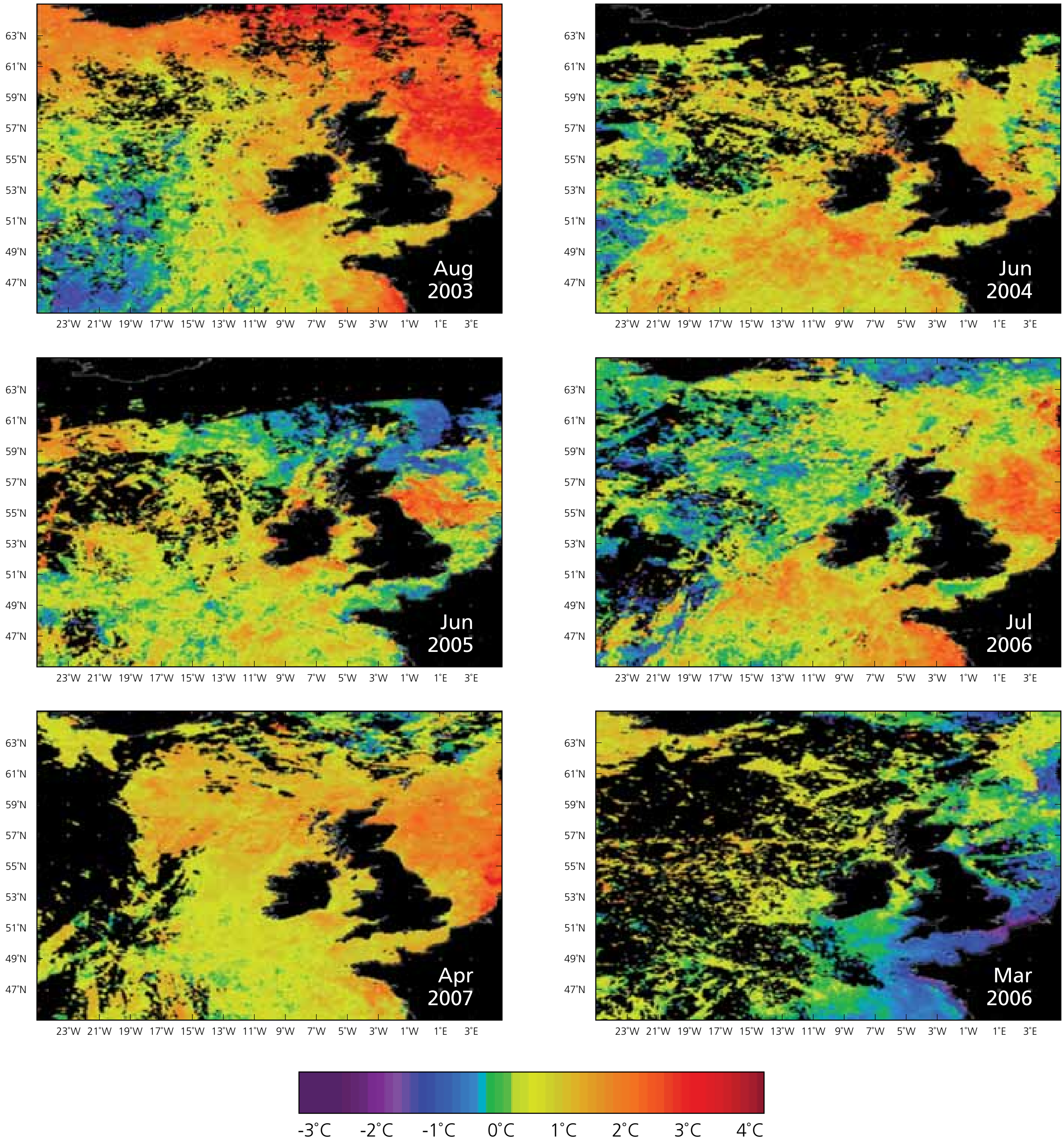


Figure 3.25 SST anomaly maps for the month of each year between 2003 and 2007 having the maximum positive anomaly (relative to 1985–2001), as well as March 2006 which had the greatest negative anomaly in the period 2003 to 2007. Courtesy of P. Miller, PML.



Such variability is superimposed on mean seasonal temperature distributions illustrated by the Met Office NCOF's operational Atlantic Margin Model output (Figure 3.26). For a model description see Bell et al. (2000), Holt et al. (2003) and Stark et al. (2007). These modelled SSTs rise to the south; seasonal range increases to the east (more 'continental' climate) and in shallow waters such as the southern North Sea and eastern-most Irish Sea. Cool plumes suggest extra mixing in strong tidal currents around several headlands and for a limited distance south of Orkney and Shetland.

Corresponding surface salinities are shown in Figure 3.27. The general pattern is a reduction from open Atlantic salinities as coasts are approached; the most extensive reductions are in the southern and eastern North Sea (to about 34 typically) and in the Irish Sea extending northwards in the Scottish Coastal current (32 to 34). Salinities are as low as 30 along the continental coast from Belgium to Denmark, and in the Baltic outflow. Nevertheless, near-oceanic salinities are carried through the English Channel and into most of the North Sea. Seasonality is most marked off Norway (fresher in summer) and appears weak in UK waters.

3.2.4.2.1 Stratification

Surface and bottom temperature, and salinity, may differ (Figures 3.26 to 3.29). Each year, from about May to October, large areas of UK shelf seas stratify as surface waters are warmed. A sharp density interface is then maintained, by wind mixing from the surface and tidal mixing from the seabed upwards. Below the density interface, cold bottom water is left over from the previous winter; it warms only very slowly after the onset of stratification. However, the water column remains vertically mixed by tidal stirring all year where the water depth is relatively shallow (typically nearer to shore) and/or depth-averaged tidal currents are large (Simpson and Hunter, 1974). Where freshwater influence is significant, salinity may cause (possibly intermittent) stratification depending on levels of freshwater discharge. (A notable example of different of surface and bottom salinities occurs around Scandinavia).

Between stratified and mixed areas there is typically a sharp change of horizontal temperature (and/or salinity) with a horizontal scale O(10 km). At such tidal mixing fronts (Hill et al., 2008) there is usually a surface front and a bottom front (as illustrated respectively in Figures 3.26 and 3.28). The bottom front usually shows the larger density gradient; bottom fronts can exist without a surface front being present. Tidal mixing fronts appear in Figure 3.28 (July) from Flamborough Head to northern Denmark, across the western end of the English Channel and Bristol Channel, around the western Irish Sea and between the inner and outer shelf areas west of Scotland.

Observed distributions of North Sea bottom temperature and salinity in winter (February) are provided annually by the ICES International Bottom Trawl Survey; Figure 3.30 shows 1971–2000 averages. Temperature correlates inversely with water depth; winter cooling removes similar quantities of heat in different areas so that shallow waters cool most. (Cooler waters in the German Bight and off Denmark also reflect lower air temperatures in winter.) Bottom salinities show a balance between oceanic and local freshwater influences; the 1971–2000 averages are correlated with water depth, distance from the coast and proximity to inflow from the open Atlantic.

Figure 3.26 SSTs for January, April, July and October. A mean is shown for the month and the five years 2003 to 2007. Values are from the POLCOMSV6.3 Atlantic Margin Model (Holt et al., 2003; run in hindcast prior to March 2007, and then within the operational system in near-real time). Courtesy of the Met Office.

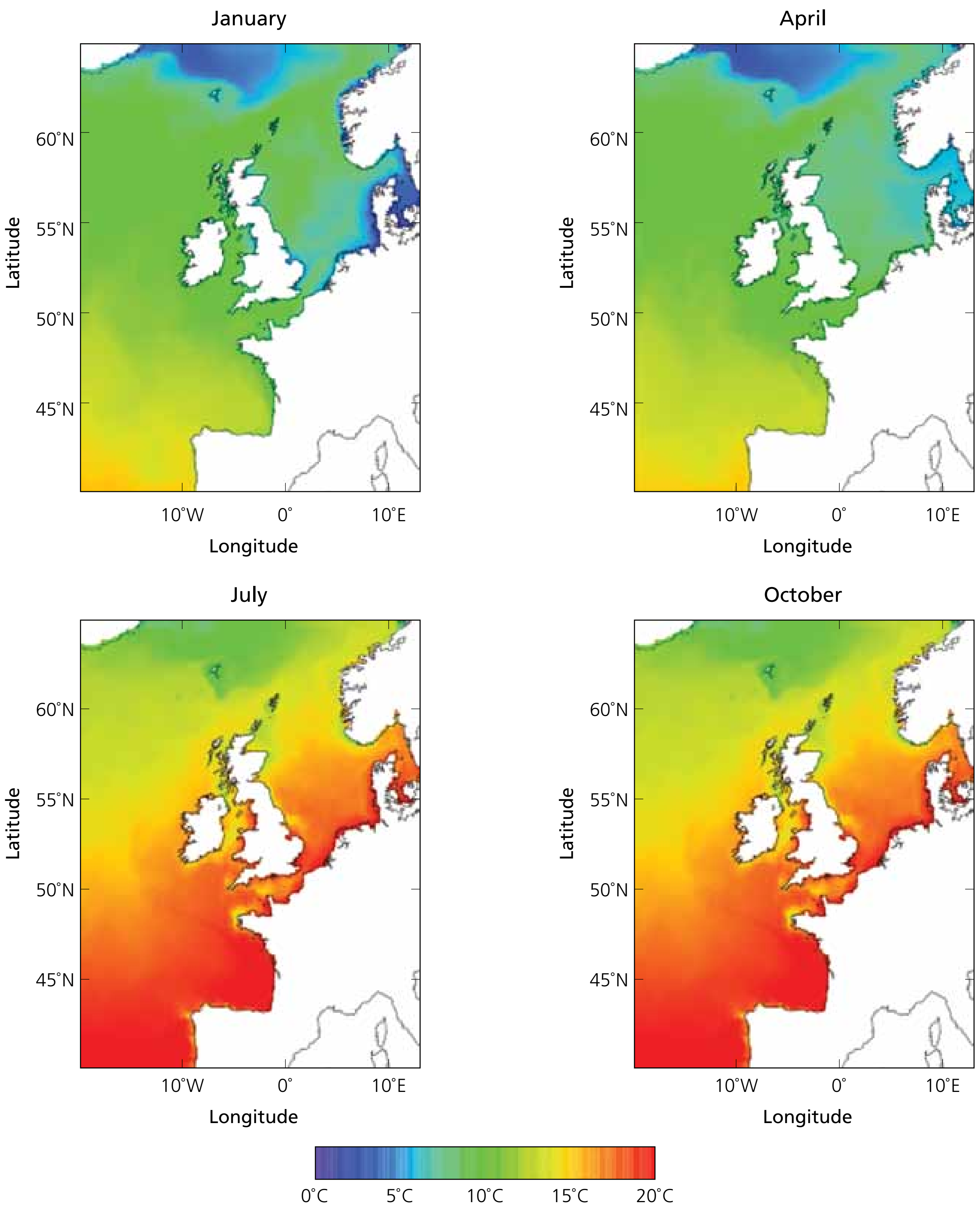


Figure 3.27 Surface salinities for January, April, July and October. A mean is shown for the month and the five years 2003 to 2007. Values are from the POLCOMSV6.3 Atlantic Margin Model (Holt et al., 2003; run in hindcast prior to March 2007, and then within the operational system in near-real time). Courtesy of the Met Office.

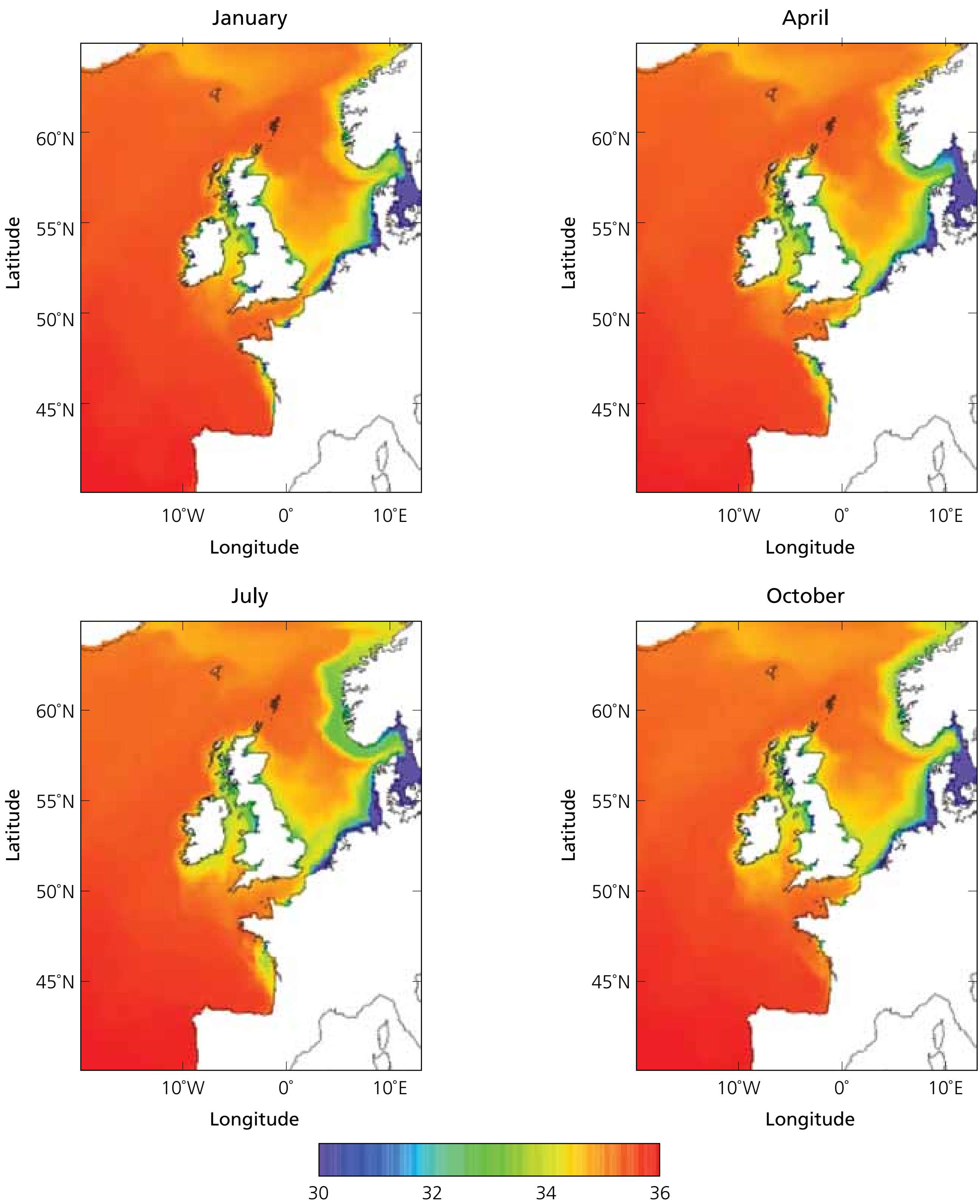


Figure 3.28 Seabed temperatures for January, April, July and October. A mean is shown for the month and the five years 2003 to 2007. Values are from the POLCOMSV6.3 Atlantic Margin Model (Holt et al., 2003; run in hindcast prior to March 2007, and then within the operational system in near-real time). Seabed temperatures highlight the general decrease in temperature with depth, especially at the edge of shallower shelf seas. Courtesy of the Met Office.

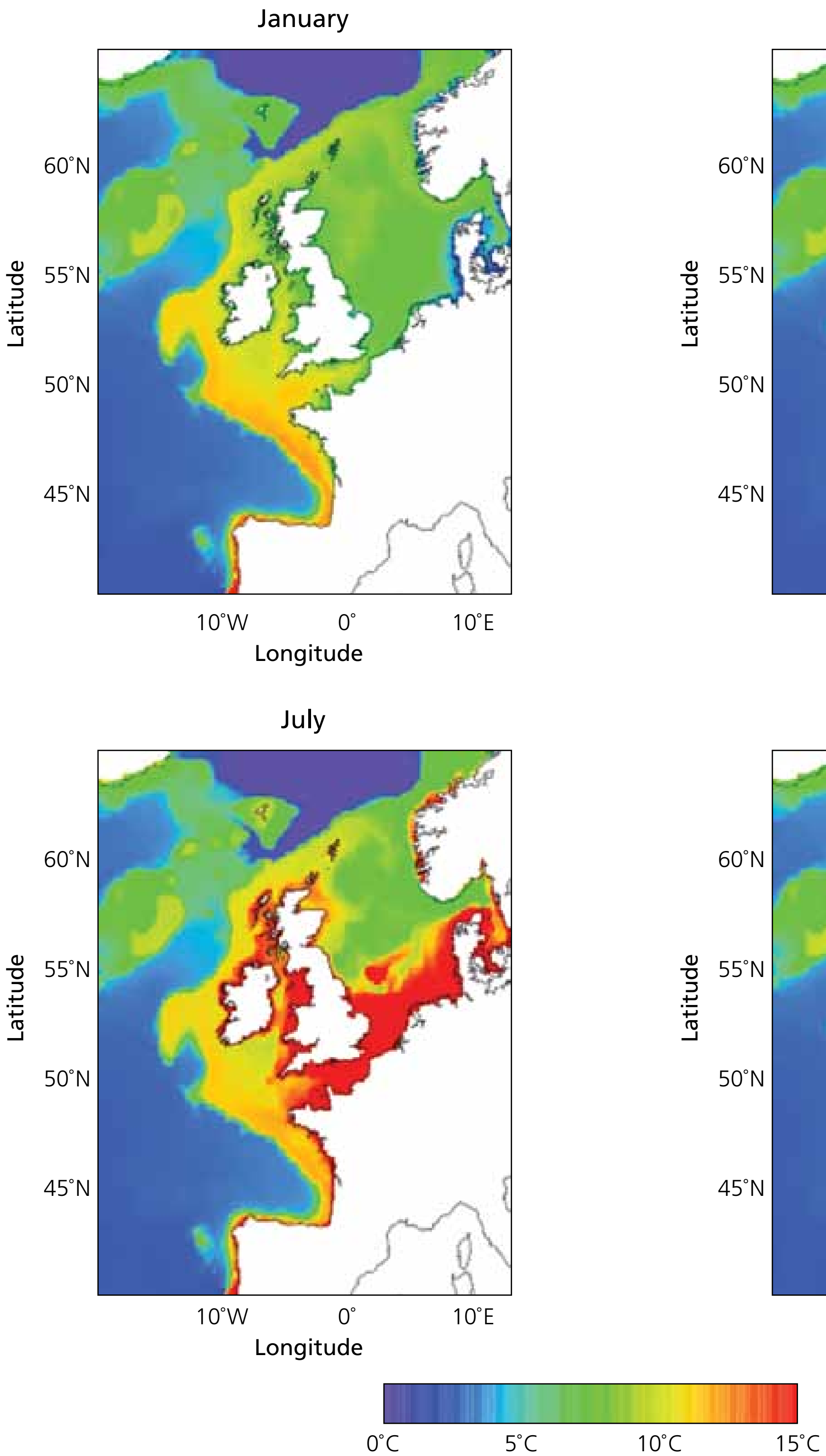


Figure 3.29 Seabed salinities for January, April, July and October. A mean is shown for the month and the five years 2003 to 2007. Values are from the POLCOMSV6.3 Atlantic Margin Model (Holt et al., 2003; run in hindcast prior to March 2007, and then within the operational system in near-real time). Courtesy of the Met Office.

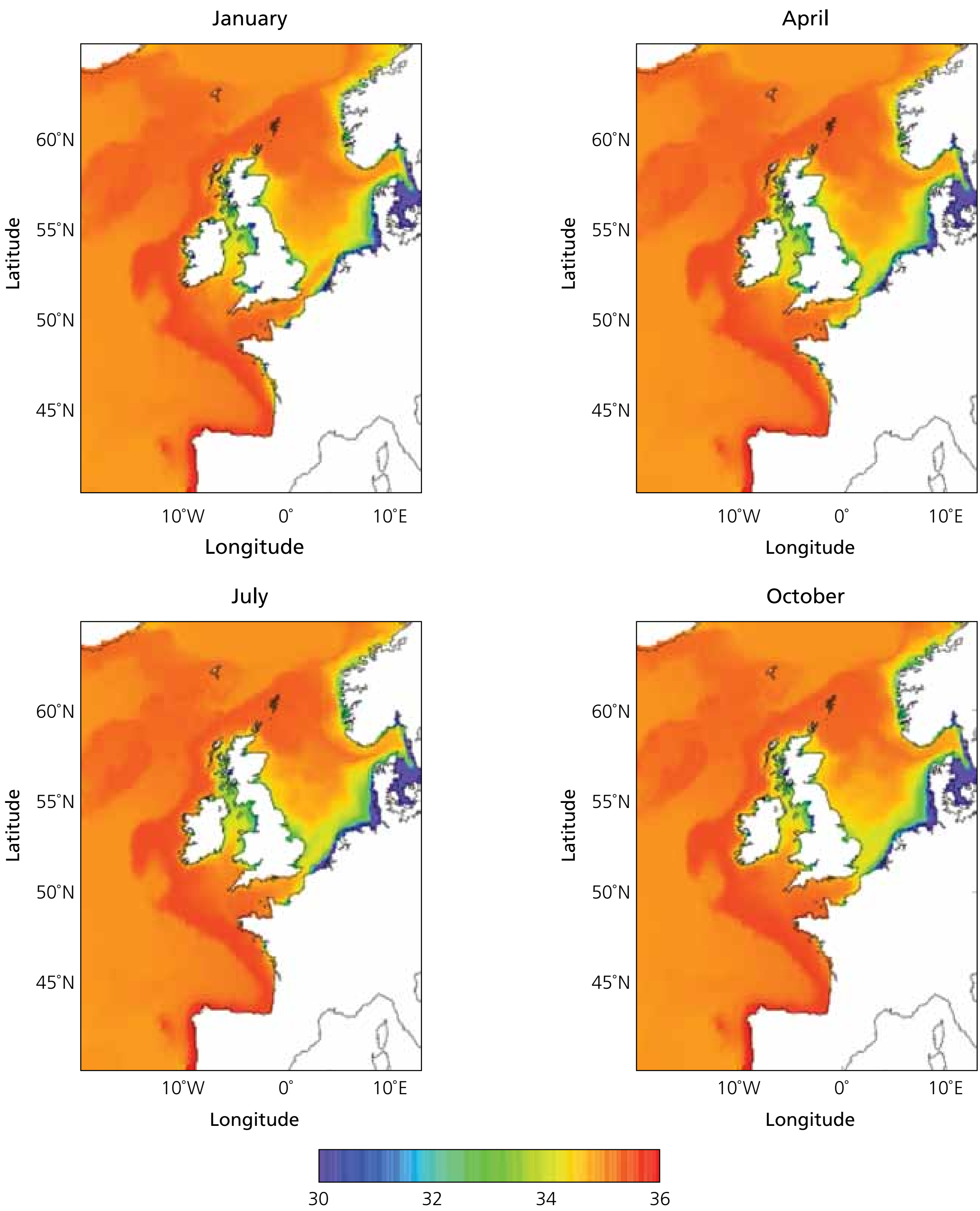
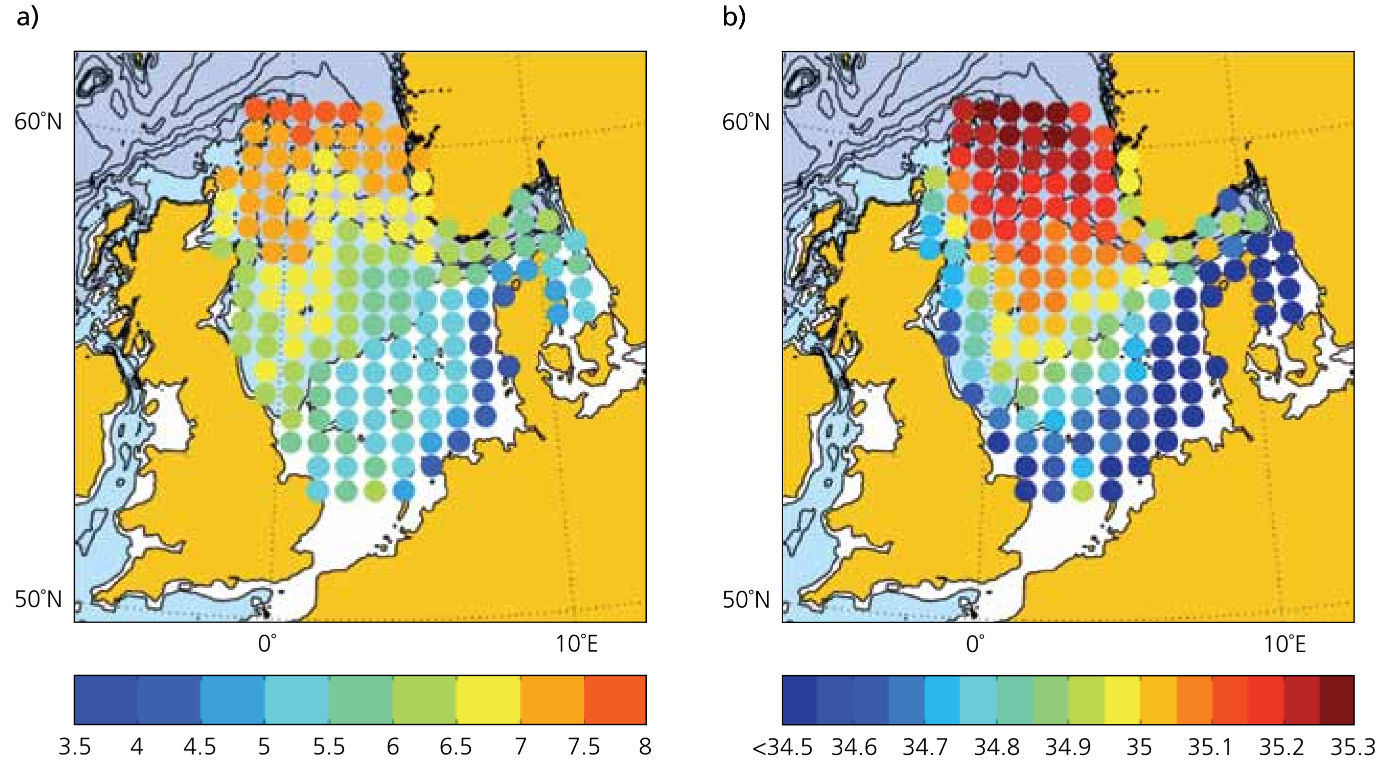


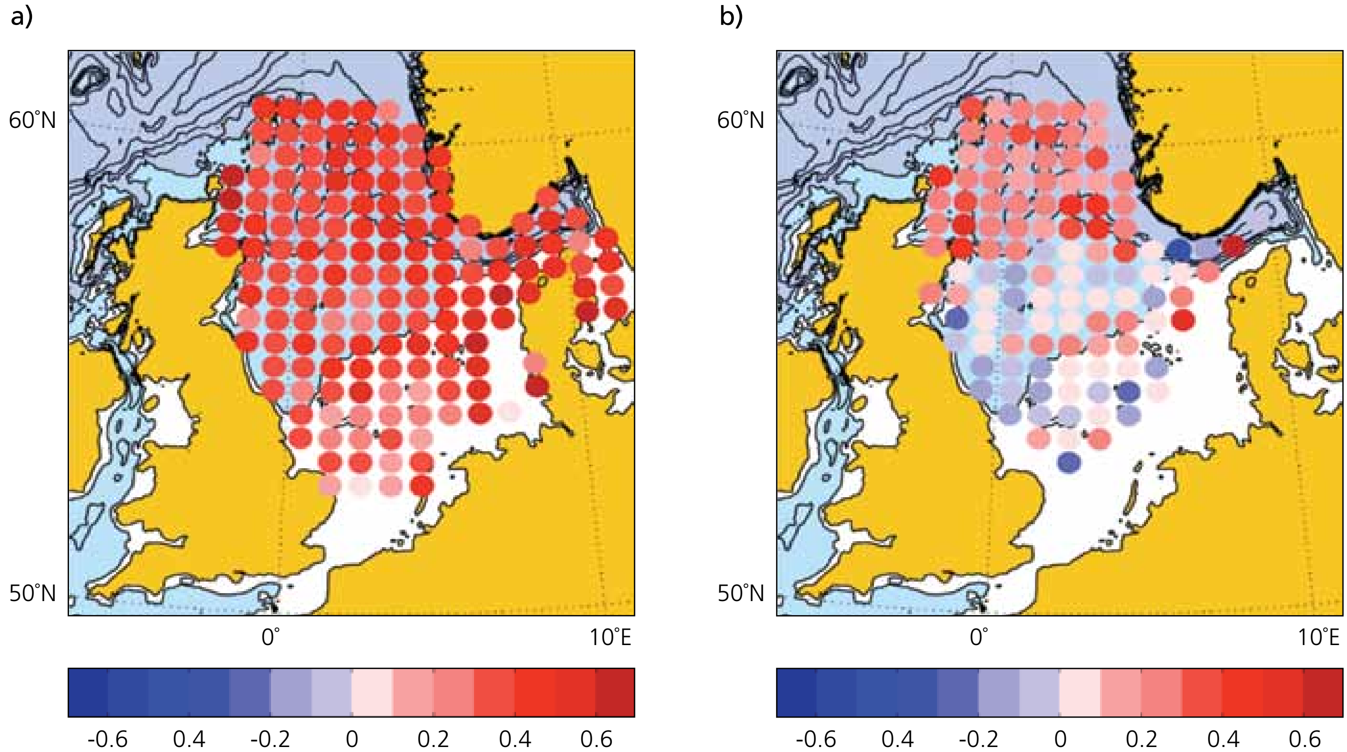
Figure 3.30 Average winter bottom (a) temperatures and (b) salinities calculated from the ICES International Bottom Trawl Survey Quarter 1 data for 1971–2000. Average values were calculated for data in each ICES statistical rectangle where there were more than 25 years of data. For salinity, the colour scale has a cut-off of 34.5; average salinity in coastal regions can be as low as 30.2. Courtesy of S. Hughes, Marine Scotland.



The overall 1971–2007 bottom temperature trend is for warming everywhere (Figure 3.31a). Example time-series for particular locations are shown in Figure 3.32 and show much interannual variability, of the order of 3 °C or more in shallow water far from the moderating influence of Atlantic water. High values around 1990 coincide with positive NAO Index but subsequent low values have variable timing in the period 1994 to 1996. The more recent rise in temperature appears unrelated to the NAO although a correlation between NAO Index and late winter 2006 and 2007 temperature was previously noted.

The overall 1971–2007 trend in salinity (Figure 3.31b) is unclear except for increasing salinity in the northern North Sea with most oceanic influence. Example time-series for particular locations are shown in Figure 3.32. The late 1970s dip associated with the Great Salinity Anomaly has decreasing influence as distance from the open ocean increases. The Great Salinity Anomaly coincided with low NAO Index. Some influence of the NAO on salinity may be expected via wind effects on inflows of Atlantic water to the shelf and via rainfall to freshwater inflows. However, since the Great Salinity Anomaly there has been little apparent correlation between salinity and NAO Index or between salinity time-series at the different locations (except Viking Bank and Fladden Ground). In all cases interannual variability (0.1 to 1 or more) is comparable with change due to any overall trend.

Figure 3.31 Linear trend in (a) winter bottom temperature (°C per decade) and (b) winter bottom salinity (per decade), from the ICES International Bottom Trawl Survey Quarter 1 data for 1971–2007. Values were calculated from linear fit to data in ICES rectangles with more than 30 years of data. Data were rejected if the root-mean-squared error exceeded 0.25. For salinity, large interannual variability in coastal regions makes a salinity trend difficult to determine with confidence; data were rejected if the root-mean-squared-error exceeded 0.25. Courtesy of S. Hughes, Marine Scotland.



The distribution of total stratification by season (Figure 3.33; 1961–1990 average) was simulated with the Atlantic Margin Model (Holt et al., 2003). Tidal mixing fronts between summer-stratified and mixed waters are apparent, but are displaced slightly into mixed areas in comparison with the bottom fronts in Figure 3.28.

Simulated evolution through 2001 (from day 91) of surface-bed temperature difference over the continental shelf is shown in a video clip at: http://chartingprogress.defra.gov.uk/resources/. The model is POLCOMS (3-D) with resolution ~ 1.8 km and 32 vertical 'levels' in 48°N–62°N, 12°W–13°E (Holt and Proctor, 2008).

Another view of summer stratification and tidal mixing fronts is provided by vertical sections across the shelf sea between mixed and stratified areas. Examples are shown in Figures 3.34 and 3.35. Near-surface waters in the Celtic Sea (stations B7 to CS05) were up to 2 °C warmer than in the Irish Sea in July 2008 (Figure 3.34), although the isolated bottom water in the Celtic Sea (e.g. CS01) was colder than bottom water in the Irish Sea (e.g. S26). The seasonal thermocline varies spatially, probably linked to total water depth (J. Sharples, NOC, pers. comm., 2009) and to enhanced mixing by internal waves at the shelf edge (CS06, CS07).

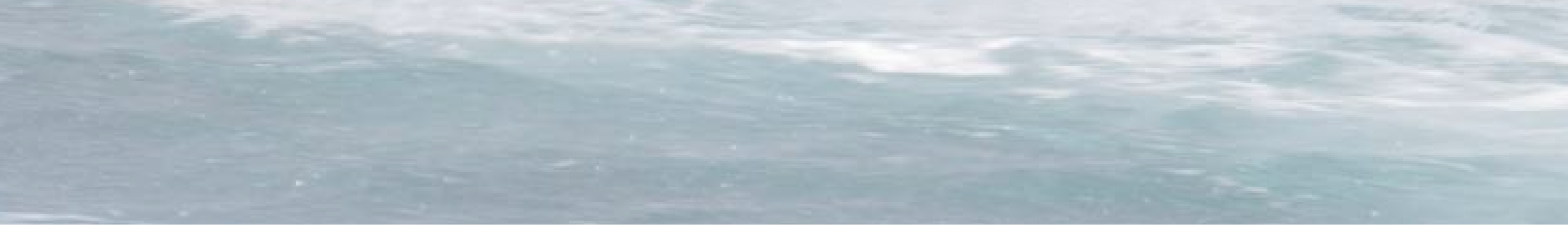


Figure 3.32 Winter (a) bottom temperature and (b) bottom salinity from the ICES International Bottom Trawl Survey at selected North Sea fishing grounds. The thin black line shows the North Atlantic Oscillation (NAO) Winter Index. The linear trend since 1970 is shown (thicker black line). Courtesy of S. Hughes, Marine Scotland.

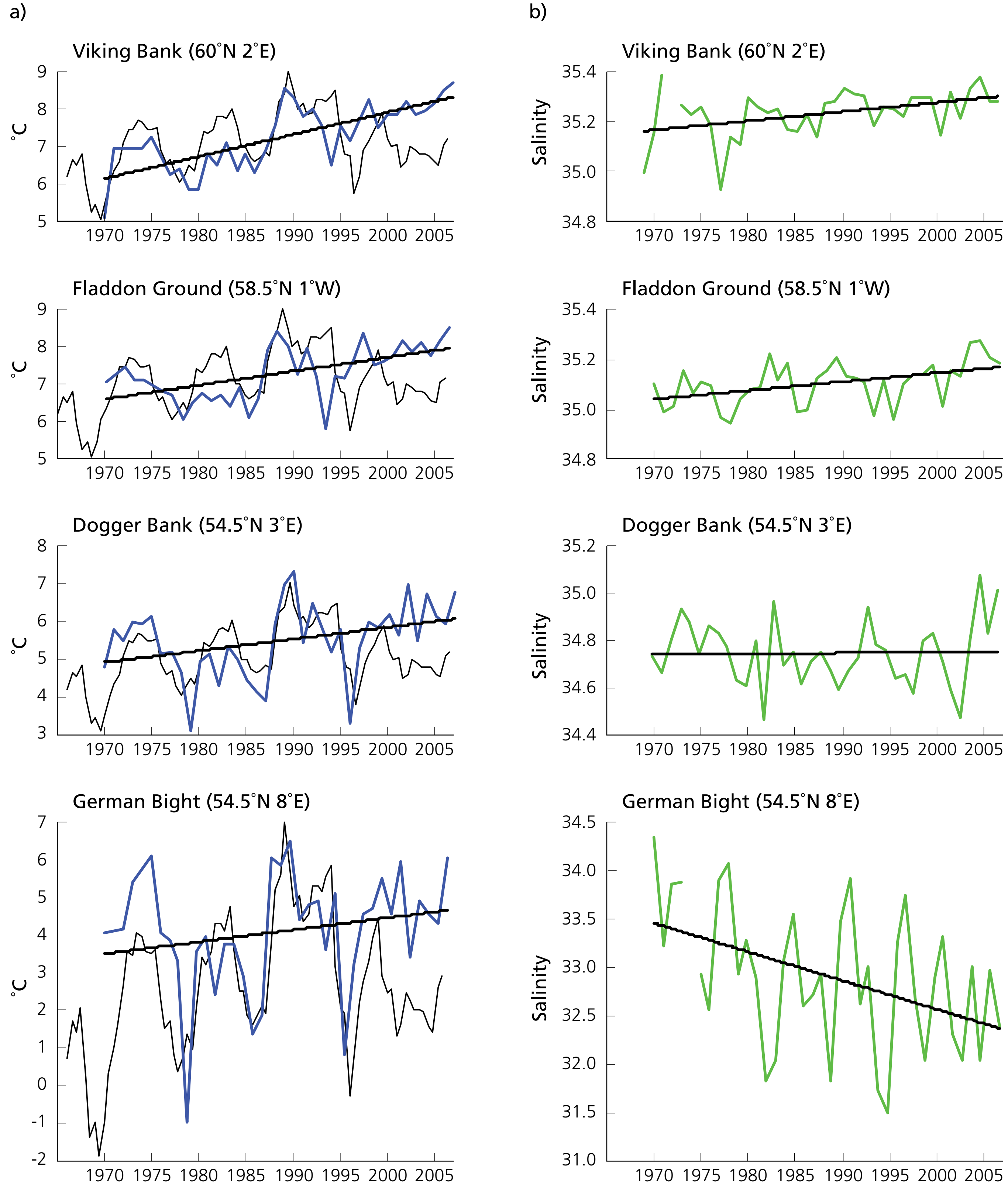


Figure 3.33 Distribution of total stratification in the North-East Atlantic by season, from the POLCOMSV6.3 Atlantic Margin Model (Holt et al., 2003). (The figure actually shows total potential energy anomaly: PEA proportional to [height × density relative to depth-mean] totalled through depth). Courtesy of J. Holt, NOC.

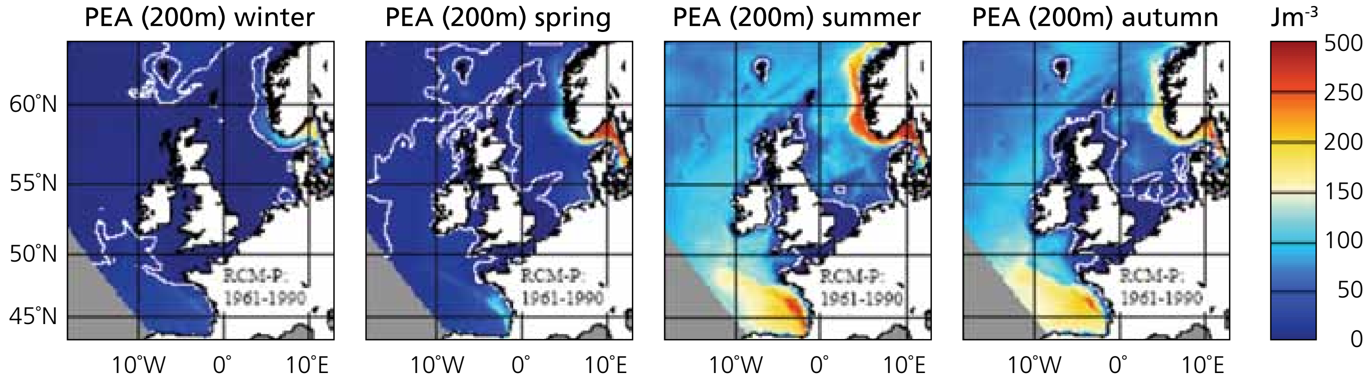
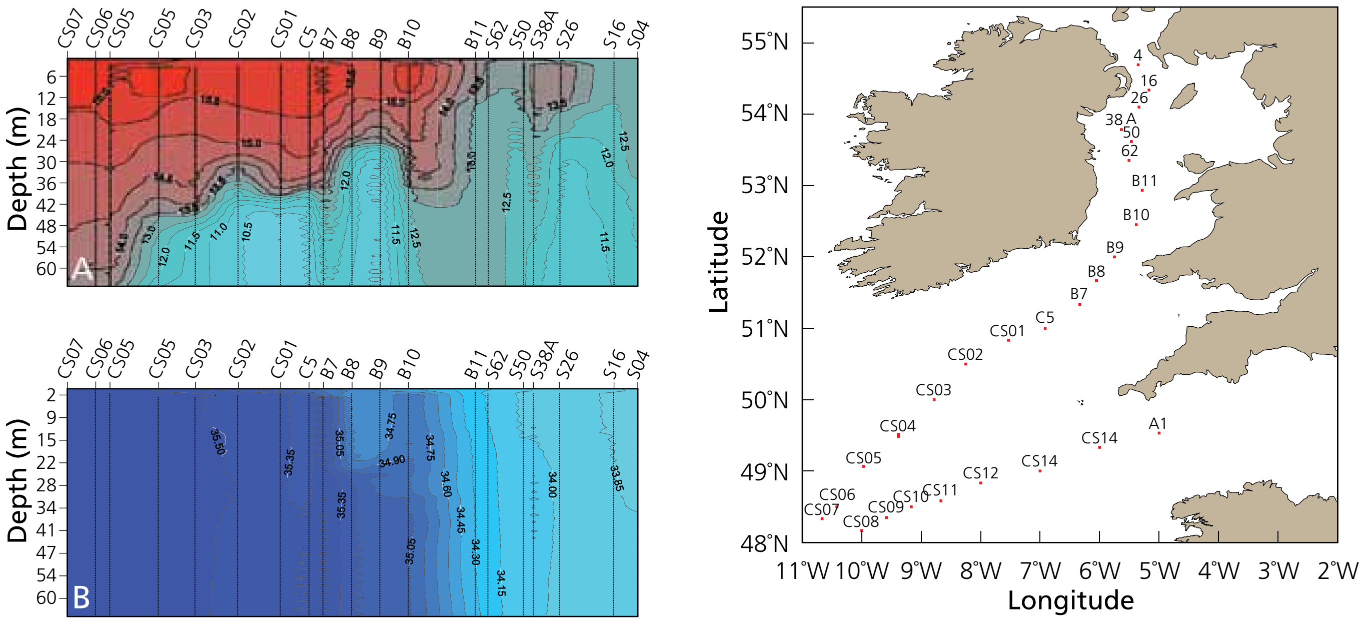


Figure 3.34 Distribution of (a) temperature and (b) salinity in the upper 65 m of the Celtic and Irish Seas in July 2008 (stations as indicated on the map). Courtesy of R. Gowen, Agri-Food and Biosciences Institute (AFBINI).



Irish Sea transects for August 2008 (Figure 3.35) show a typical summer situation; the water in Liverpool Bay (LBY01 and CEFAS M) is warm (because shallow) and fresh (through river inputs) relative to western Irish Sea waters. The outer region of Liverpool Bay and the eastern Irish Sea are usually vertically mixed; in contrast, the western Irish Sea is stratified largely due to the vertical gradients in temperature. The water beneath the stratified region is much colder. Some fresher water at the surface can also be seen near the Irish coast.

Variation in stratification through time at one location is illustrated in Figures 3.36 and 3.37. Data over 12 years (Figure 3.36) show that the onset of stratification varies (determined by local meteorological conditions), taking place sometime between April and May (e.g. Figure 3.37). (The start of phytoplankton production depends on the establishment of stratification.) In June and July, surface warming continues and the depth of the warmest surface water decreases. In August to October, the near-surface heat mixes downwards forming a deeper surface layer of warmer water; eventually the water is mixed throughout its depth. Such a cycle is typical of summer-stratified waters (exact timings vary interannually and with location).

Overall it is concluded that shelf-sea temperature is controlled primarily by mixing and local weather, with some influence of Atlantic water near where it moves onto the shelf. Salinities are influenced primarily by Atlantic water salinity, and locally by freshwater from land and rivers. Surface temperatures have risen, particularly since the mid-1980s, but salinity trends vary (tending to increase where influenced most by Atlantic water). Temperature has a strong seasonal cycle, larger in shallow water; summer maxima decrease from south to north. Interannual to decadal variability in salinity is as large as its multi-decadal trend, and in temperature is of the order of 1 to 2 °C, with extremes of 2 to 3 °C. Summer stratification (from about May to October) occurs in large areas of UK shelf seas as surface waters are warmed; below, cold bottom water warms only very slowly. The water column remains vertically mixed where the depth is relatively shallow and/ or tidal currents are large.

3.2.4.3 Time series at specific locations

The following sections proceed clockwise around the UK (from north of Scotland) with time series from ferry routes, and from individual offshore and coastal locations supporting the overall conclusions in Section 3.2.4.2. Locations are indicated in Figure 3.38.

Atlantic water, more than 10^6 m^3/s in total, enters the northern North Sea primarily via the Fair Isle current between Orkney and Shetland, around Shetland and southwards along the western slope of the Norwegian Trench. Overall salinity values (typically between 34 and 35.4 in the North Sea) are set by the inflowing Atlantic water. (The Norwegian Coastal Current outflow carries less saline surface water from the Baltic and Scandinavian fjords and rivers.) Water of Atlantic origin also penetrates into the southern North Sea through Dover Strait: the transport of about 10^5 m^3/s (Prandle et al., 1993b, 1996) is important in raising southern North Sea salinity. The main input of freshwater into the North Sea is from rivers discharging along its southern seaboard and the Baltic, reducing salinity in the southern and eastern North Sea. *Charting Progress* shows time series of sea-surface salinity anomalies averaged over the northern North Sea from 1950 to 2002. Salinity is higher in winter; possible explanations are: (1) evaporation over the sea, greater in autumn-winter than in spring-summer (Dooley, H., pers. comm., ICES, 2003);

Figure 3.35 Temperature and salinity section across the Irish Sea in August 2008 (stations as indicated on the map). Courtesy of R. Gowen, AFBINI.

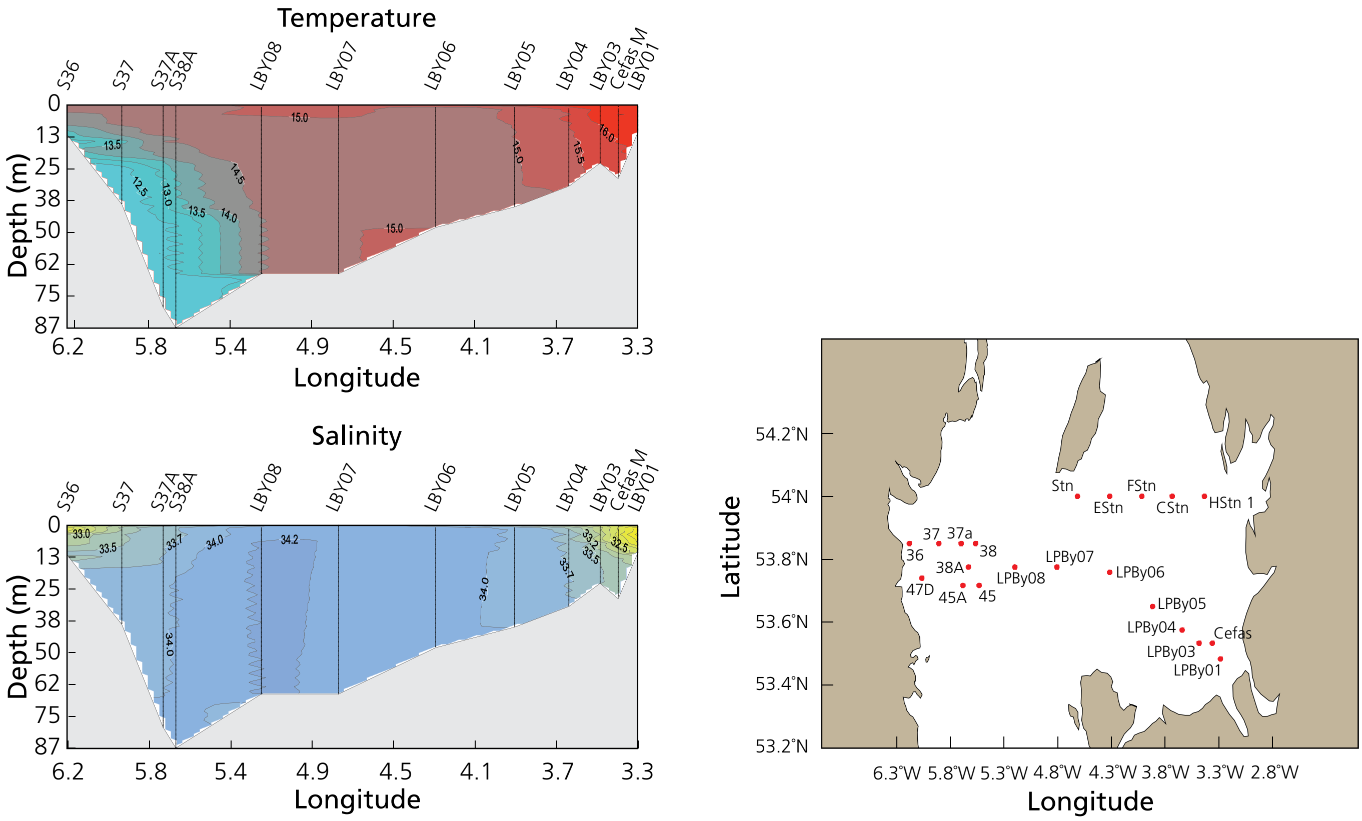


Figure 3.36 Time series showing seasonal cycles of mean daily near-surface (2 m) and bottom (90 m) temperature in the western Irish Sea, at stations 45 and 38a (see Figure 3.35), using thermistors attached to an instrumented mooring. Courtesy of R. Gowen, AFBINI.

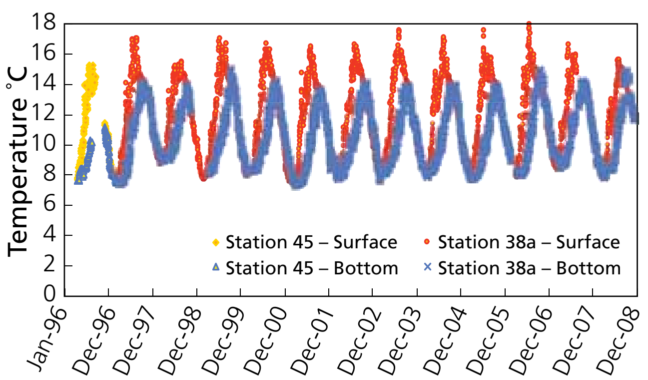


Figure 3.37 Evolution of thermal stratification in the western Irish Sea over the course of 2002. Courtesy of R. Gowen, AFBINI.

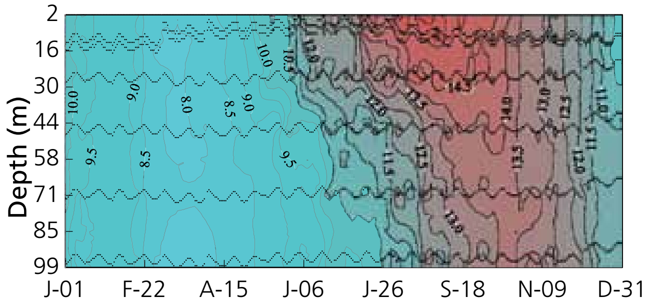
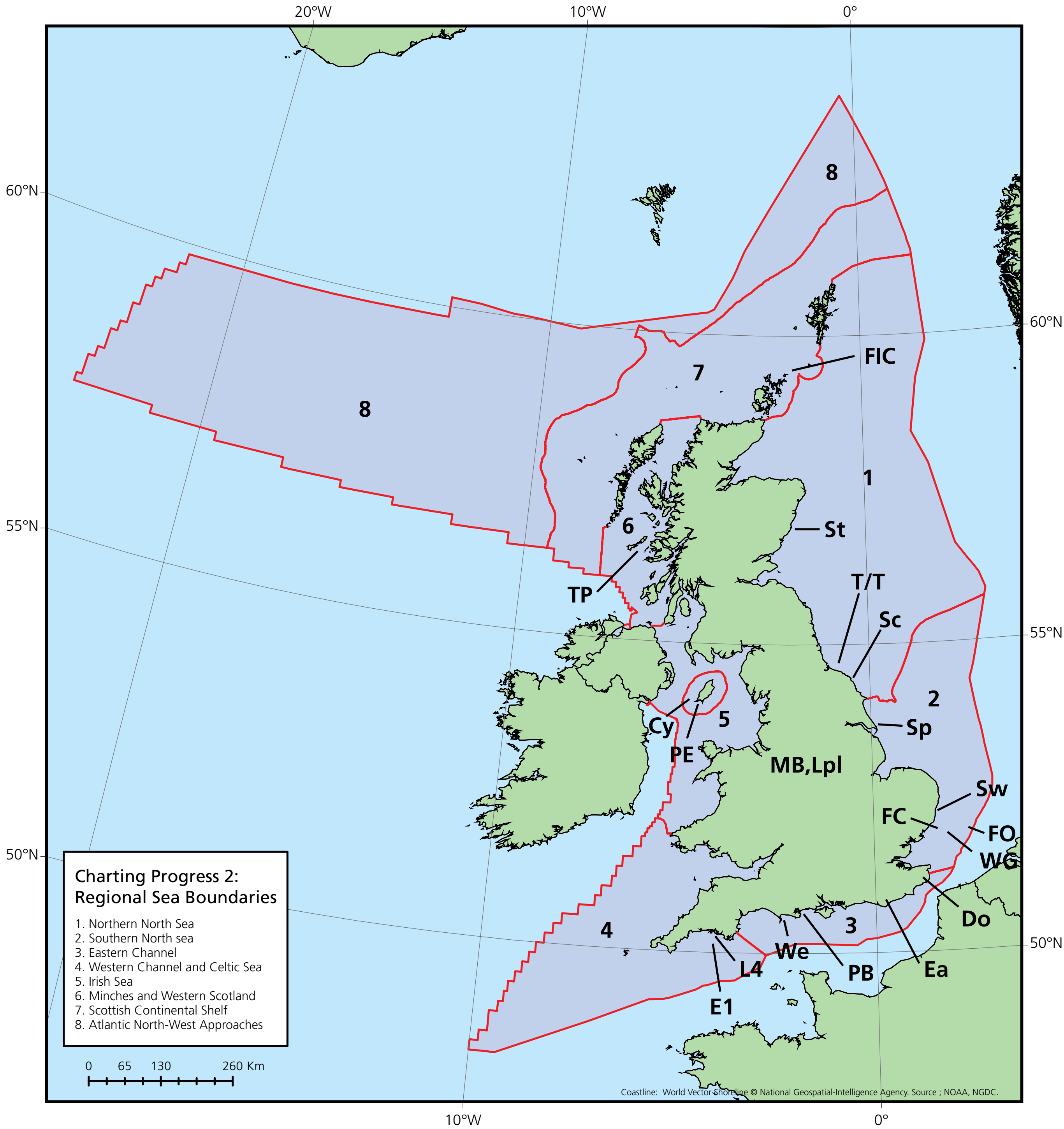


Figure 3.38 Location of CP2 Regions and time-series measurements discussed in Section 3.2.4.3. FIC – Fair Isle current; St – Stonehaven; T/T – Tyne/Tees; Sc – Scarborough; Sp – Spurn Point; Sw – Southwold; WG – West Gabbard; FC, FO – (Harwich-Rotterdam) Ferry Coastal, Ferry Offshore; Do – Dover; Ea – Eastbourne; PB – Poole Bay; We – Weymouth, Cy – Cypris; PE – Port Erin; MB, Lpl – Mersey Bar and Liverpool Bay; TP – Tiree Passage.



(2) more wind-driven flow of higher-salinity Channel water through Dover Strait to the southern North Sea. There was no clear winter trend. In the summer time series, there was an apparent freshening in the late 1970s and early 1980s and incomplete recovery thereafter (to 2002).

Figure 3.39 shows that in the Fair Isle Current, temperature and salinity vary on seasonal, year-to-year and 5-10-year timescales. High salinities occurred in 2003; since the reporting in *Charting Progress* values fell until a sharp rise in 2007. Temperature shows a sharp rise in the period 1987 to 88, a fall in 1992 to 1994, and then two sharp rises to a maximum in 2003. Comparisons of Fair Isle current temperature and salinity with Atlantic water north of Scotland are made in Figure 3.40. There is correlation on a 5-year timescale, and in the long-term trend of temperature, but interannual variability in the Fair Isle Current markedly exceeds that in the Atlantic water.

3.2.4.3.1 Northern North Sea

For Region 1 (Figure 3.38), coastal sea temperature and salinity are available from Stonehaven (Figure 3.41), and temperature from Scarborough (Figure 3.42) and an

Figure 3.39 Fair Isle Current water (a) temperature and (b) salinity anomalies. Nominal position: 59°17'N, 2°10'W. Courtesy of S. Hughes, Marine Scotland.

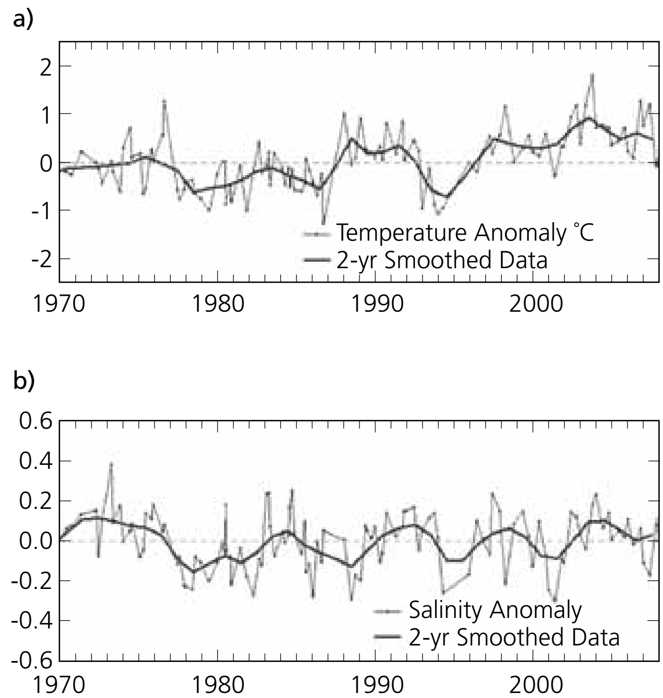
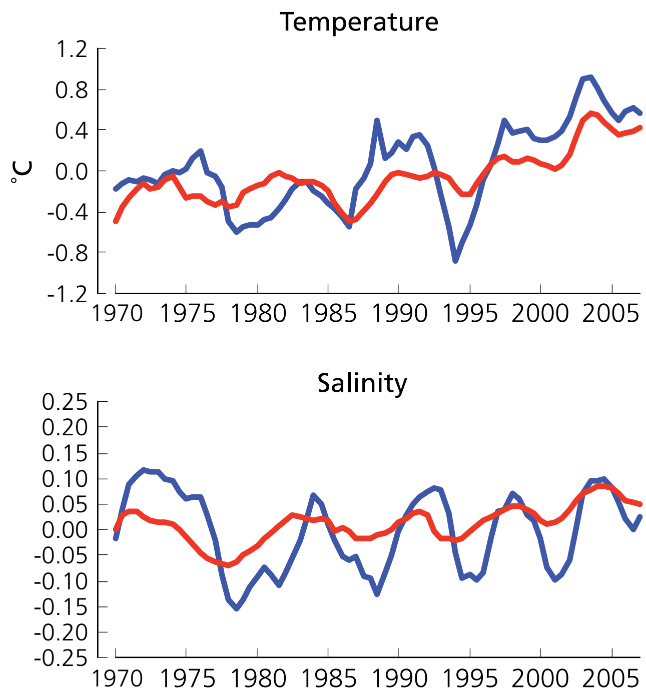
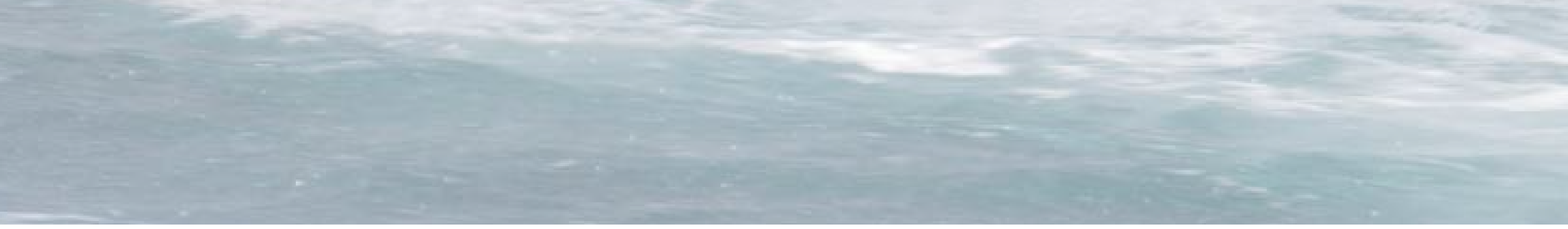


Figure 3.40 Temperature and salinity anomalies (smoothed and seasonal cycle removed) showing a comparison between the Fair Isle inflow to the North Sea (blue line) and Atlantic water north of Scotland (red line). Courtesy of S. Hughes, Marine Scotland.



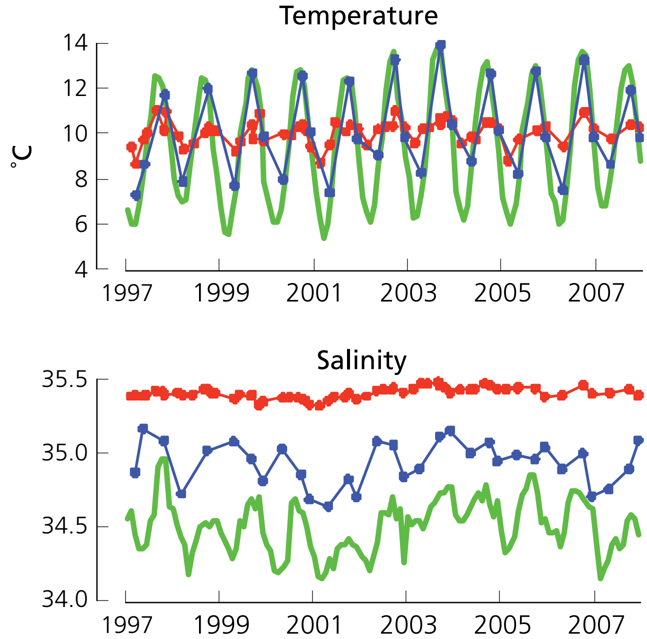


offshore buoy in the Tyne/Tees area (Figure 3.43). The Stonehaven time series show some correspondence with the Fair Isle Current on an annual timescale (temperature has a seasonal cycle, salinity has a few months delay at times); salinity shows additional variability against which no trend is significant. The Scarborough temperature shows a marked dip and then rise in the late 1980s, a dip in the early 1990s to the 1971–2000 average and then a rise from 1994 to a sustained level nearly 1 °C above that average. Stonehaven and Scarborough show notable interannual variability. The 2006 and 2007 winters differ; the warmer (2007; also fresher at Stonehaven) coincided with strongly positive NAO Index. The 2007–2006 temperature difference, maximal in March (about 1.5 °C for Scarborough), slowly decreases until a rapid reversal in July-August. Although only for two years, the Tyne/Tees temperature statistics illustrate interannual variability of the order of 2 to 3 °C in summer months and ranges of 5 to 6 °C for surface temperature within any one summer month.

3.2.4.3.2 Southern North Sea

For Region 2 (Figure 3.38), annual temperature time series from 1880 at Humber and Newarp Light Vessels are shown in *Charting Progress*, albeit with gaps and ending in the 1980s. Interannual variability, typically 0.5 to 1 °C for annual means 8 to 10 °C and 8.5 to 10.5 °C respectively, is greater than any overall trend over that whole period. Coastal sea temperatures are available from Spurn Point and Southwold (replacing Sizewell; Figures 3.44 and 3.45), and from West Gabbard off Harwich (Figure 3.46) and surface temperature and salinity time-series are available near 52 °N from the Harwich-Rotterdam ferry route at 'offshore' and 'coastal' locations (Figures 3.47 and 3.48, respectively).

Figure 3.41 Weekly depth-averaged sea temperature and salinity at Stonehaven (green line) from 1997 to the end of 2007. Data from offshore sites in the North Sea and North Atlantic are also included (Blue – Fair Isle Current, North Sea; Red - North Atlantic water north of Scotland). Courtesy of S. Hughes, Marine Scotland.



The Spurn Point, Southwold and both ferry time series show a dip and then a marked rise in the late 1980s, dips in the early 1990s and again in 1996 down to the 1971–2000 average; thereafter values fluctuate but average about 1 °C above the 1971–2000 mean. The 2006 and 2007 winter temperatures differ, the warmer (2007) coinciding with strongly positive NAO Index. The temperature difference is maximal in March: about 2 °C at West Gabbard and Southwold, greater than 3 °C in both ferry time series. There is reversal by June at Spurn Point and Southwold, by August at West Gabbard and by July at both ferry stations. 'Coastal' winter temperatures are lower than 'offshore' and the minimum is typically reached in February rather than March; both effects are attributable to shallower water (less thermal capacity) and are

Figure 3.42 Scarborough. (a) Sea temperature time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) Sea temperature seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and the monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.

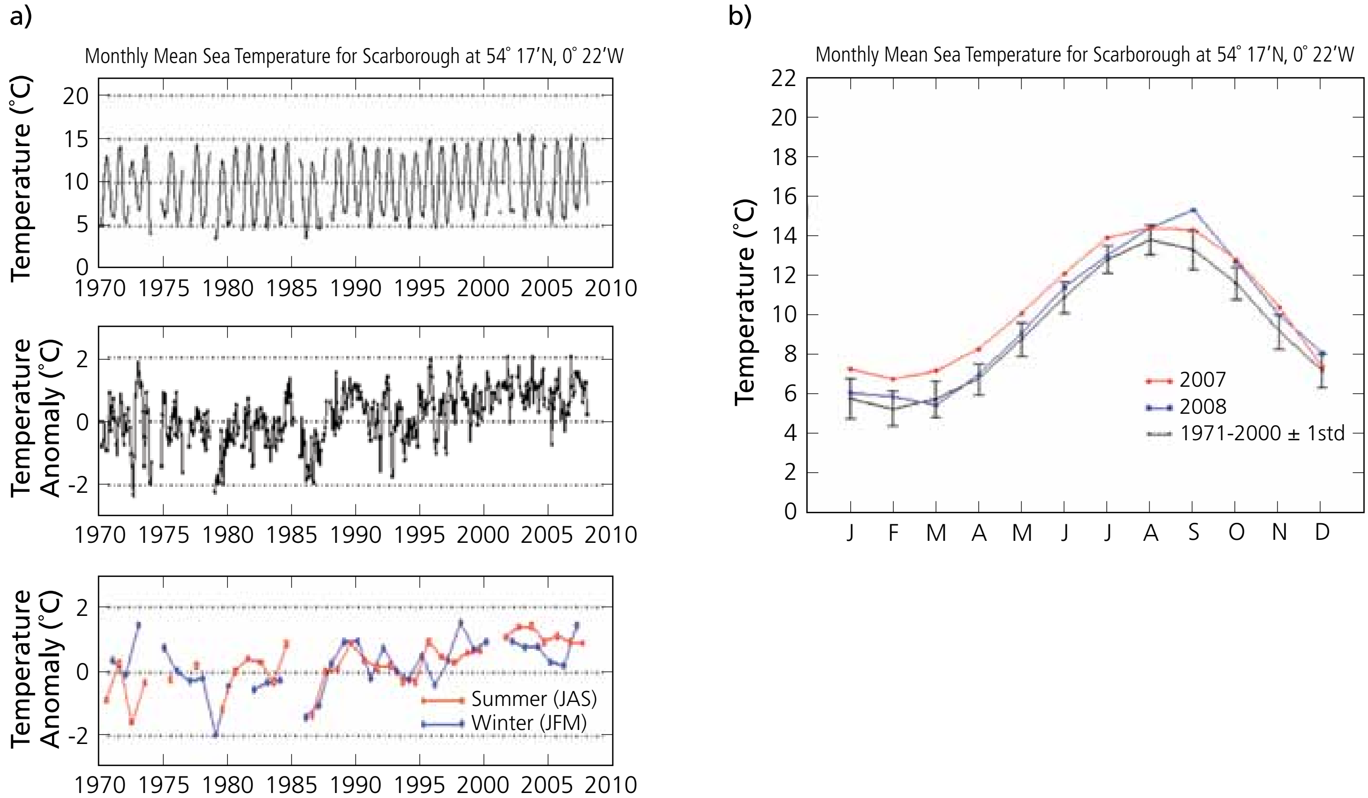
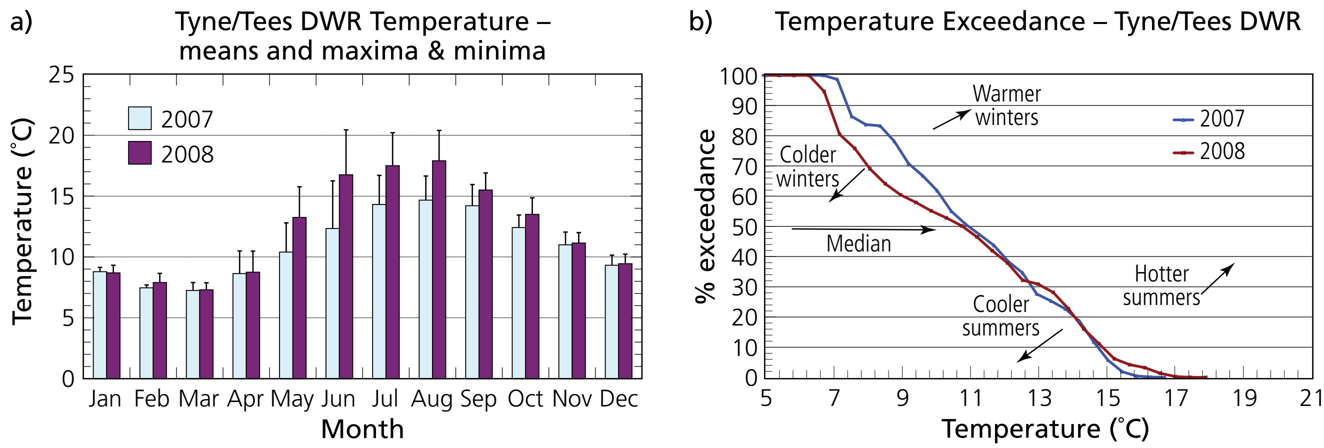


Figure 3.43 Tyne/Tees, 54°55'N, 0°45'W. (a) Monthly sea temperatures for 2007 and 2008. The plots show means (colour), maxima and minima (bars) and (b) exceedances emphasising winter and summer variations. Courtesy of J. Rees, Cefas.



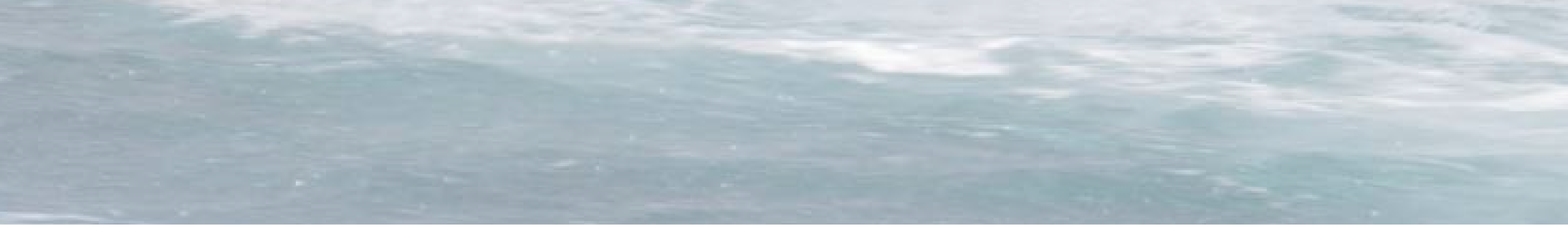
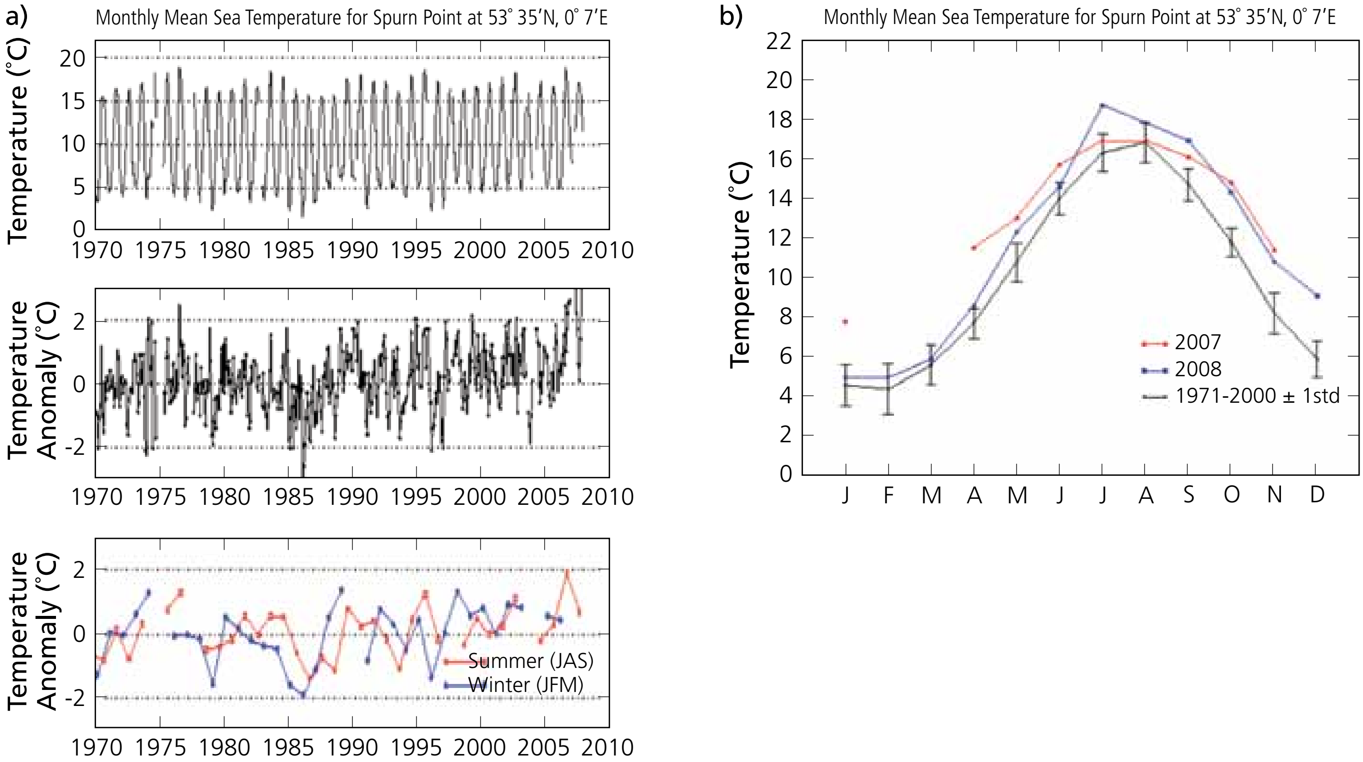


Figure 3.44 Spurn Point. (a) Sea temperature time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) Sea temperature seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.



common with the coastal sites (Scarborough, Spurn Point, Southwold). Interannual variability for monthly values is of the order of ± 1 °C and the range of temperature within any one month is up to 5 °C.

Salinity shows no clear long-term trend, whether 'offshore' (Figure 3.49) or 'coastal' (Figures 3.50). After low values in 2001 (somewhat earlier at 'coastal'), salinity rose to near-average values through most of the period 2002 to 2007, with some short excursions to fresher values and a more marked drop in 2007. The average 'coastal' seasonal cycle shows a maximum in November and a minimum in May; the average 'offshore' cycle is about two months later (February maximum, June-July minimum). However, 2006 and 2007 exemplify that individual years can be very different, almost month-by-month which suggests local freshwater influence. Figure 3.51 shows the mean annual cycle in a temperature-salinity diagram; lower-salinity summers and higher-salinity winters probably reflect changes in freshwater input from rivers and inflow of water from the English Channel to the southern North Sea.

Figure 3.45 Southwold. (a) Sea temperature time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) Sea temperature seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and the monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.

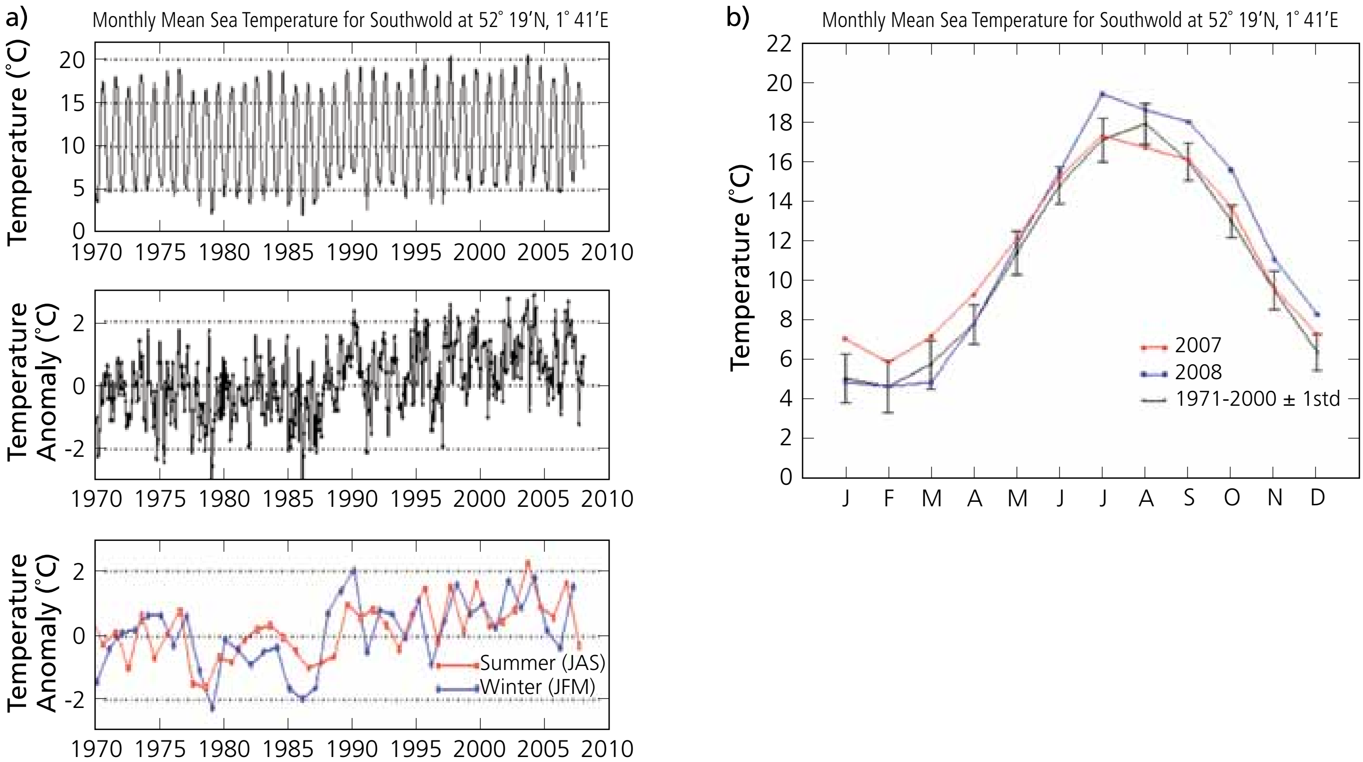
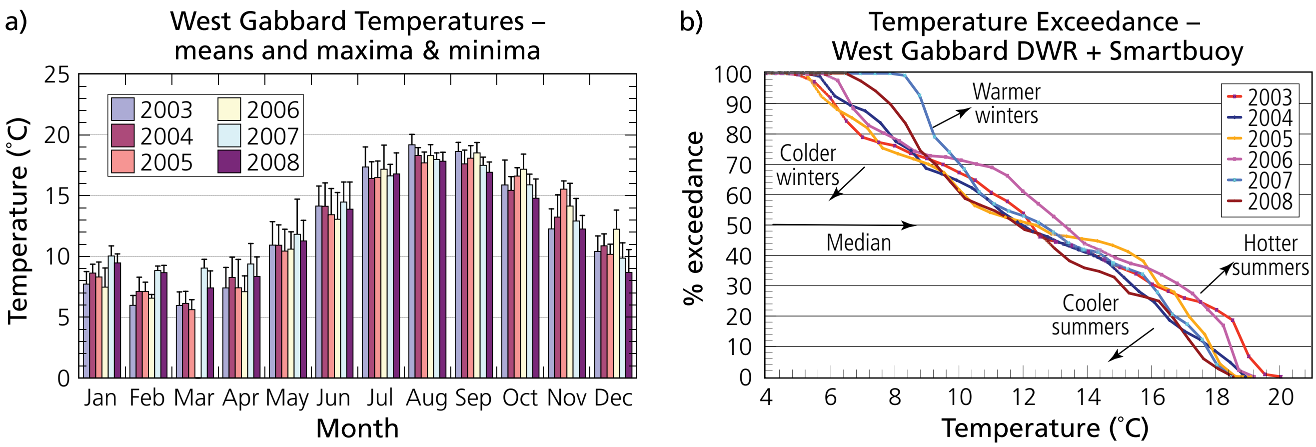


Figure 3.46 West Gabbard (Harwich). (a) Monthly sea temperatures for 2003 to 2008. The plot shows means (colour), maxima and minima (bars) and (b) exceedances emphasising winter and summer variations. Courtesy of J. Rees, Cefas.



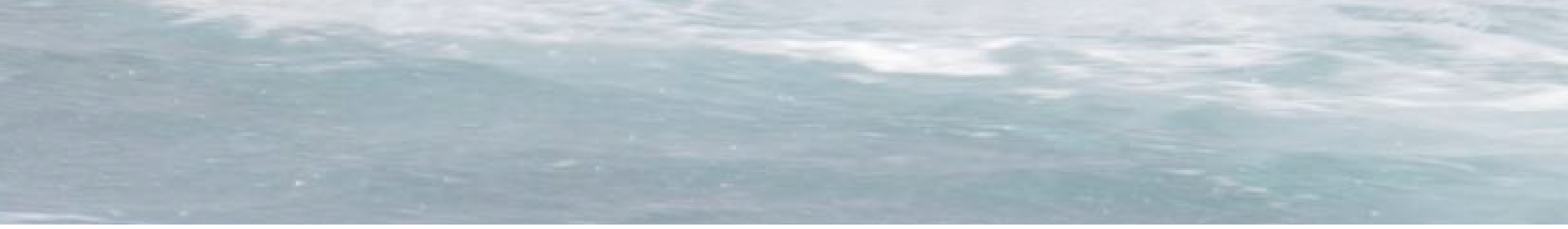


Figure 3.47 Harwich-Rotterdam ferry. (a) SST offshore time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) SST offshore seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and the monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.

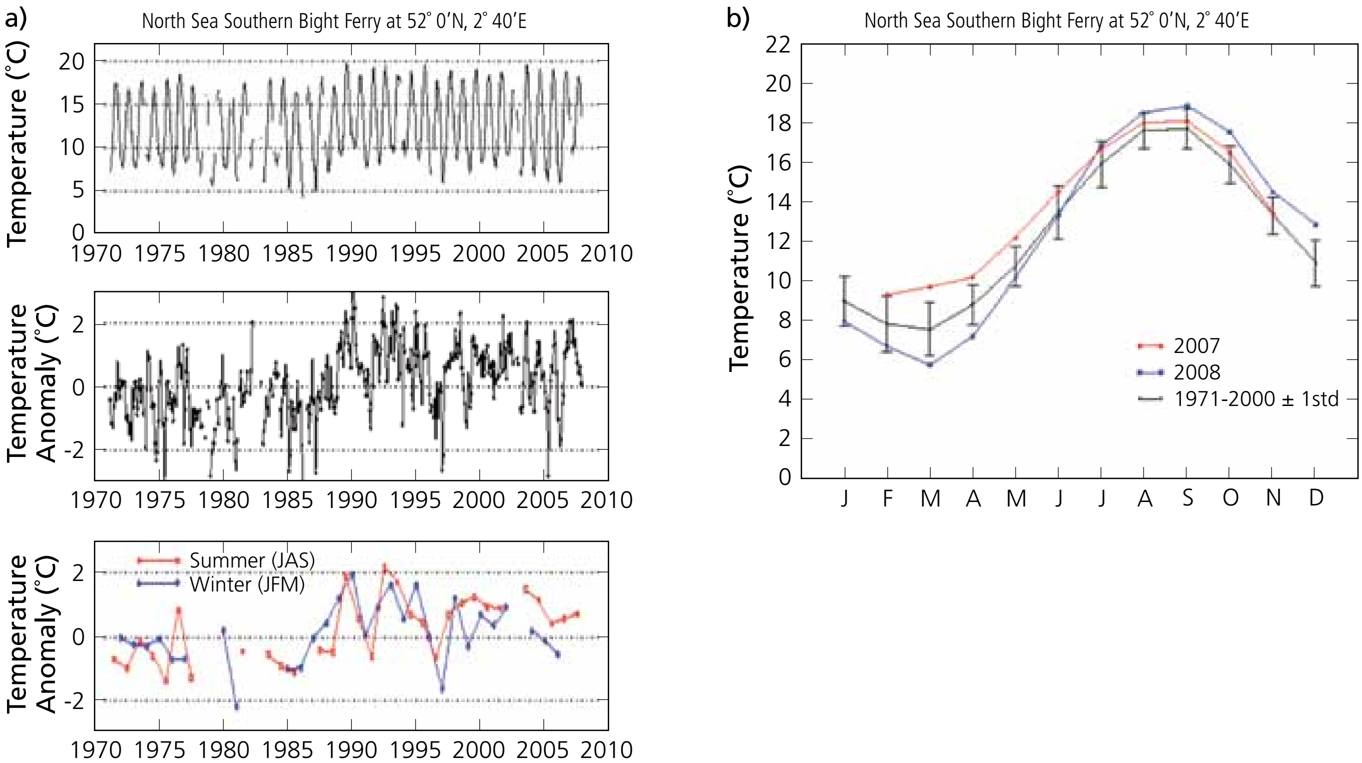
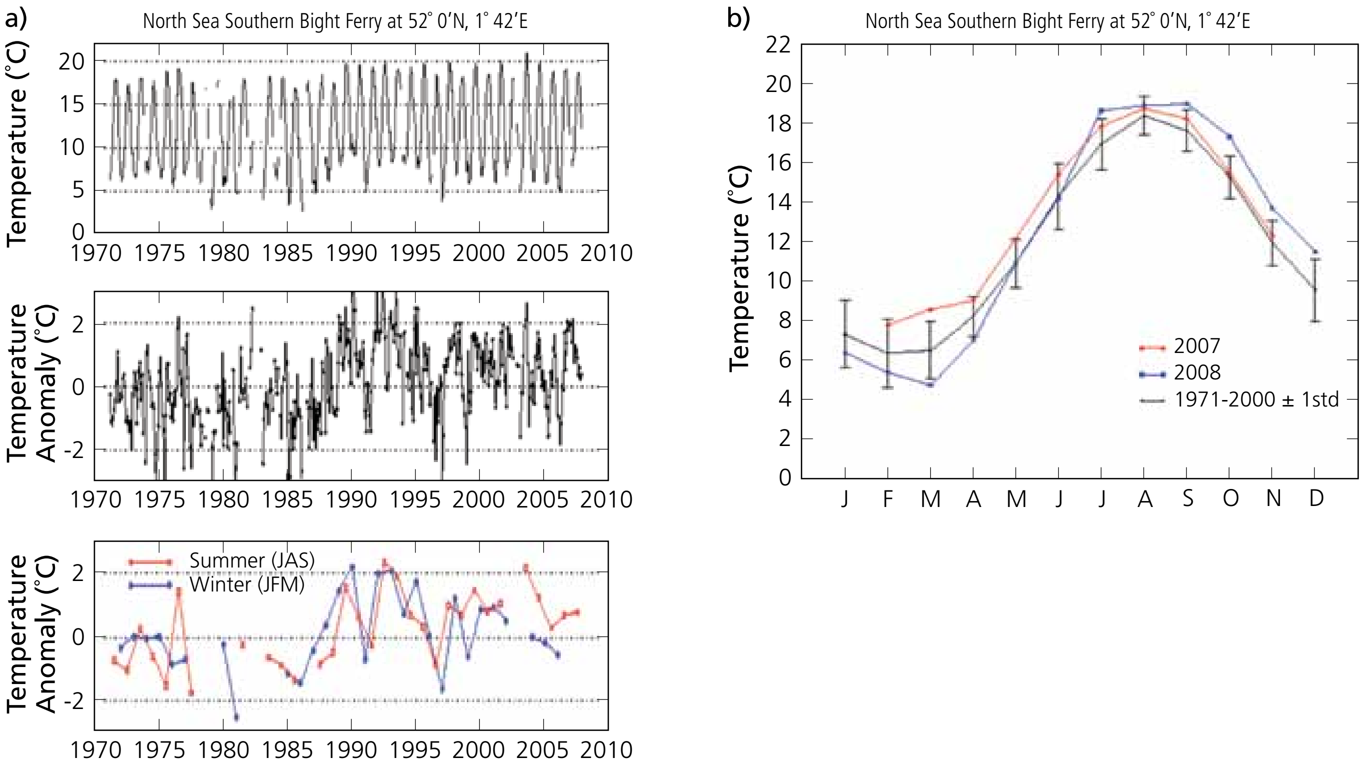


Figure 3.48 Harwich-Rotterdam ferry. (a) SST coastal time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) SST coastal seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and the monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.



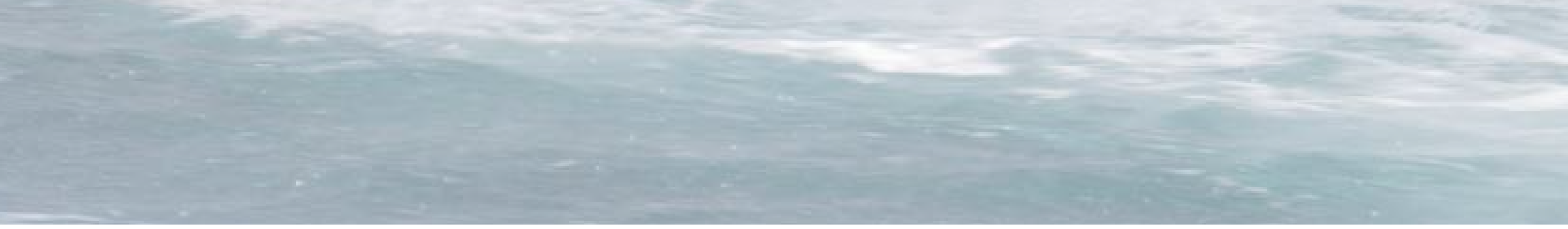


Figure 3.49 Harwich-Rotterdam ferry. (a) Surface salinity offshore time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) Surface salinity offshore seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.

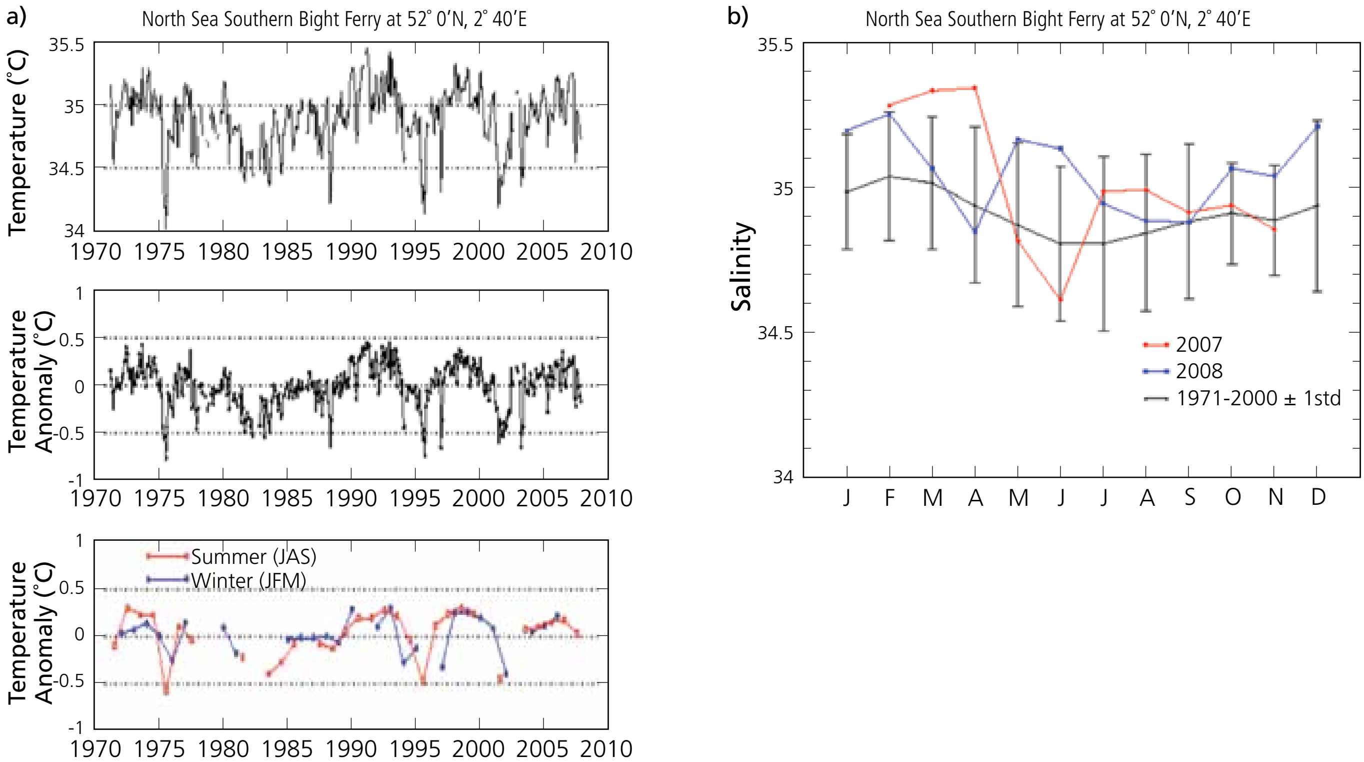


Figure 3.50 Harwich-Rotterdam ferry. (a) Surface salinity coastal time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) Surface salinity coastal seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.

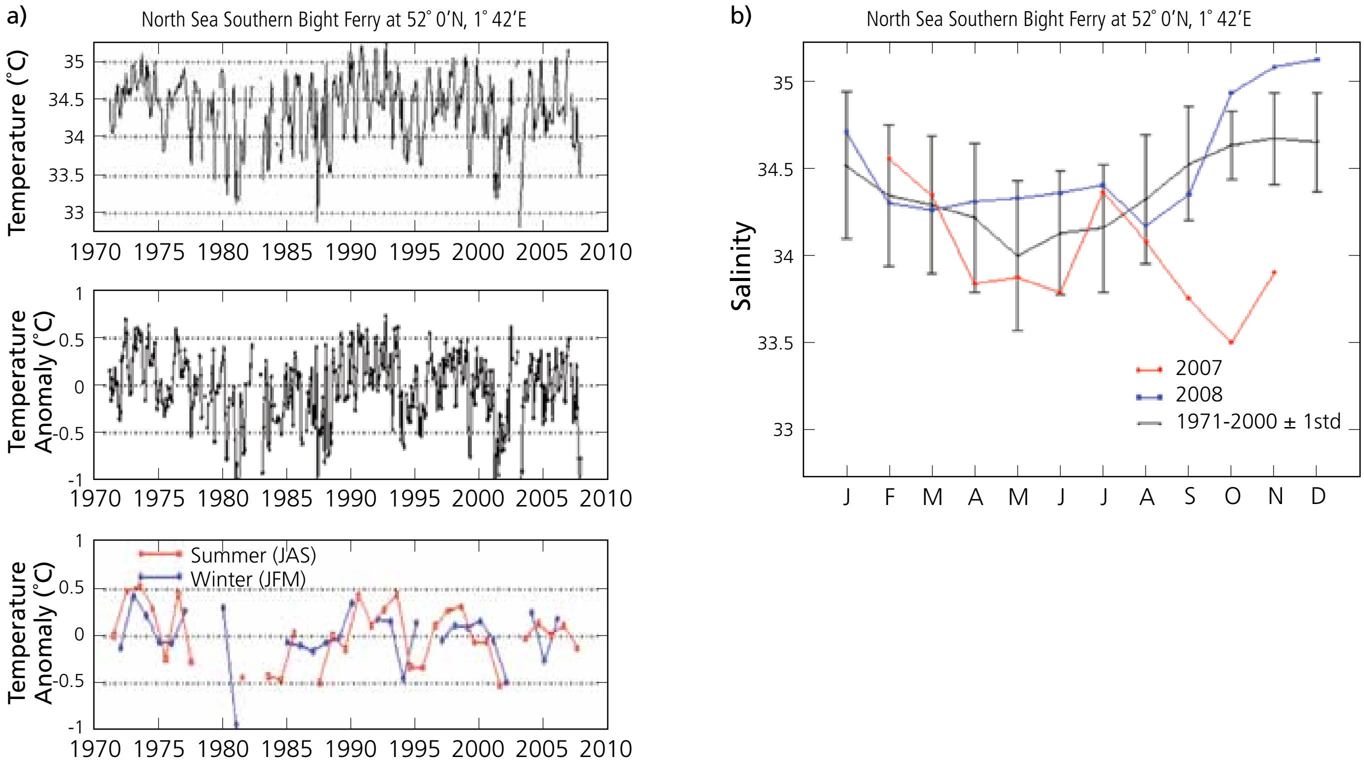
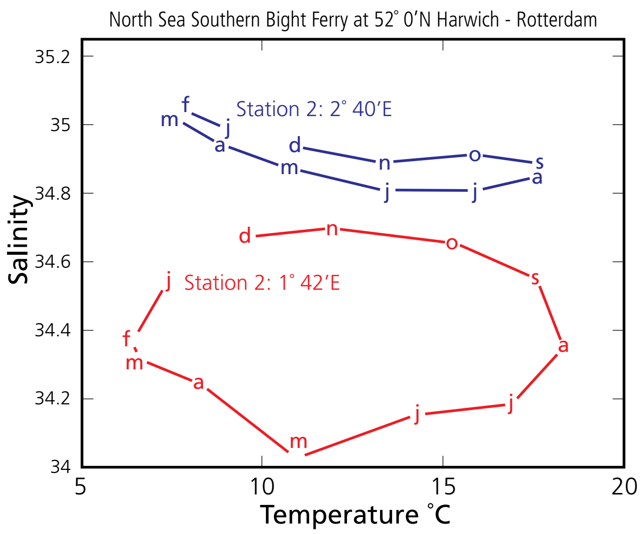


Figure 3.51 Temperature-Salinity plot showing 1971–2000 averages for each month at a 'coastal' (red) and 'offshore' (blue) site on the Harwich-Rotterdam ferry route. Courtesy of S. Dye, Cefas.



3.2.4.3.3 English Channel

For Region 3 (Figure 3.38), coastal sea temperature is available from Dover, Eastbourne, Weymouth and Poole Bay (Figures 3.52, 3.53, 3.54 and 3.55). The Dover and Eastbourne time series show a marked dip and then rise in the late 1980s, a dip in the early 1990s to the 1971–2000 average but a rise thereafter to an average level nearly 1 °C above the 1971–2000 average, albeit with large fluctuations. The 2006 and 2007 winter temperatures differ, the warmer (2007) coinciding with a strongly positive NAO Index. Whereas these coastal minima (in shallow water) are usually in February, satellite coverage suggests that SST is usually at a minimum in March, as were the coastal minima in 2006 with more cooling (negative NAO Index). The temperature difference between 2006 and 2007, maximal (nearly 4 °C) in March, slowly decreases until a rapid reversal in June-July. The Weymouth record differs in several respects: less variability until the late 1980s with no dip in the mid-1980s; a stronger rising trend (especially in summer) from low temperatures in 1996; the 2007-2006 winter temperature difference peaked at about 3 °C. For all the records, interannual variability for monthly values is of the order of ± 1 °C and the range of temperature within any one month is up to 5 °C. All these aspects of behaviour are very similar to conditions in the southern North Sea (Region 2).

Figure 3.52 Dover. (a) Sea temperature time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) Sea temperature seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and the monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.

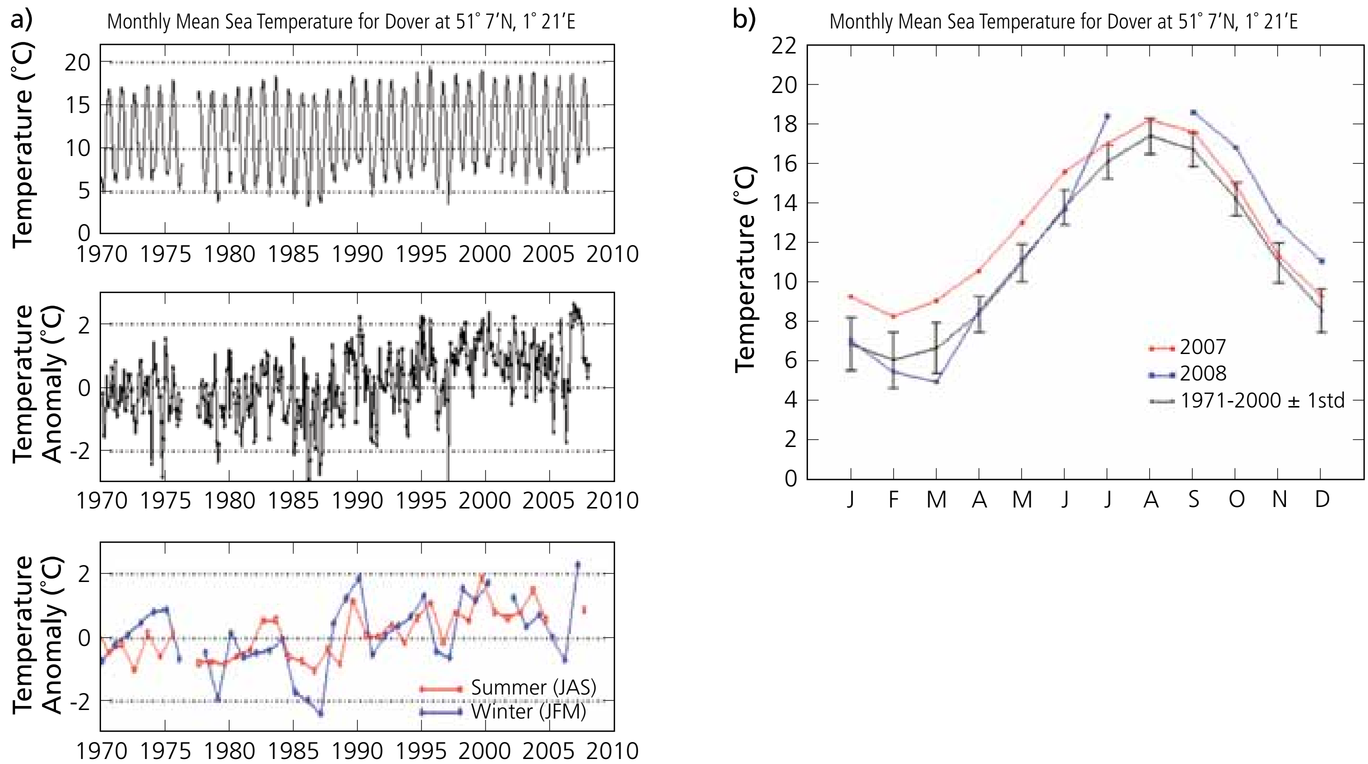


Figure 3.53 Eastbourne. (a) Sea temperature time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971–2000 average, and the winter and summer anomalies. (b) Sea temperature seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.

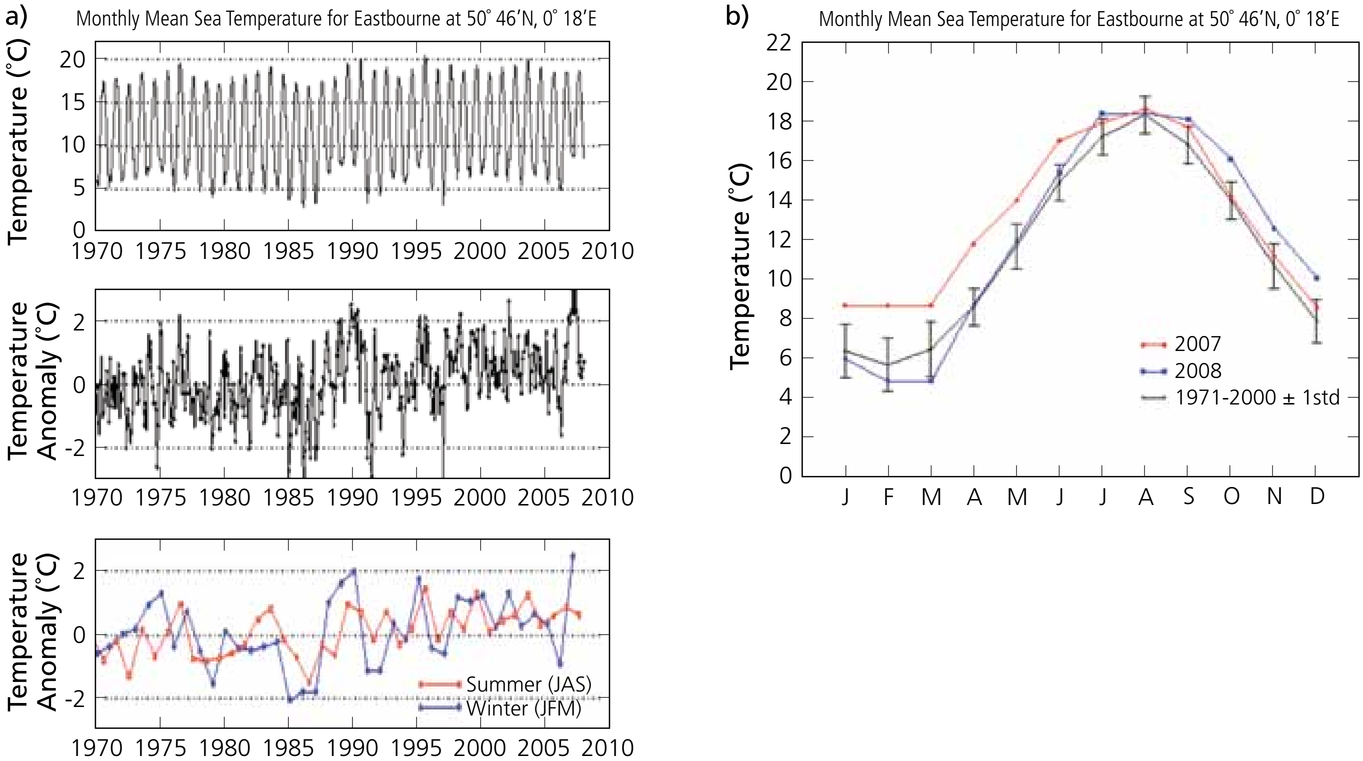


Figure 3.54 Weymouth. (a) Sea temperature time-series for 1970 to 2007. Respective panels show the monthly mean, the monthly anomaly relative to the 1971-2000 average, and the winter and summer anomalies. (b) Sea temperature seasonal cycle for the period 1971 to 2000. The plot shows the average ± 1 standard deviation and monthly mean values for two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Courtesy of S. Dye, Cefas.

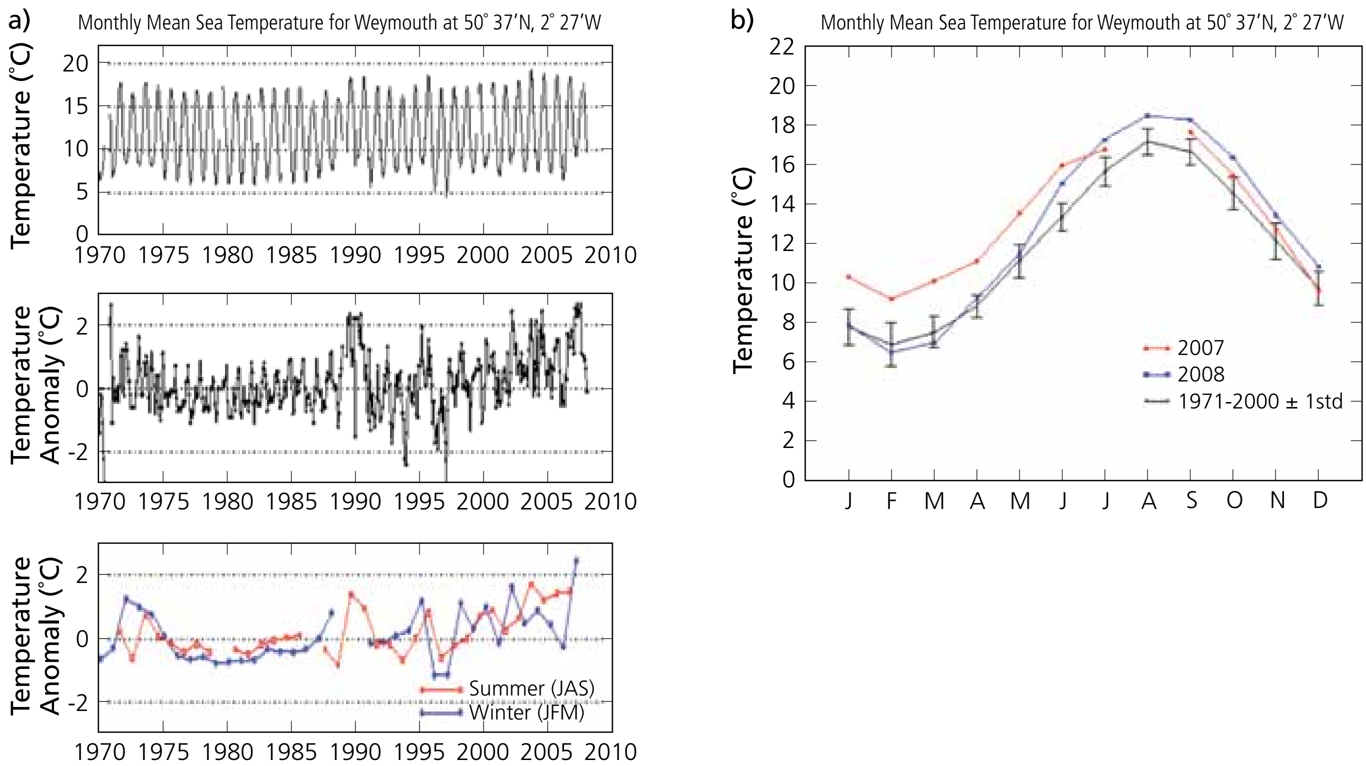
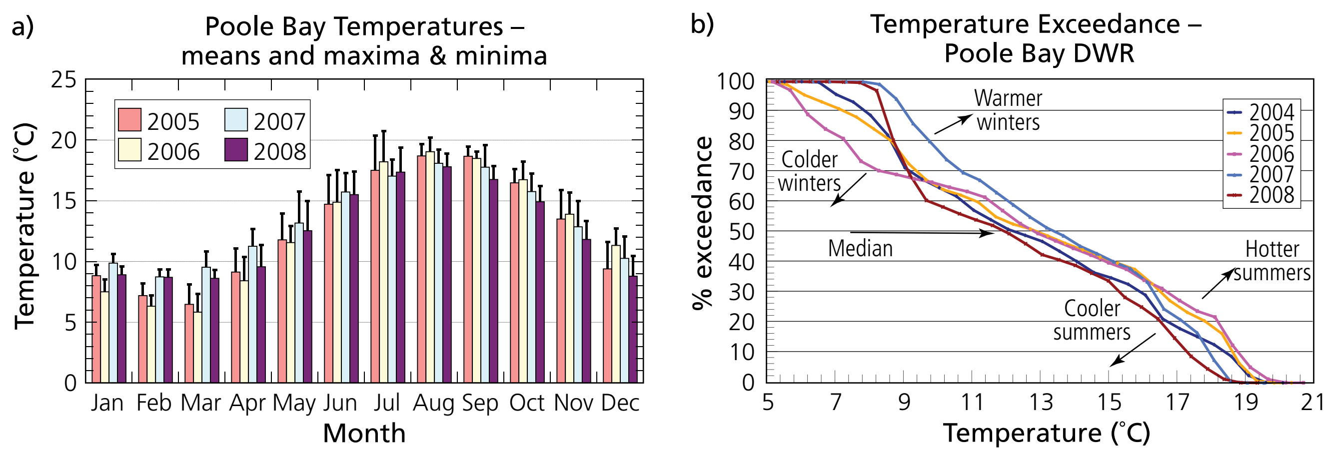


Figure 3.55 Poole Bay. (a) Monthly sea temperatures for the years 2005 to 2008. The plot shows means (colour), maxima and minima (bars) and (b) exceedances emphasising winter and summer variations. Courtesy of J. Rees, Cefas.



3.2.4.3.4 Western Channel – ferry route

For the Channel (Portsmouth to the south-west and beyond, Regions 3 and 4) temperature and salinity data are available from the *Pride of Bilbao* FerryBox (www.ukdmos.org). Plots of weekly data (temperatures, Figures 3.56 to 3.58; salinities, Figures 3.59 and 3.60) are organised into two groups. The first group shows data on a grid of latitude and day of year (weekly resolution): (a) for each year (2005, 2006, 2007), (b) the 2005–2007 mean, and (c) each year's difference from the mean. The second group shows time series of all available gridded data from 2003 to 2007 at selected latitudes: 50.5° N (UK coastal); 50.0° N (shallow well-mixed central English Channel with depths of 30 to 60 m); 49.5° N (shallow summer stratifying western Channel).

The temperature and salinity fields indicate year to year variability (from 2003) rather than progressive change. In stratified waters at 49° N and 49.5° N a clear temperature peak occurred in 2006. This would be consistent with a very calm period being followed by stormy weather. At these latitudes the hot weather of 2003 produced peak temperatures around week 27, before a period of bad weather in the English Channel. For waters on the shelf, 2006 waters were warmer later in the year; this carried over to warmer waters in the spring of 2007. This warmer water would have been enhanced by the fine stable weather of spring 2007. However, summer 2007 was the coldest recorded in all areas in this data set.

The salinity data particularly show variability in the transport of freshwater from rivers on the French Atlantic coast. The strong intrusion seen in 2003 relative to 2004 was investigated by Kelly-Gerreyn et al. (2006). At the southern entrance to the western English Channel (48.5 °N, 5.1 °W, near Ushant), low-salinity (< 35) surface waters (LSSW) were observed in late winter (March-April) in three successive years (2002–2004; Kelly-Gerreyn et al., 2006). Subsequently LSSW accumulation was weak in 2005, strong in 2006 and weak in 2007. By comparison with studies of data for French river discharges and measurements in French coastal waters (Puillat et al., 2004), the source of the LSSW was identified as northward-spreading plumes from the Loire and Gironde (French Biscay coast). Fastest plume travel-times were associated with north-easterly winds, consistent with Ekman theory. Differences between years in mean winter (January-March) combined river discharges (D) were consistent with the minimum salinities (S_{min}) of the LSSW in successive years for the period 2002 to 2004:

$D = 1579, 3630, 4211\ m^3/s$

$S_{min} = 34.53, 33.90, 33.68$

Winter-mean (1905–1974) salinity is otherwise 35.33 near Ushant.

Subsequent intrusion of the LSSW into the western English Channel is very variable from year to year. During the period 2003 to 2007, the low-salinity intrusion was freshest (mean = 35.11 ± 0.21) and most penetrative (reaching 50.7 °N, 1.0 °W by the end of the year) in 2003 and 2006. In 2003 and 2006 the progressive movement of the LSSW to the north and into the English Channel can be seen as a minimum-salinity feature in the time-series plots occurring at different times at different latitudes. Kelly-Gerreyn et al. (2006) considered that the strong 2003 intrusion resulted from the coincidence of high dispersion from spring tides and favourable winds (southwesterly / southeasterly) enhancing the longer term residual flow. They were unable to identify a link of the LSSW to phases of the winter NAO Index.

Figure 3.56 Bilbao to Portsmouth. (a) Weekly temperature data gridded by latitude for the years 2005 to 2007, (b) mean weekly temperature data gridded by latitude for the period 2005 to 2007 and (c) difference in each year's weekly temperature data from the mean value for the period 2005 to 2007. Data from MiniPack CTD-F. Courtesy of D. Hydes, NOC.

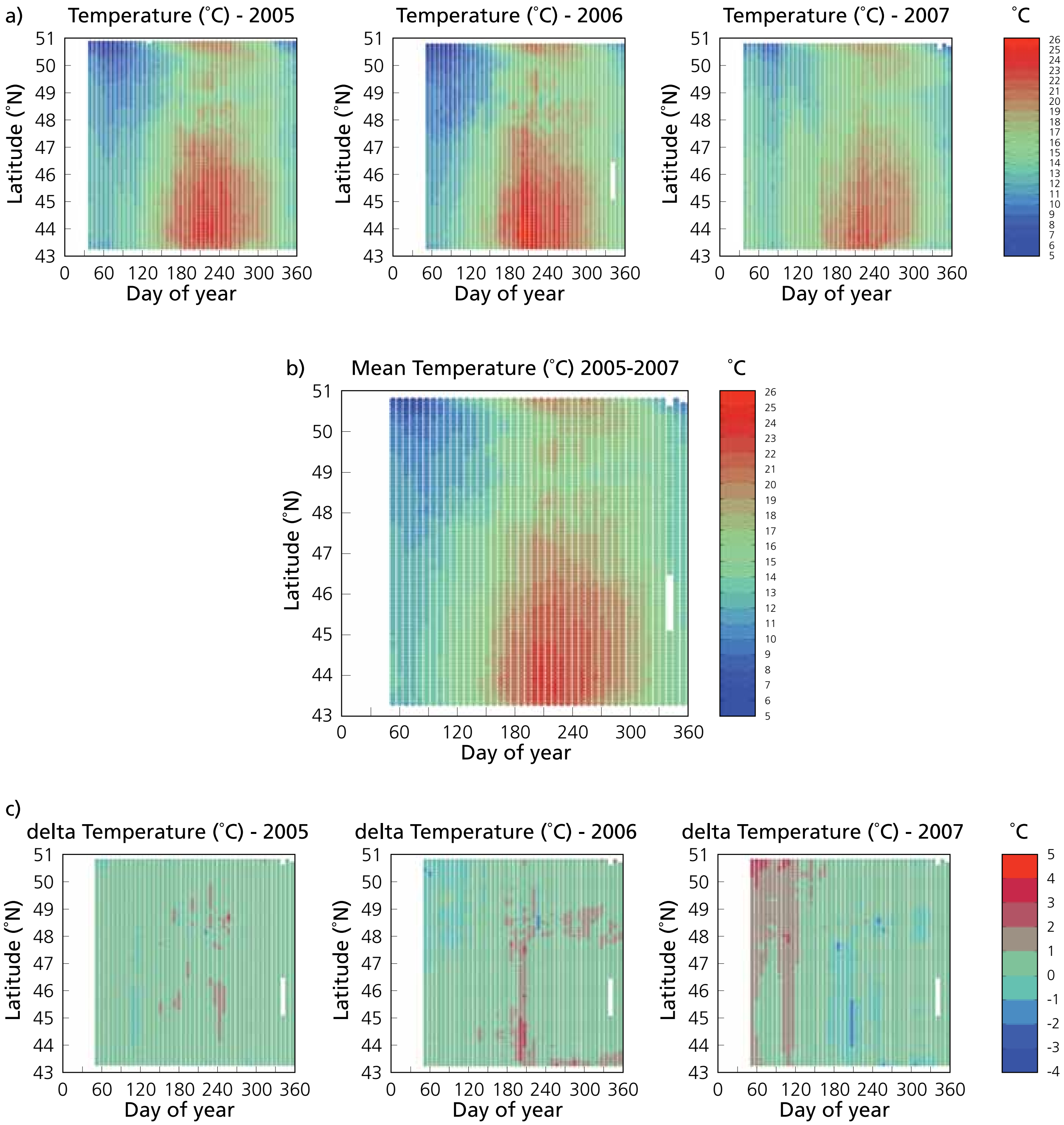


Figure 3.57 Pride of Bilbao FerryBox time-series for seawater temperature the period 2003 to 2007. Data from MiniPack CTD-F. Courtesy of D. Hydes, NOC.

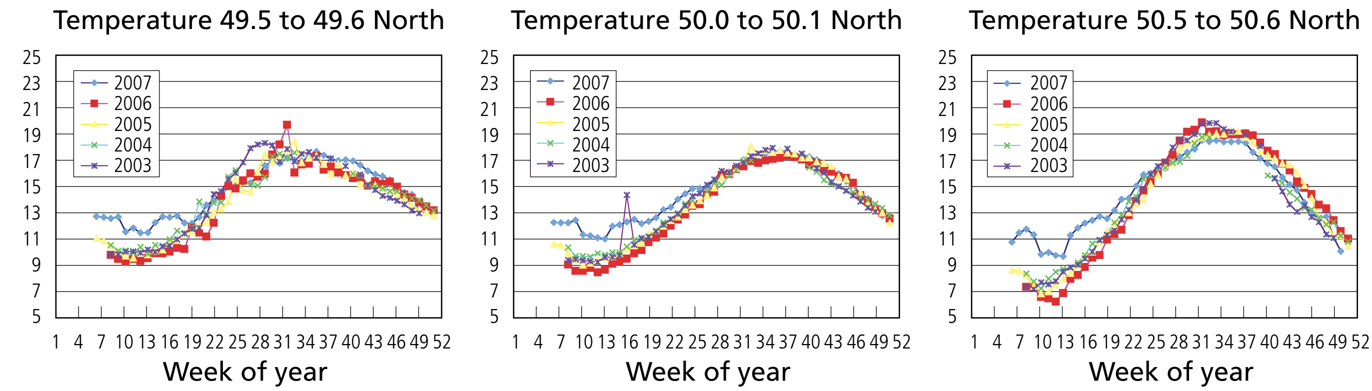
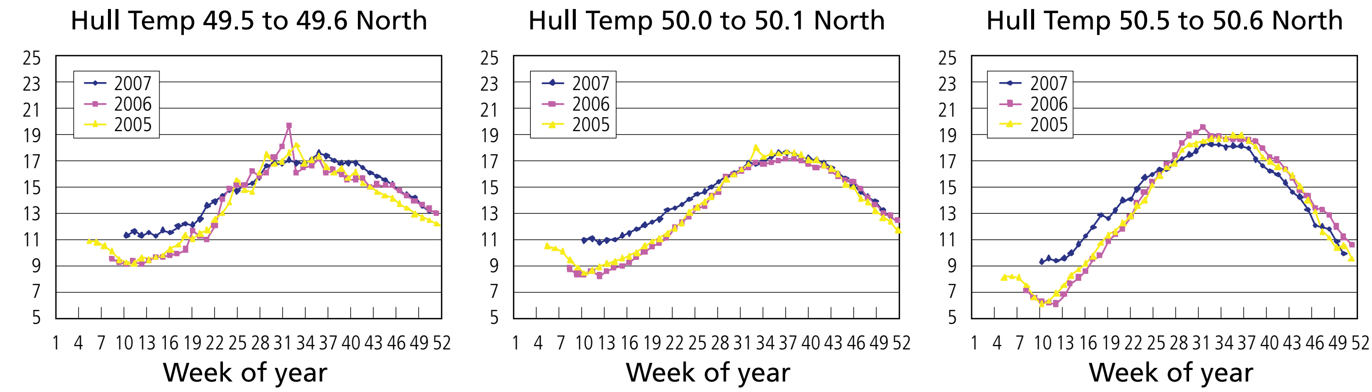


Figure 3.58 Pride of Bilbao FerryBox time-series for seawater temperature for the period 2003 to 2007. Data from a hull mounted SBE 48. Courtesy of D. Hydes, NOC.



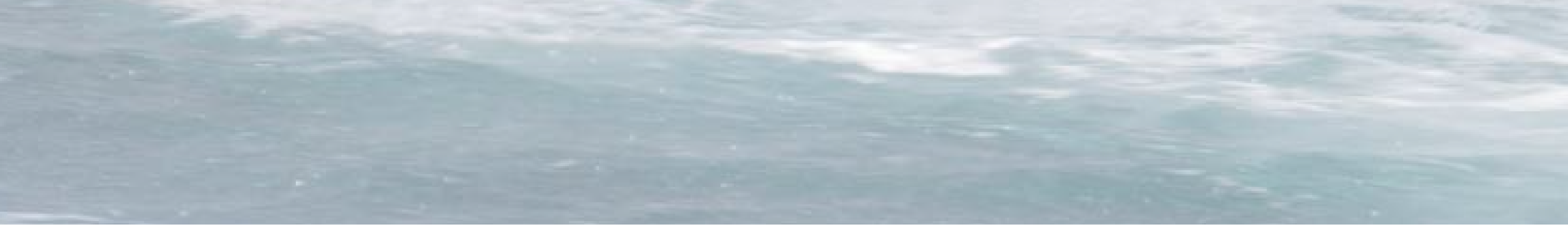


Figure 3.59 Bilbao to Portsmouth. (a) Weekly salinity data gridded by latitude for the years 2005 to 2007, (b) mean weekly salinity data gridded by latitude for the period 2005 to 2007, and (c) difference in each year's weekly salinity data from the mean value for 2005 to 2007. Data from MiniPack CTD-F. Courtesy of D. Hydes, NOC.

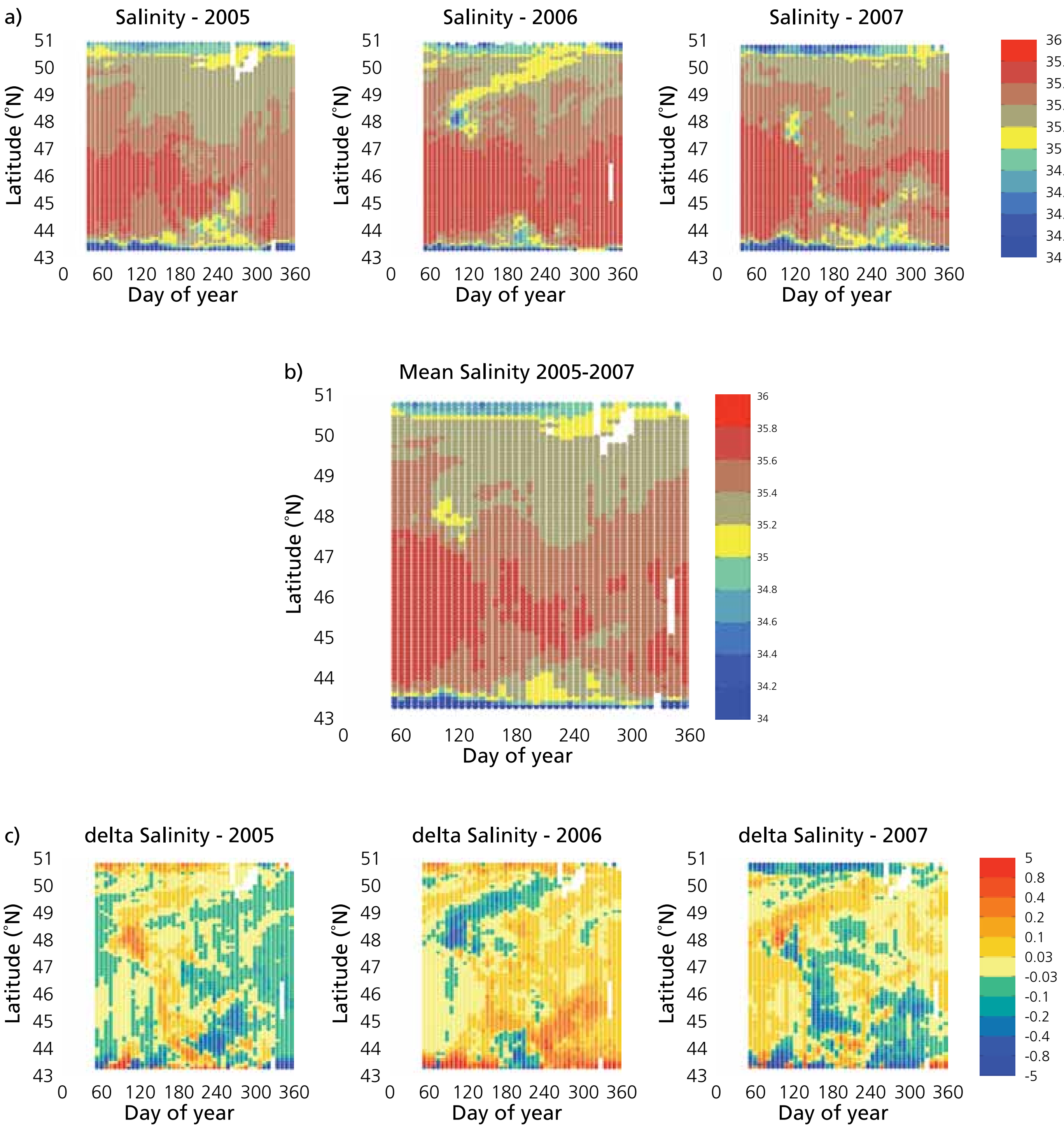
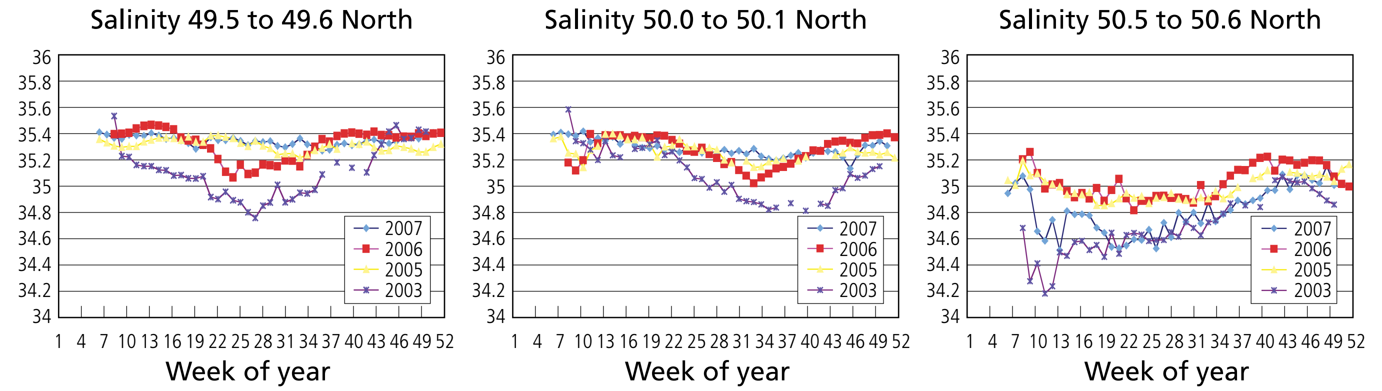


Figure 3.60 Pride of Bilbao *FerryBox time-series for salinity for 2003 to 2007. Courtesy of D. Hydes, NOC.*



Overall these findings emphasise the dependence of surface temperatures on weather and salinities on the amount and transport of freshwater from rivers.

3.2.4.3.5 Western Channel and Celtic Sea

The western English Channel (Region 4) has stations E1 (50° 02′N, 4° 22′W; water depth 75 m; started by the Marine Biological Association in 1902) and L4 (50° 15′ N, 4° 13′ W; 50 m; started by Plymouth Marine Laboratory in 1988; see www.ukdmos.org). (A Celtic Sea transect is shown in Section 3.2.4.2). E1 and L4 are strongly influenced by tides and weather. E1 is mainly influenced by North Atlantic water, and develops a summer thermocline: typically stratification starts in early April, persists throughout the summer and is eroded by the end of October. The typical depth of the summer thermocline is around 20 m. The L4 time series is shorter and noisier, with coastal and river Tamar influence.

Figure 3.61 for E1 shows monthly temperature anomalies since 1903, at the surface and at 50 m depth. Recent values are warm, 1 to 2 °C above the long-term (1903–2007) average. The monthly plots show that on average the coolest temperature (9 °C) is in March and the warmest (16 °C) is in August at the surface and in October (14 °C) at the bottom. 2007 included the warmest February, March and autumn values ever recorded. The summer of 2007 was closer to average. This is apparent throughout the depth of the water column. Figure 3.62 for L4 shows more variability and the shorter duration makes any firm conclusions more difficult, again February and autumn 2007 were warm.

Figure 3.63 shows the monthly salinity anomalies at E1 since 1903. There is an average seasonal cycle with a maximum in February and minimum in August, possibly associated with more intense summer rainfall depressing the summer salinity values. However, interannual and shorter-term variability greatly exceed this average seasonal variation. There appears to be a maximum at about 35.5 related to salinity in the adjacent open Atlantic. Excursions to lower salinity can be greater. Interestingly, May 2007 was notably wet and the outcome in salinity is obvious. Other values in 2007 were typically 0.1 above long-term averages. Figure 3.64 for L4 shows more variability, even from week to week at the surface; bottom salinities are less variable than surface values. The shorter duration and variability at L4 make any firm conclusions difficult.

Figure 3.61 (a) Temperature anomalies for surface water and at 50 m (equivalent to bottom temperature) at station E1 of the Marine Biological Association between 1903 and 2007. (b) Monthly-average temperatures for surface water and at 50 m. The solid line represents the average for all years of data, the dotted lines are the maximum and minimum for all years, and asterisks show 2007 data. Courtesy of T. Smyth, PML.

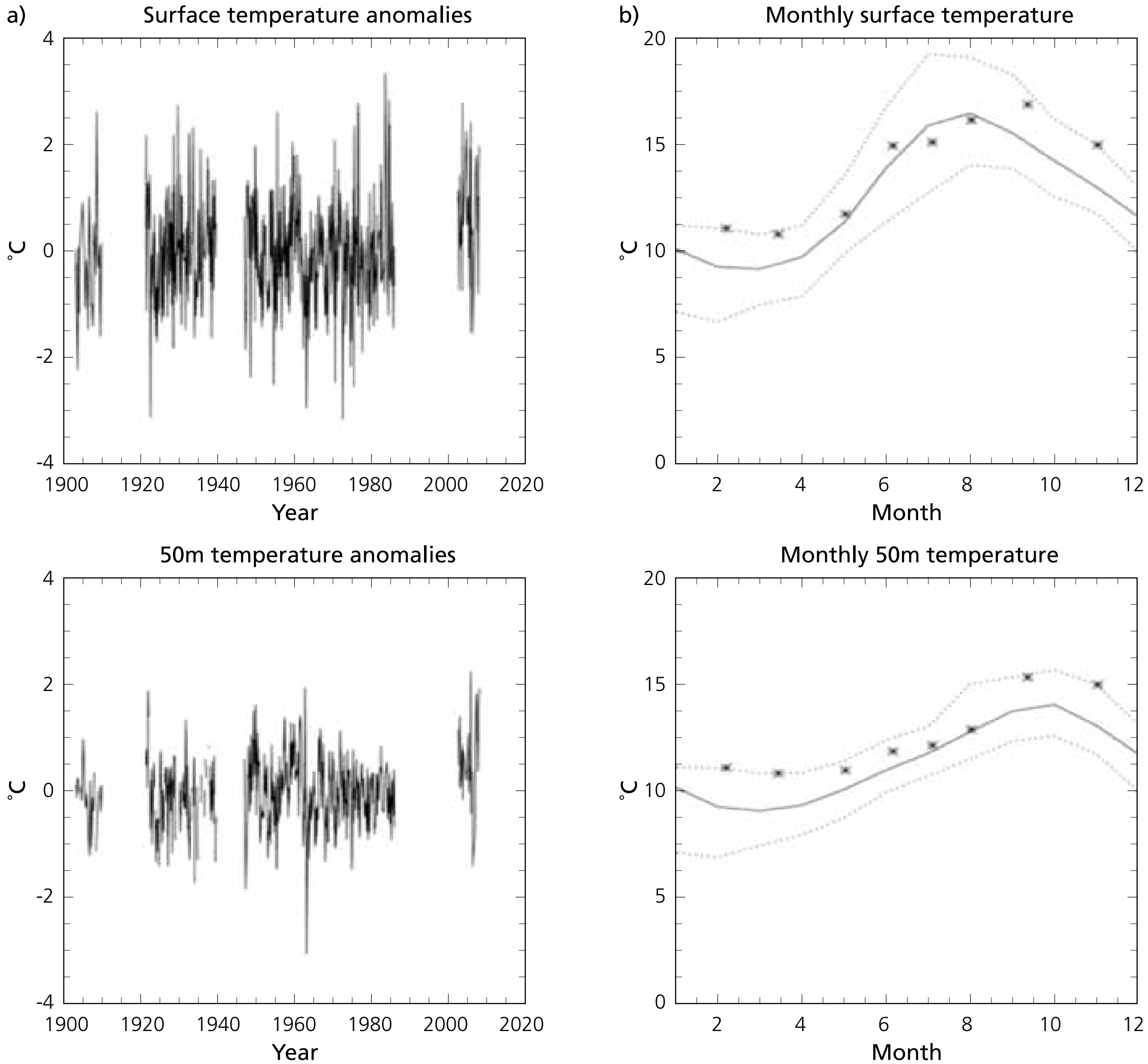


Figure 3.62 (a) Temperature anomalies for surface water and at 50 m (equivalent to bottom temperature) at station L4 between 1993 and 2007. (b) Monthly-average temperatures for surface water and at 50 m. The solid line represents the average for all years of data, the dotted lines are the maximum and minimum for all years, and asterisks show weekly 2007 data. Courtesy of T. Smyth, PML.

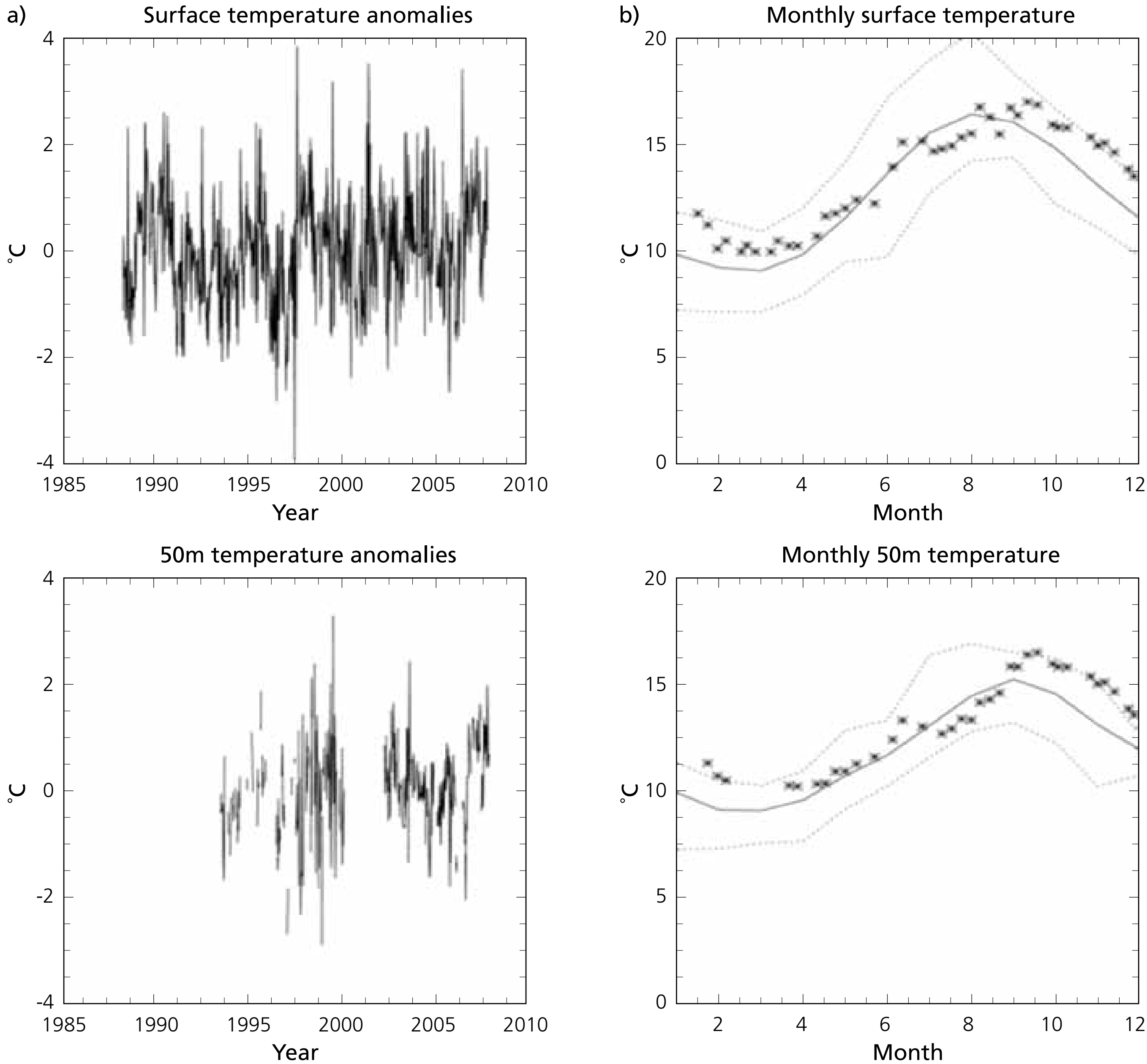


Figure 3.63 (a) Salinity anomalies for surface water and at 50 m (equivalent to bottom salinity) at station E1 of the Marine Biological Association between 1903 and 2007. (b) Monthly-average salinities for surface water and at 50 m. The solid line represents the average for all years of data, the dotted lines are the maximum and minimum for all years, and asterisks show 2007 data. Courtesy of T. Smyth, PML.

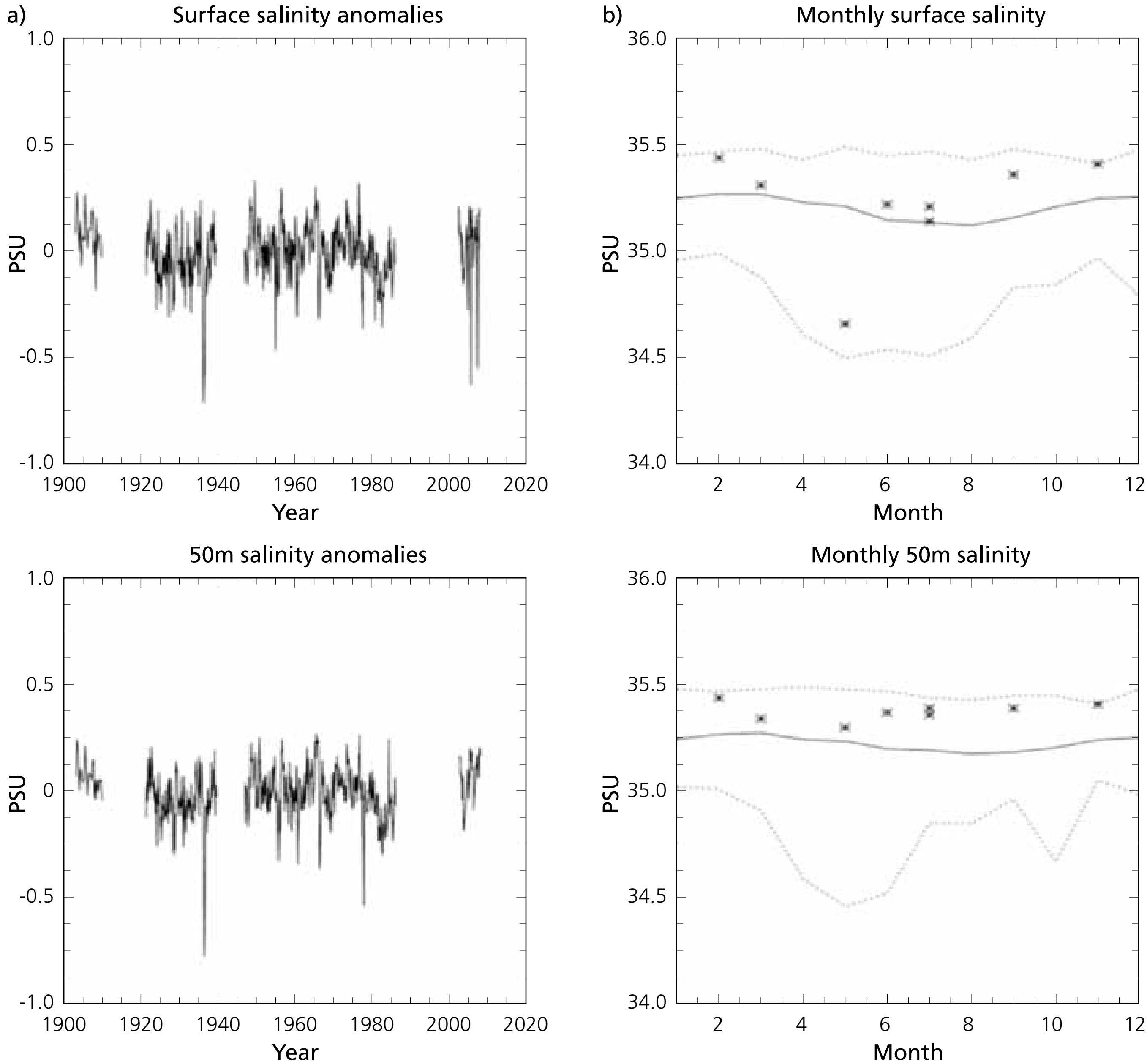
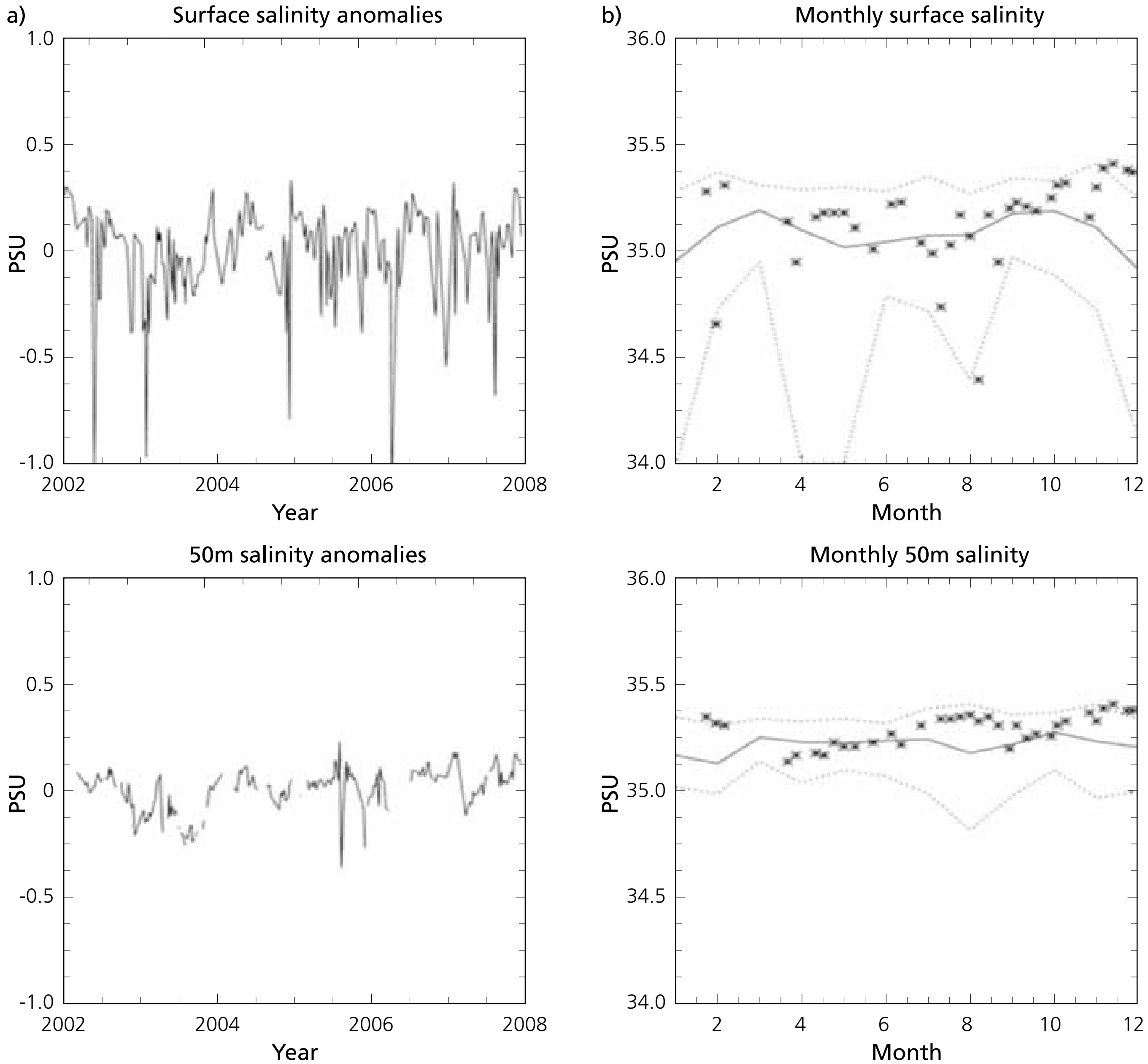
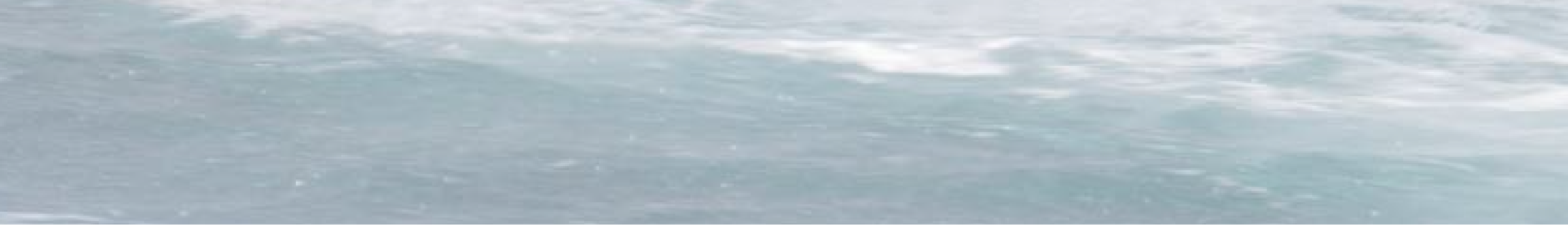


Figure 3.64 (a) Salinity anomalies for surface water and at 50 m (equivalent to bottom salinity) at station L4 between 2002 and 2007. (b) Monthly-average salinities for surface water and at 50 m. The solid line represents the average for all years of data, the dotted lines are the maximum and minimum for all years, and asterisks show weekly 2007 data. Courtesy of T. Smyth, PML.





3.2.4.3.6 Irish Sea

Isle of Man Government Laboratory (IoMGL) measurements of temperature and salinity are available along 54° N (in collaboration with the UK Environment Agency), at Cypris and Port Erin Breakwater (data to 2006 were obtained by the Port Erin Marine Laboratory).

The 54° N temperature series show summer stratification at sites A to C west of the Isle of Man (Figure 3.65). Sometimes there is stratification also at sites G to I to the east; this may be reinforced by salinity (Figure 3.67; e.g. site G in 1993, 1995) aided by freshwater input from several rivers (from North Wales round to Morecambe Bay). In winter there is little surface-bottom temperature difference (Figure 3.66); the majority of winter temperature differences have warmer water near the bed while the surface is fresher (for stability; e.g. site G in 2003, 2004; Figure 3.68).

Cypris and Port Erin (Figures 3.69, 3.70 and 3.72) show a rising trend in temperature, about 1 °C over the past 50 years; the best-fit curve at Cypris and the 5-year running mean at Port Erin both suggest a faster rise in the past 20 years. Nevertheless, year-to-year variability often exceeds 0.5 °C. On average the seasonal cycle at Port Erin has a minimum in March and a maximum in August. The difference between the years 2006 (negative NAO Index) and 2007 (positive NAO Index; Figure 3.71) is less than at coastal stations in the North Sea, English Channel or Liverpool Bay; it hardly varies from March to May but reverses by July.

The local sea-air differential has decreased significantly over the period 1948 to 2007 (Figure 3.73); local air temperature has risen faster than sea temperature. An inverse linear relationship exists between the NAO Index and the local sea-air temperature differential (e.g. for a positive NAO Index, prevalent westerlies tend to be associated with warmer air and less sea-air difference). Hisscott (2006) postulated that one possible consequence of this changing sea-air temperature difference is a change in the frequency of fog around the Isle of Man coast. The number of days with fog observed by the Met Office at Ronaldsway is closely correlated with the sea-air temperature difference. Fog in summer has become more frequent since the mid-1970s whereas fog in winter became less frequent during the period 1947 to 2004.

Liverpool Bay temperatures from a Cefas Smart Buoy (Figure 3.74) and Coastal Observatory mooring show: an average rise of 1.1 °C between earlier measurements (1935–1961) and 2002–2007 (Figure 3.75); a marked contrast between the 2006 (cold) and 2007 (warm) winters (negative and positive NAO Index, respectively), as in the North Sea and Channel; this contrast almost disappears by June.

Overall salinity trends and curvature at Cypris and Port Erin (Figures 3.76 and 3.77) are small relative to interannual variability. In Liverpool Bay, salinity in the period 2002 to 2007 shows no clear change from a 1935–1961 average (Figure 3.75). Cypris salinity is somewhat correlated inversely with the NAO Index (Figure 3.78), possibly via less freshwater input in negative-NAO Index winters. There is also much variability on shorter time scales, reflecting short-term freshwater inputs. Variability and reduced salinity in Liverpool Bay show the influence of river inflows, which are greater in winter than summer on average.

Figure 3.65 Summer temperature (end-June / beginning-July) along 54° N. Courtesy of T. Shammon, IoM Government.

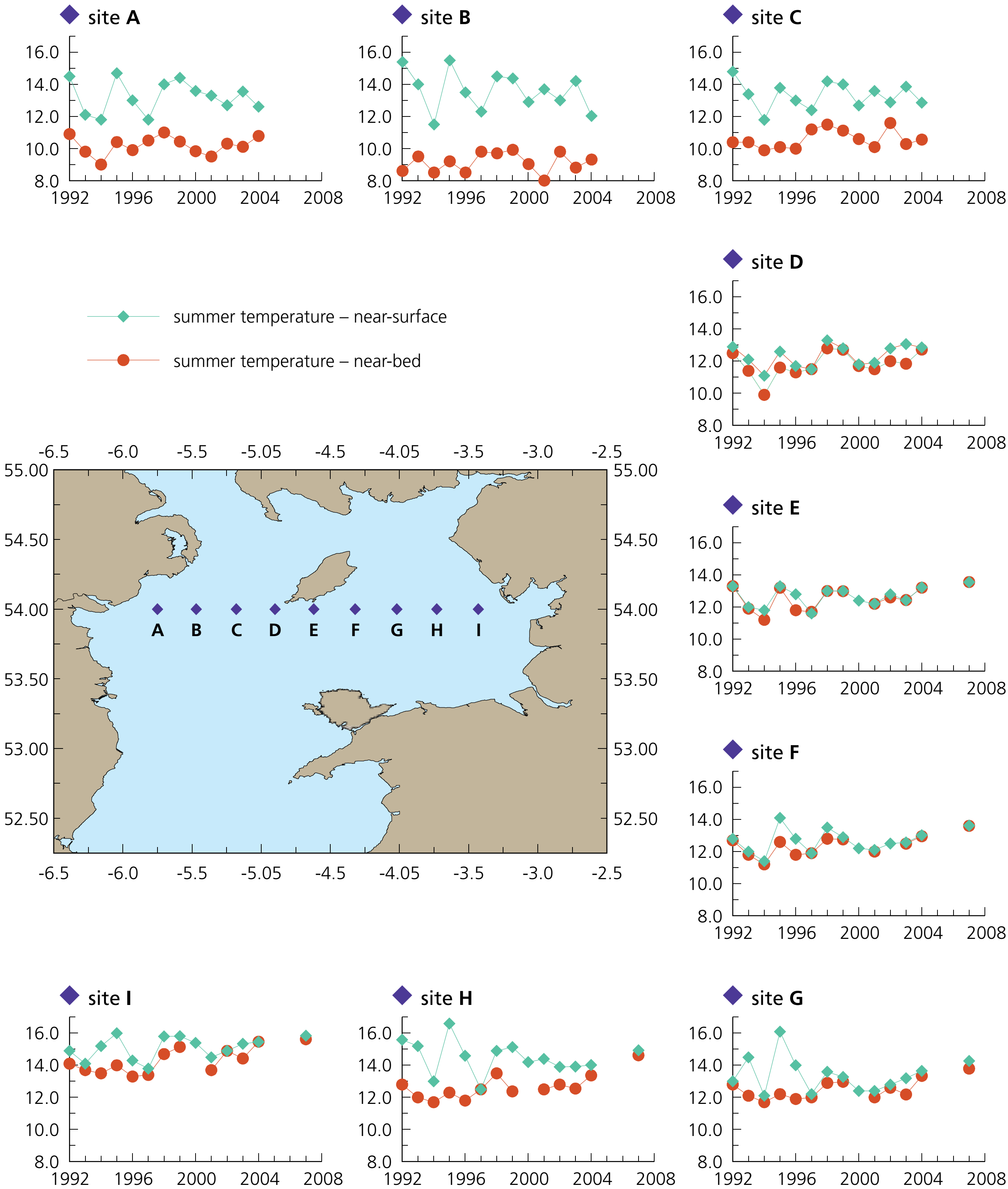


Figure 3.66 Winter temperature (end-January / beginning-February) along 54° N. Courtesy of T. Shammon, IoM Government.

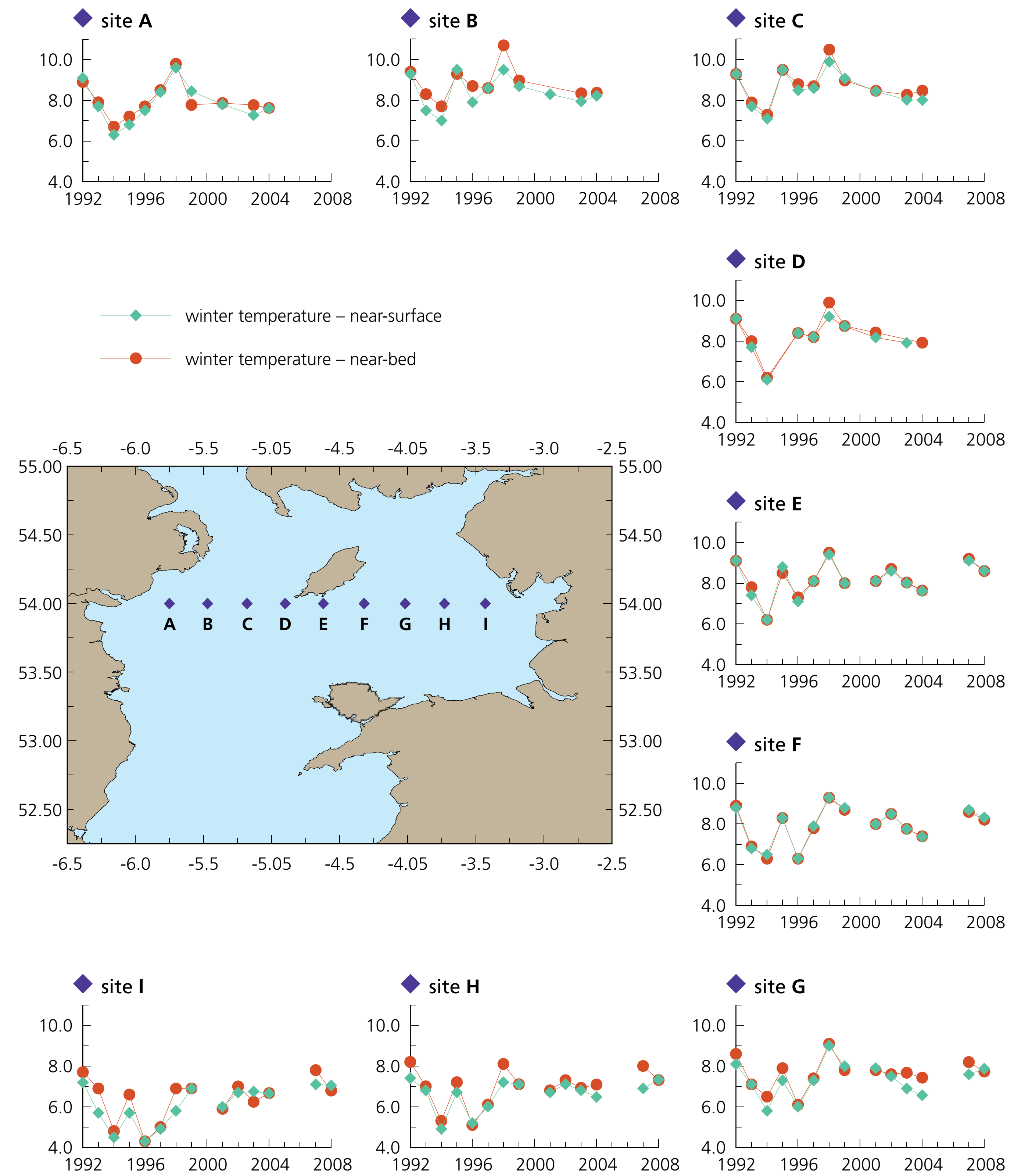
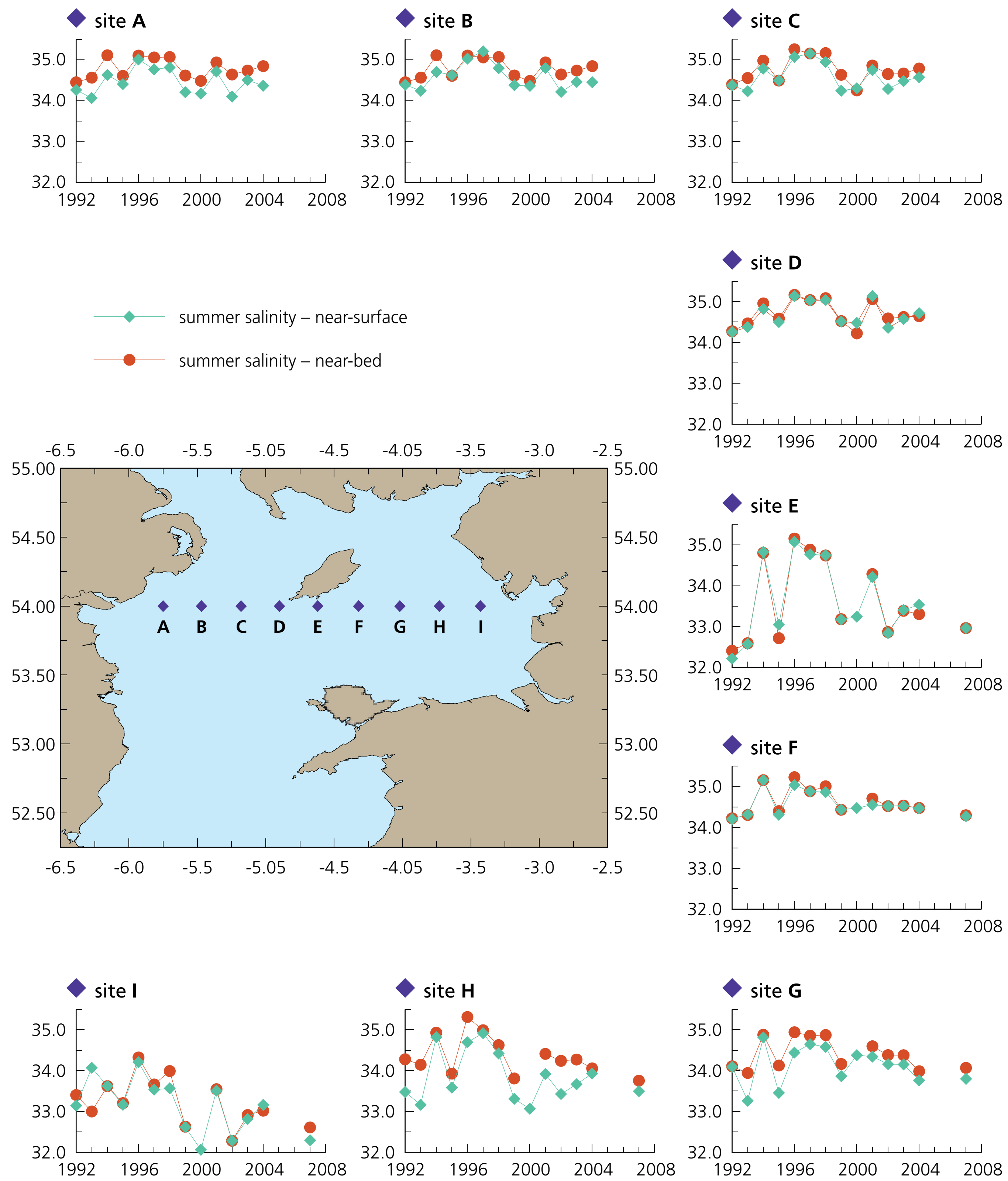


Figure 3.67 Summer salinity (end-June / beginning-July once each year) along 54° N. Courtesy of T. Shammon, IoM Government.



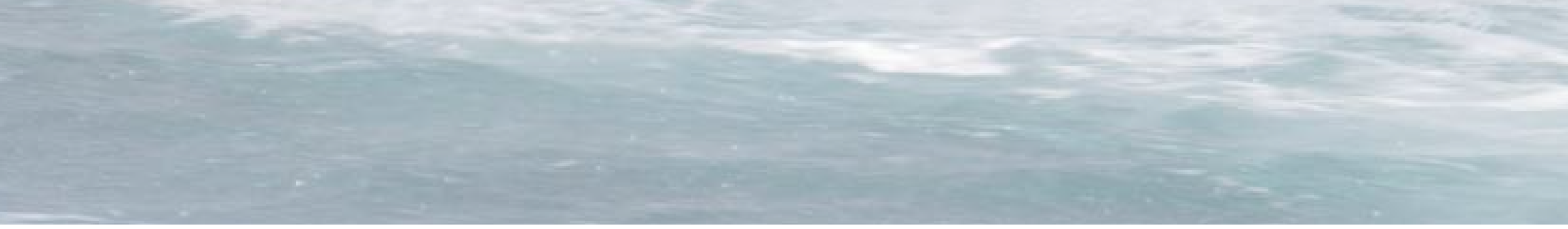


Figure 3.68 Winter salinity (end-January / beginning-February once each year) along 54° N. Courtesy of T. Shammon, IoM Government.

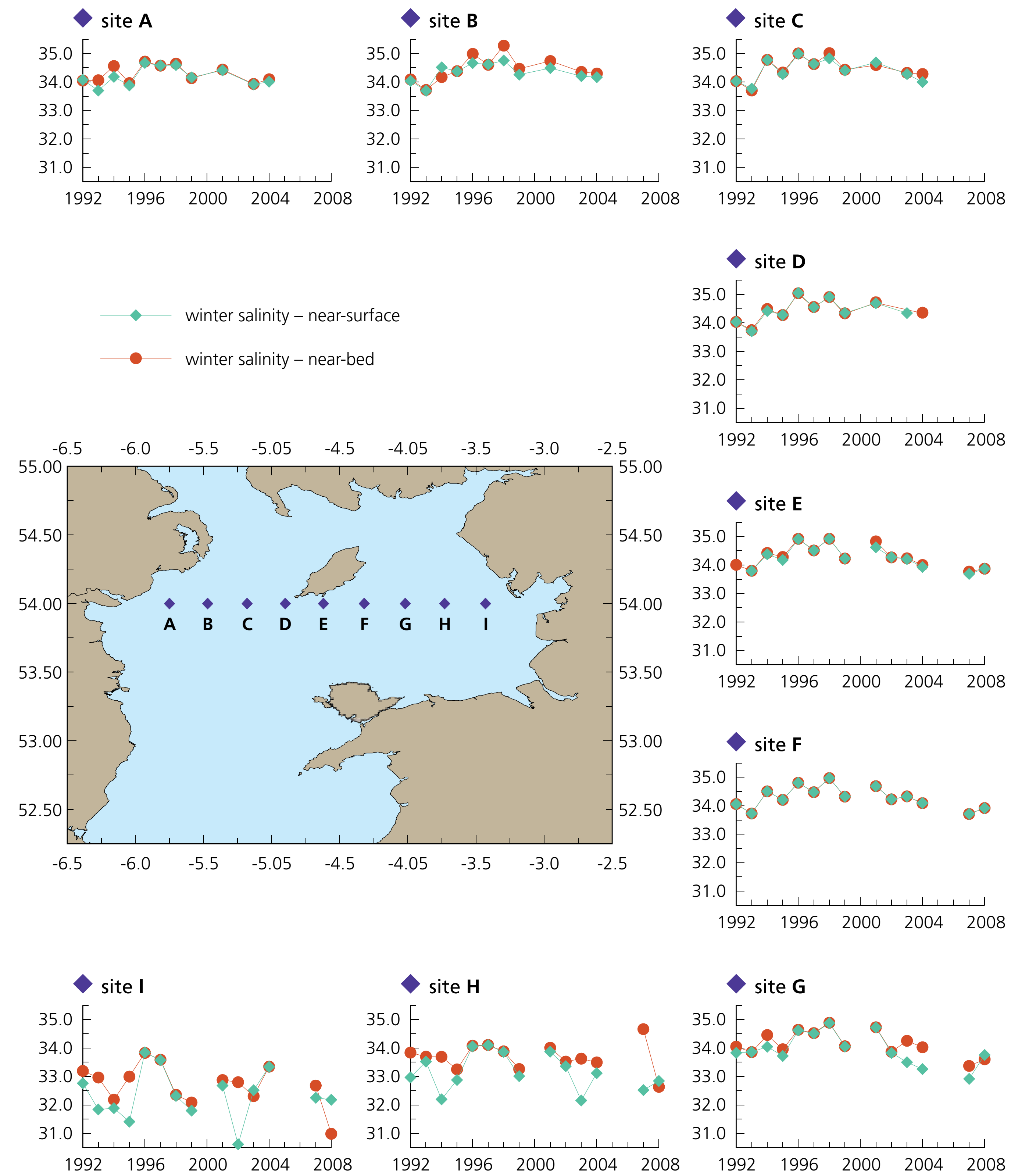


Figure 3.69 Sea temperature at Cypris (54° 05.50'N, 04° 50.00'W), 1954 to 2008. The long-term trend is based on a second-order polynomial. Port Erin Marine Laboratory data to 2006. Courtesy of T. Shammon, IoM Government.

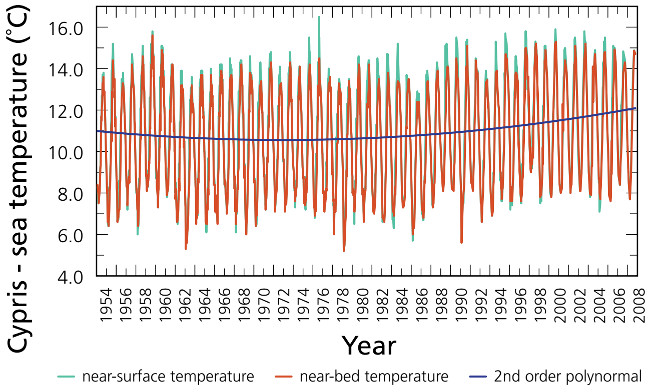


Figure 3.70 Anomalies of annual mean SST at Port Erin and the 5-year running mean. Anomalies are relative to the 100-year mean, 1904 to 2003. Port Erin Marine Laboratory data to 2006. Courtesy of T. Shammon, IoM Government.

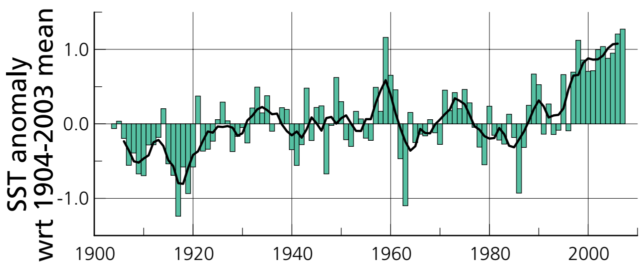


Figure 3.71 Monthly average SSTs at Port Erin (Isle of Man). The plot shows the 100-year mean, the maxima and minima and two contrasting NAO years: 2006 (negative NAO Index) and 2007 (positive NAO Index). Port Erin Marine Laboratory data to 2006. Courtesy of T. Shammon, IoM Government.

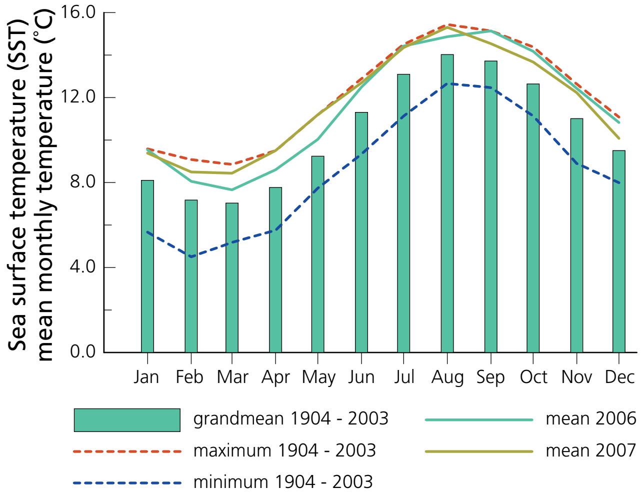
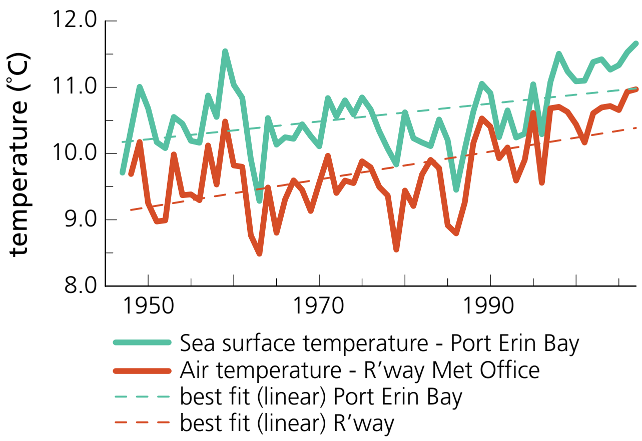


Figure 3.72 Annual mean SSTs at Port Erin and annual mean air temperatures at Ronaldsway Meteorological Office, Isle of Man. Port Erin Marine Laboratory data to 2006. Courtesy of T. Shammon, IoM Government.



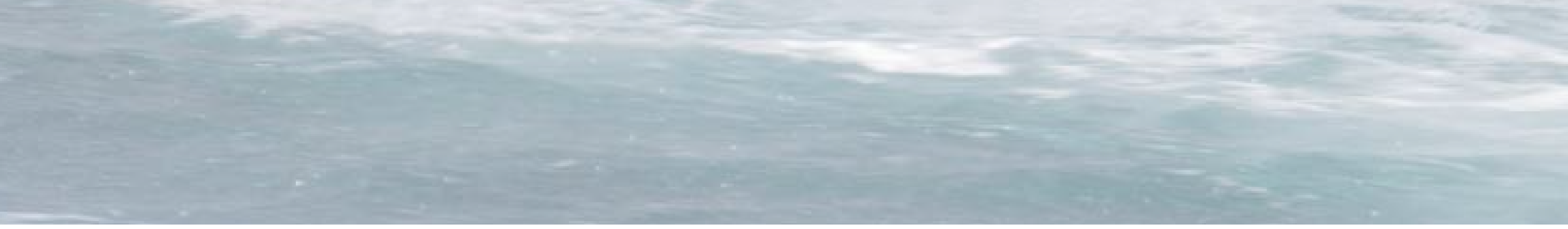


Figure 3.73 Annual mean sea-air differentials on the Isle of Man (SSTs at Port Erin minus air temperatures at Ronaldsway Meteorological Office). The plot shows the long-term trend based on the second order polynomial. Courtesy of T. Shammon, IoM Government.

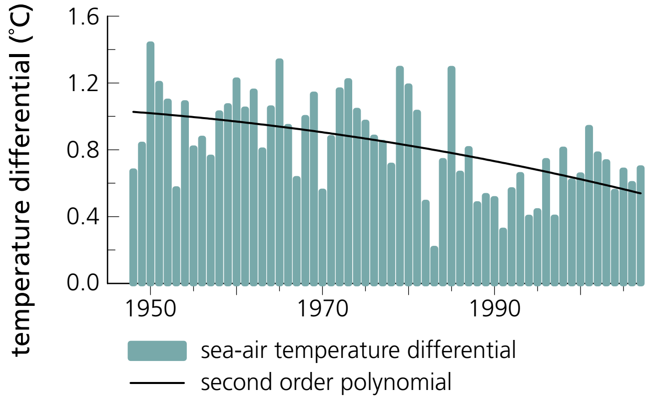


Figure 3.74 Liverpool Bay. (a) Monthly sea temperatures for the years 2003 to 2008. The plot shows means (colour), maxima and minima (bars) and (b) exceedances emphasising winter and summer variations. Courtesy of J. Rees, Cefas.

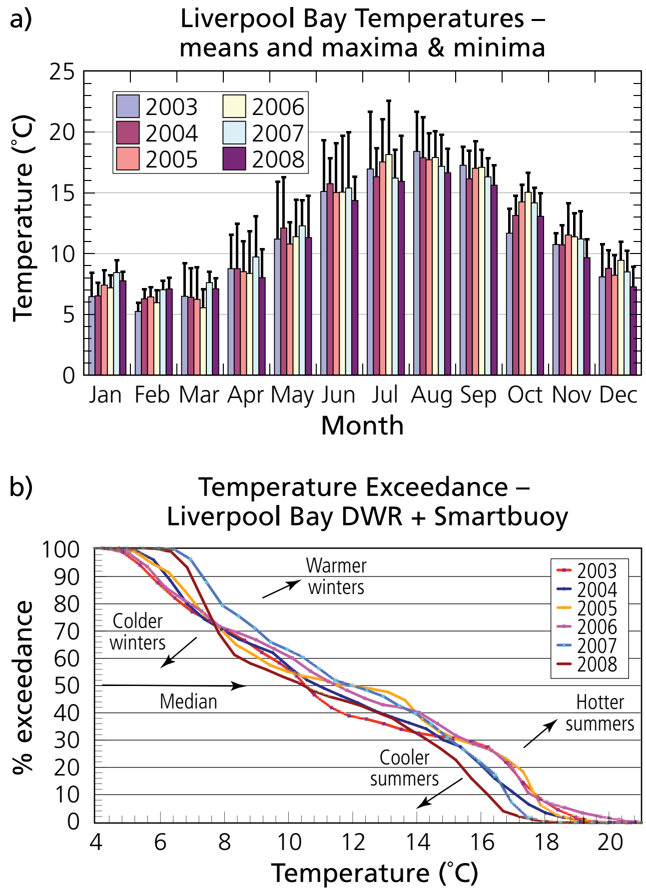


Figure 3.75 Monthly mean (a) SSTs (°C) and (b) salinities at Mersey Bar. The red line represents the average for the period 1935 to 1961, and the blue line the average for 2002 to 2007. Courtesy of J. Howarth, NOC.

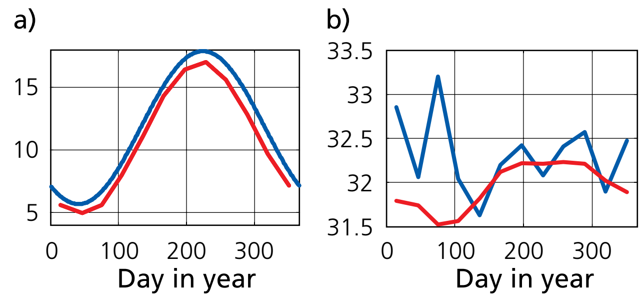


Figure 3.77 Anomalies of annual mean salinity at Port Erin and the 5-year running mean. Anomalies are relative to the mean for the period 1966 to 2005. Courtesy of T. Shammon, IoM Government.

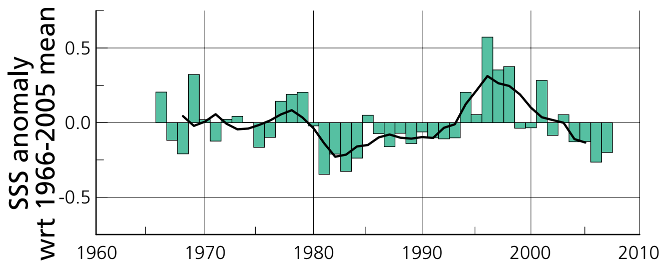


Figure 3.76 Salinity at Cypris (54° 05.50'N, 04° 50.00'W) from 1954 to 2008. The second-order polynomial gives the overall trend and curvature. Courtesy of T. Shammon, IoM Government.

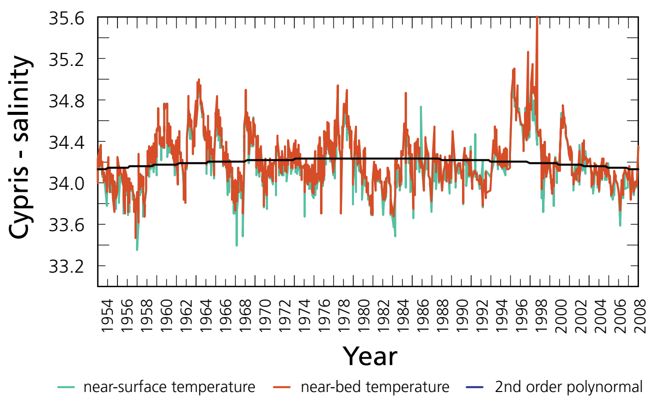
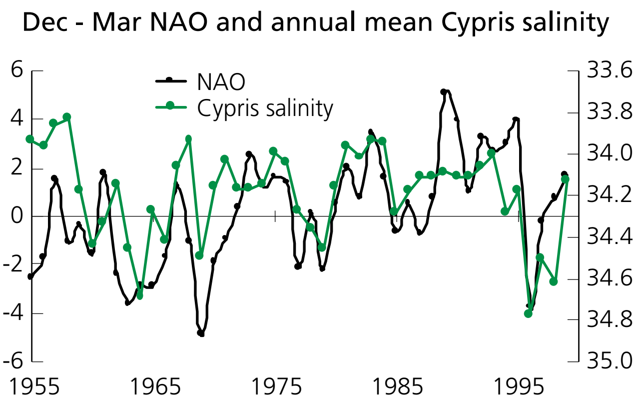
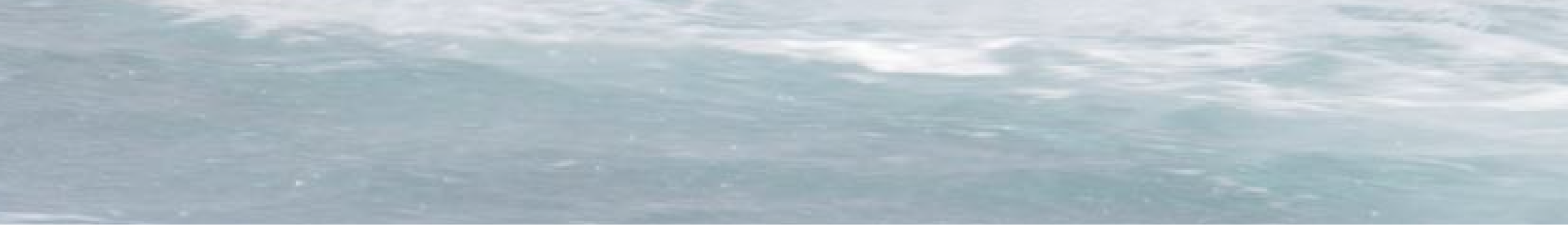


Figure 3.78 Combined plot of the NAO Index and salinity at Cypris (note inverted scale). Courtesy of T. Shammon, IoM Government.





3.2.4.3.7 West Scotland

Data for West Scotland come from a long-term mooring in Tiree Passage (Region 6). The water column here is well mixed or weakly stratified throughout the year, except for occasional episodes: intrusions of high salinity water from the shelf break are sometimes apparent, mainly confined to the west of Tiree Passage. Over the full time series the mean water temperature was 10.1 °C, and the dominant mode of variance in the temperature record was the seasonal cycle (93.5% of the total variance), with an amplitude of 3.2 °C (Figures 3.79a and 3.80a). In contrast, seasonality of salinity is weak (amplitude 0.11, Figure 3.80b), with a weak maximum in March and minimum in September.

The temperature anomaly series (after subtracting the series-average seasonal cycle; Figure 3.81) shows a cooling from 1981 to the mid-1980s, maxima in the late 1980s and mid- to late 1990s with a minimum in the early 1990s. These anomalies are similar to (1) those for the full NE Atlantic upper layer (Holliday, 2003a) with highs in the late 1980s and late 1990s, lows in the early 1980s and mid-1990s; (2) North Sea and Channel series in Sections 3.2.4.3.2 and 3.2.4.3.3. The data for 2002 onwards show relative warmth, peaking in September 2006 at 1.76 °C above the long-term monthly mean for September. The overall trend (1981–2008) is warming at a rate of +0.54 °C per decade. However, the error bounds on the linear trend (Figure 3.81) show that the simple linear model is a poor predictor of interannual change; additional interannual variability is of the order of ± 1 °C.

Interannual monthly-averaged salinity variability is large compared with the seasonal signal. Variability peaks in October and is least in May (Figure 3.80b). The distribution is skewed by some particularly fresh months. From a peak value of 35.17 in January 2005 salinity in the Tiree Passage decreased to a record minimum of 32.80 in November 2006, and then rose to a record peak of 35.36 in March 2008, near to the limit set by Atlantic water salinity and 1.04 above the long-term mean of 34.32 (Figure 3.79b).

Figure 3.79 Measured hourly and monthly averaged (a) temperature and (b) salinity in Tiree Passage. Courtesy of M. Inall, SAMS.

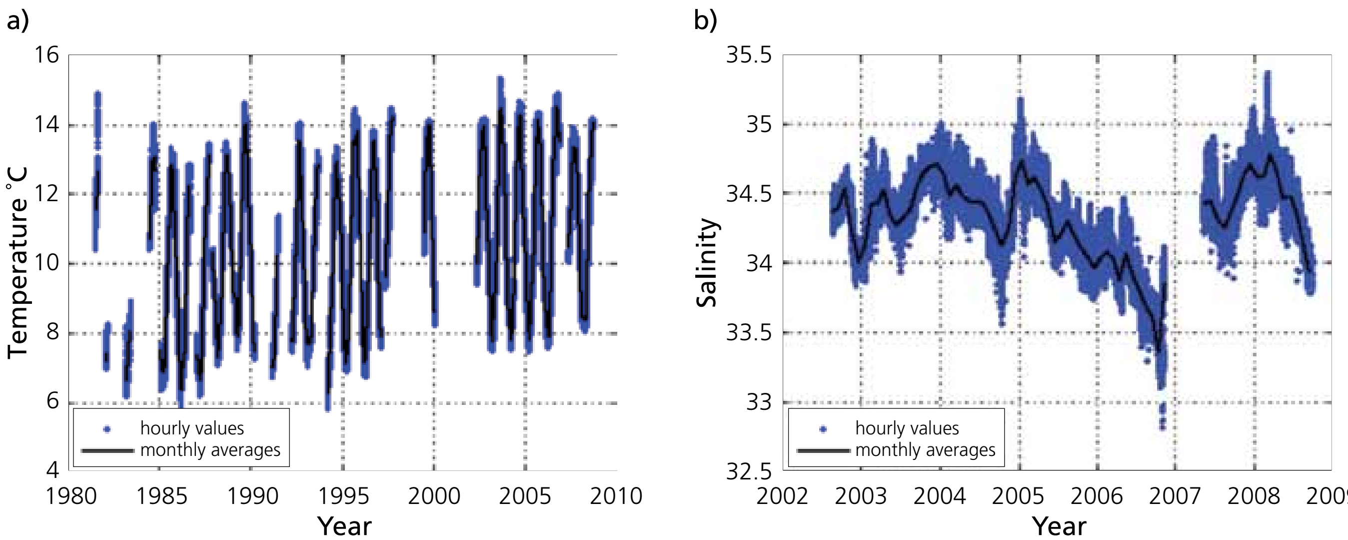


Figure 3.80 Mean monthly (a) temperature and (b) salinity, ±1 standard deviation and the minimum and maximum monthly values for the Tiree Passage time series (temperature 1981–2008; salinity 2002–2008). Courtesy of M. Inall, SAMS.

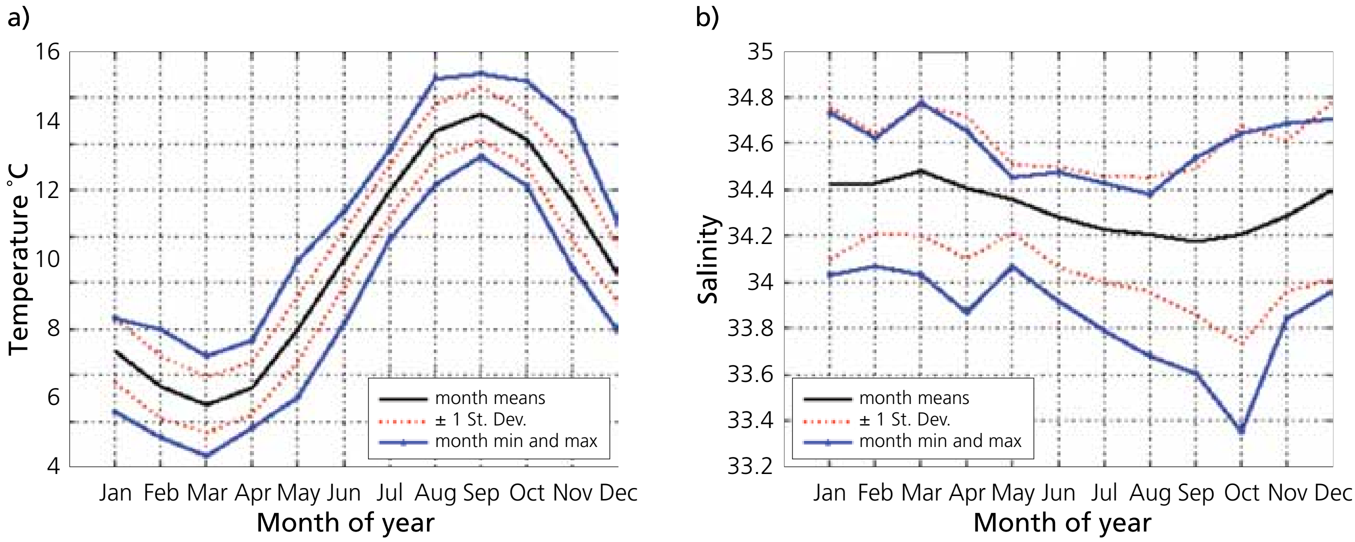
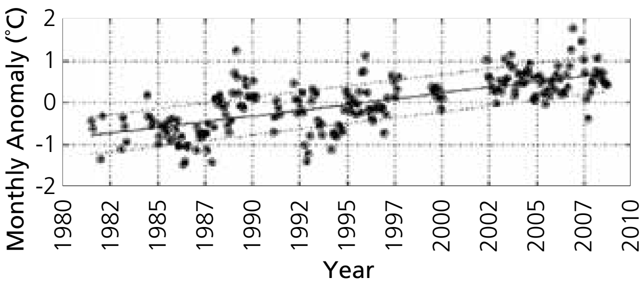
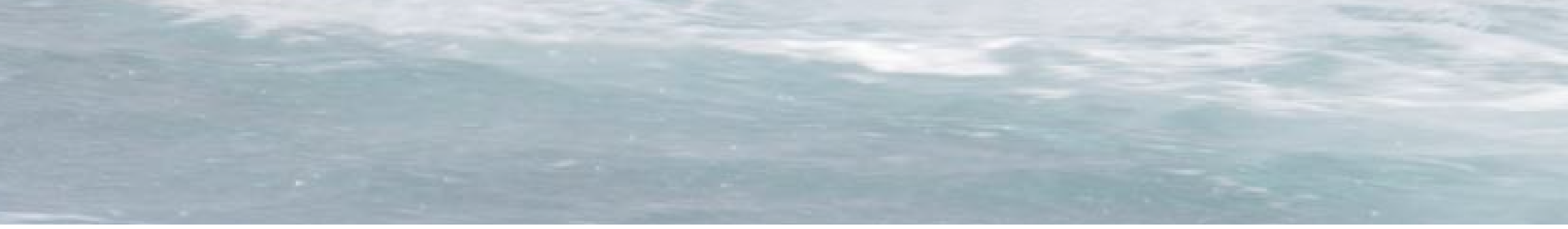


Figure 3.81 Monthly mean temperature at Tiree Passage as an anomaly relative to the mean temperature for each month of the year. Error estimates of one standard deviation are shown. Courtesy of M. Inall, SAMS.





3.2.5 What the new evidence tells about environmental status

The evidence shows global and North Atlantic warming trends, especially since the mid-1980s, likewise in Atlantic waters adjacent to the UK. Near-surface warming is of the order of 0.5 to 1 °C since the mid-1980s. Salinity in Atlantic waters adjacent to the UK has increased by 0.05 to 0.1 since a late 1970s minimum, contrary to global trends at UK latitudes. On top of these overall trends is spatial and interannual-to-decadal variability of similar magnitude (of the order of 0.5 to 2 °C in temperature and 0.05 to 0.1 in salinity). Against the overall trends, Argo and FOAM analyses appear to indicate a recent cooling and freshening in deep-water areas west of the UK since mid-2005. The causes and physical and biogeochemical implications of this are as yet unknown. (It may just exemplify interannual variability. Holliday (2003b) previously attributed varying Rockall Trough salinity to varying proportions of waters arriving from the south (more saline) and the west (fresher)). These conditions are important in controlling shelf-edge flows, exchanges between shelf and deep-sea waters and hence UK shelf-seas' salinity and flushing.

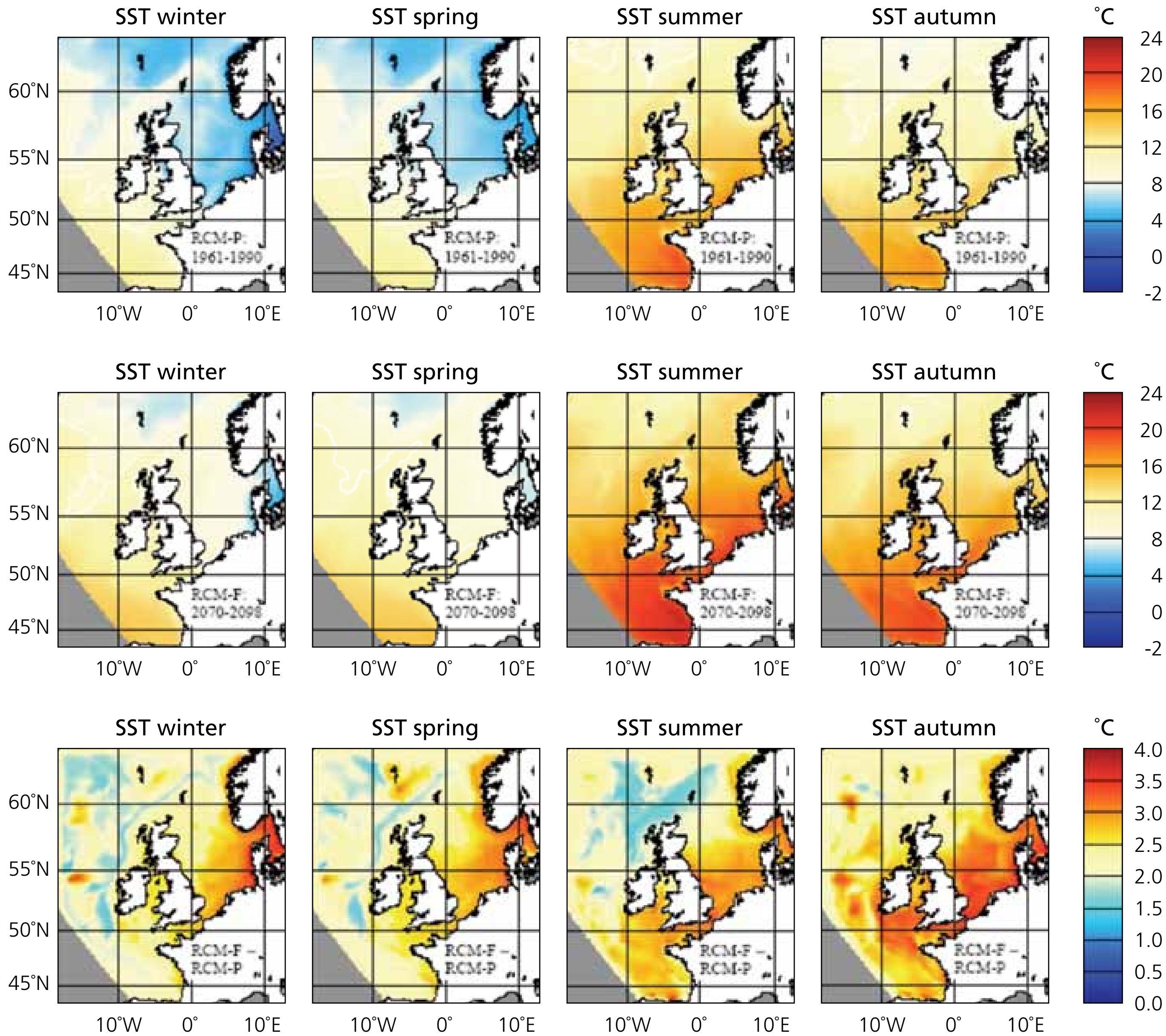
Despite this recent cooling, conditions in all regions around the NE Atlantic are warm in comparison with the mid-1980s and before (Hughes et al, 2008).

In shelf-sea areas, the main controls on the temperature are the local atmospheric conditions (over the past few months), the depth (h) of water and tidal-current strength (U) in combination (larger h/U^3 gives summer stratification). Thus the trend to warmer waters has been sustained, albeit many locations had a maximum in the exceptional summer of 2003. March 2007 was relatively warm following a strongly positive winter NAO Index (an indicator of warm air and westerly winds). Shelf-sea salinities are generally controlled overall by values (typically 35.2 to 35.6) in the adjacent open ocean; salinity in most shelf areas exceeds 34 most of the time. Salinities are decreased by net freshwater inputs from the atmosphere (slightly) and from rivers and estuaries (locally). The latter are important around many coasts, especially in the Irish Sea and southern North Sea. For example, the inverse correlation of Irish Sea salinity with NAO Index may relate to less freshwater input in negative-NAO Index winters; short-term Irish Sea salinity variability reflects freshwater inputs. River inputs are localised and occur over short time scales (weeks to months); the associated variability can dominate any seasonal cycle or longer-term variability.

Salinity's natural spatial and temporal variability on a range of time scales obscures any potential trend. Hence it is difficult to establish representative 'indicator' values for salinity.

For the future, MCCIP (2008) reported climate models indicating that SST will continue rising in all UK coastal waters, with stronger warming in the south-east (~ 0.15 to 0.4 °C per decade in the southern North Sea) than in the north-west (~ 0.05 to 0.2 °C per decade at Rockall). These predictions accord with the expectation that shelf-sea temperatures are likely to follow the atmospheric climate quite closely. There is a risk that climate change will be associated with a slowing of the Atlantic Meridional Overturning Circulation; this directly affects the volume of warm Atlantic water passing to the west of the UK, and to a limited extent the water on the adjacent UK shelf; elsewhere the effects will be more indirect via the effect on the atmospheric climate. There are modelled future seasonal scenarios, for example for the period 2070 to 2098 as illustrated for surface temperature

Figure 3.82 Distribution of SST by season, modelled for 1961–1990 and 2070–2098 (Atlantic Margin Model, HadRCM, SRES A1B). Note the altered scale in the four plots showing the difference between the Past (1961–1990) and the Future (2070–2098). Courtesy of S. Wakelin, NOC.



(Figure 3.82), a measure of stratification (Figure 3.83) and timing of the start and end of seasonal stratification (Figure 3.84). These results are for the Atlantic Margin Model (Holt et al., 2003) forced by the atmosphere of HadRCM (a fine-resolution nesting of the European region in HadCM3) for the 'unperturbed' member of the UKCP ensemble with the medium IPCC emissions scenario SRES A1B. The projections show: most warming in the south and east, especially in autumn; a slight increase of intensity (but not area) of summer stratification over the (stratified areas of) shelf; a much larger increase in deeper-water stratification (and in the Norwegian Coastal Current); and a

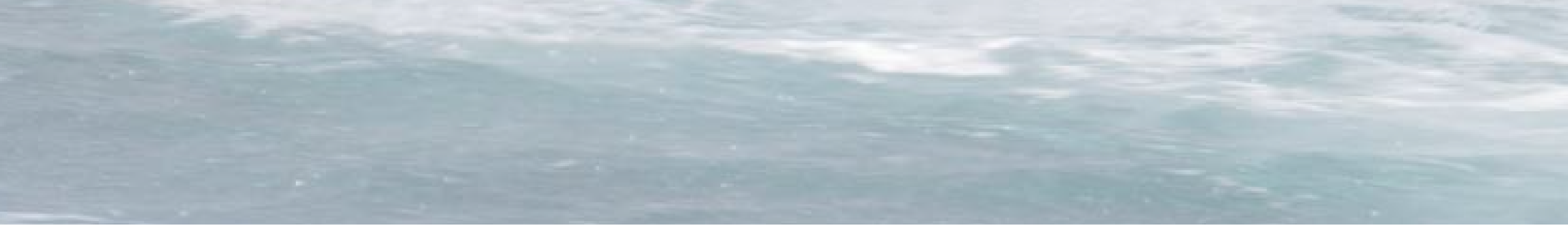
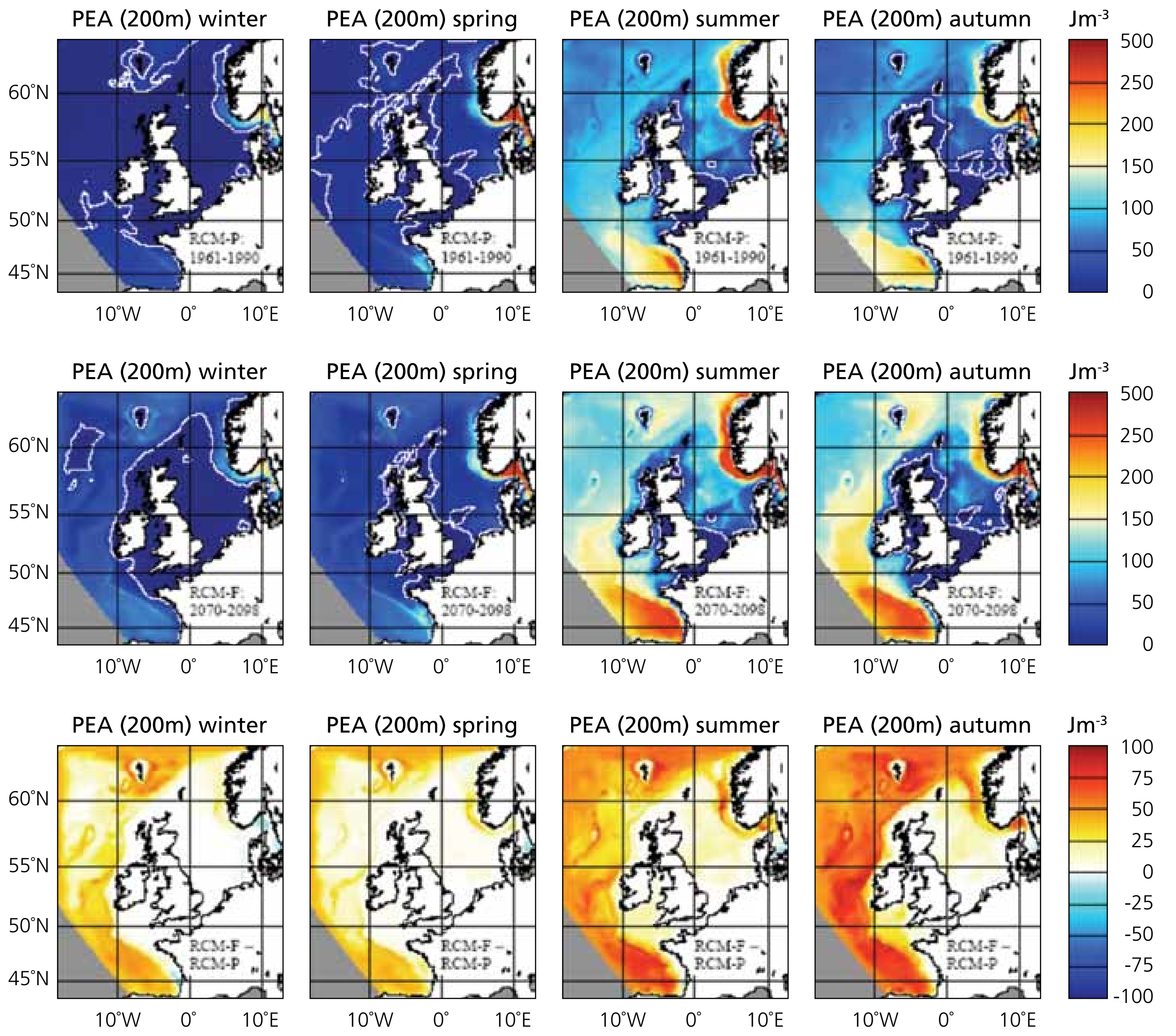


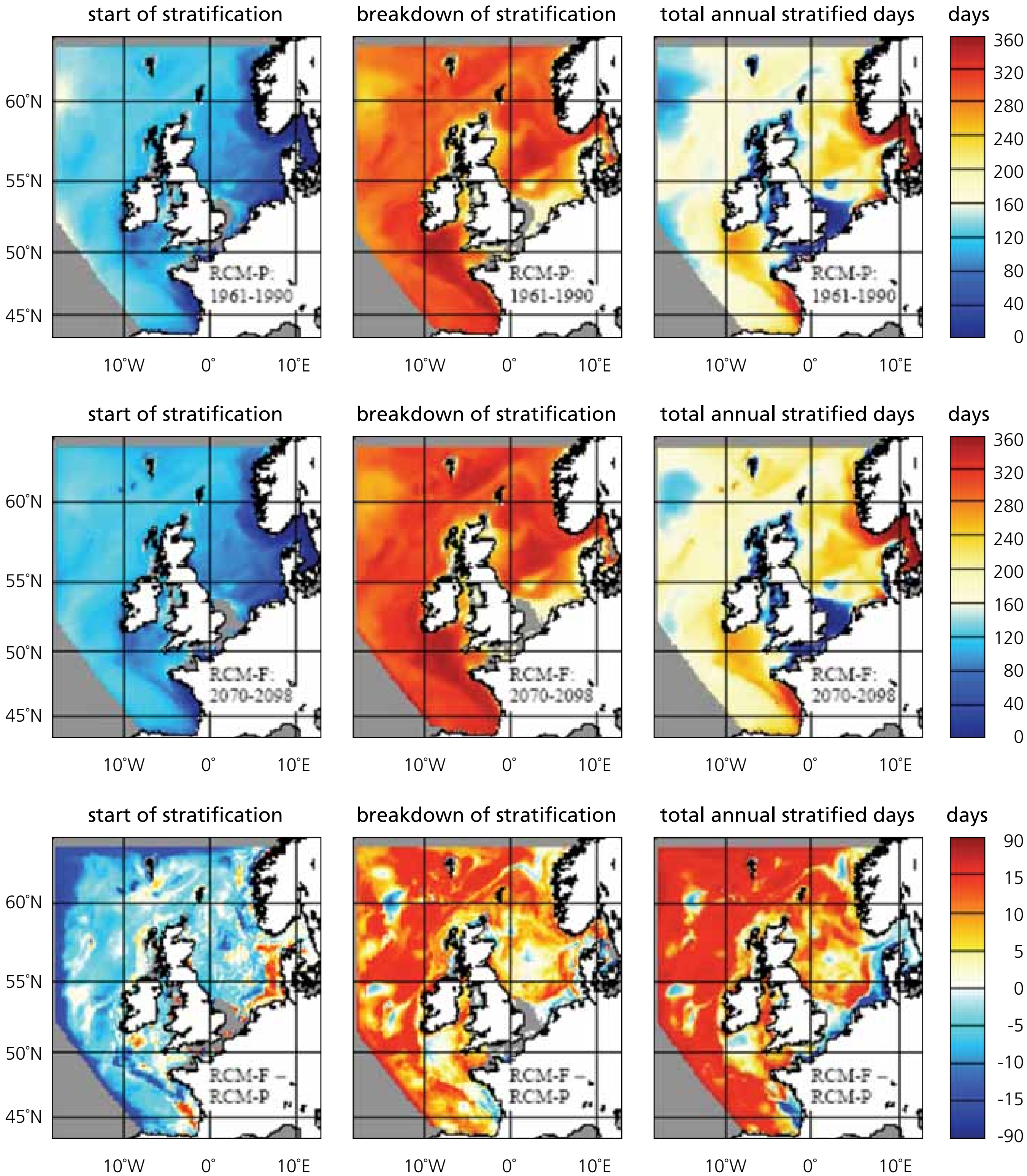
Figure 3.83 Distribution of total stratification by season, for 1961–1990 and 2070–2098 from the POLCOMSV6.3 Atlantic Margin Model (Holt et al., 2003). (The figure actually shows total potential energy anomaly: PEA proportional to [height × density relative to depth-mean] totalled through depth). Note the altered scale for the difference between the Past (1961–1990) and the Future (2070–2098). Courtesy of J. Holt, NOC.



general increase in the number of stratified days, again more in autumn than spring, but with considerable local variability.

Future shelf-sea salinities are likely to follow adjacent oceanic values on annual to decadal timescales across the shelf as a whole. However, these changes have hitherto been of the order of 0.1, smaller than shorter-term variability associated with freshwater inputs to shelf seas. This is exemplified by the variability in the Fair Isle current considerably exceeding that in the adjacent Atlantic water. Shelf-sea salinities will also be affected by climate change; possibly reduced if freshwater inputs from rivers and net rainfall minus evaporation increase (Figure 3.85).

Figure 3.84 Distribution of average start and end days for seasonal stratification, modelled for 1961–1990 and 2070–2098 (Atlantic Margin Model, HadRCM, SRES A1B). Note the altered scale for the difference between the Past (1961–1990) and the Future (2070–2098). Courtesy of S. Wakelin, NOC.



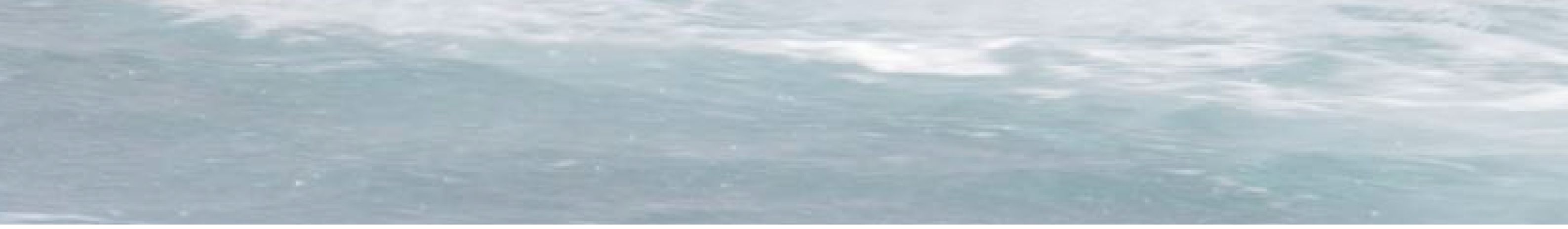
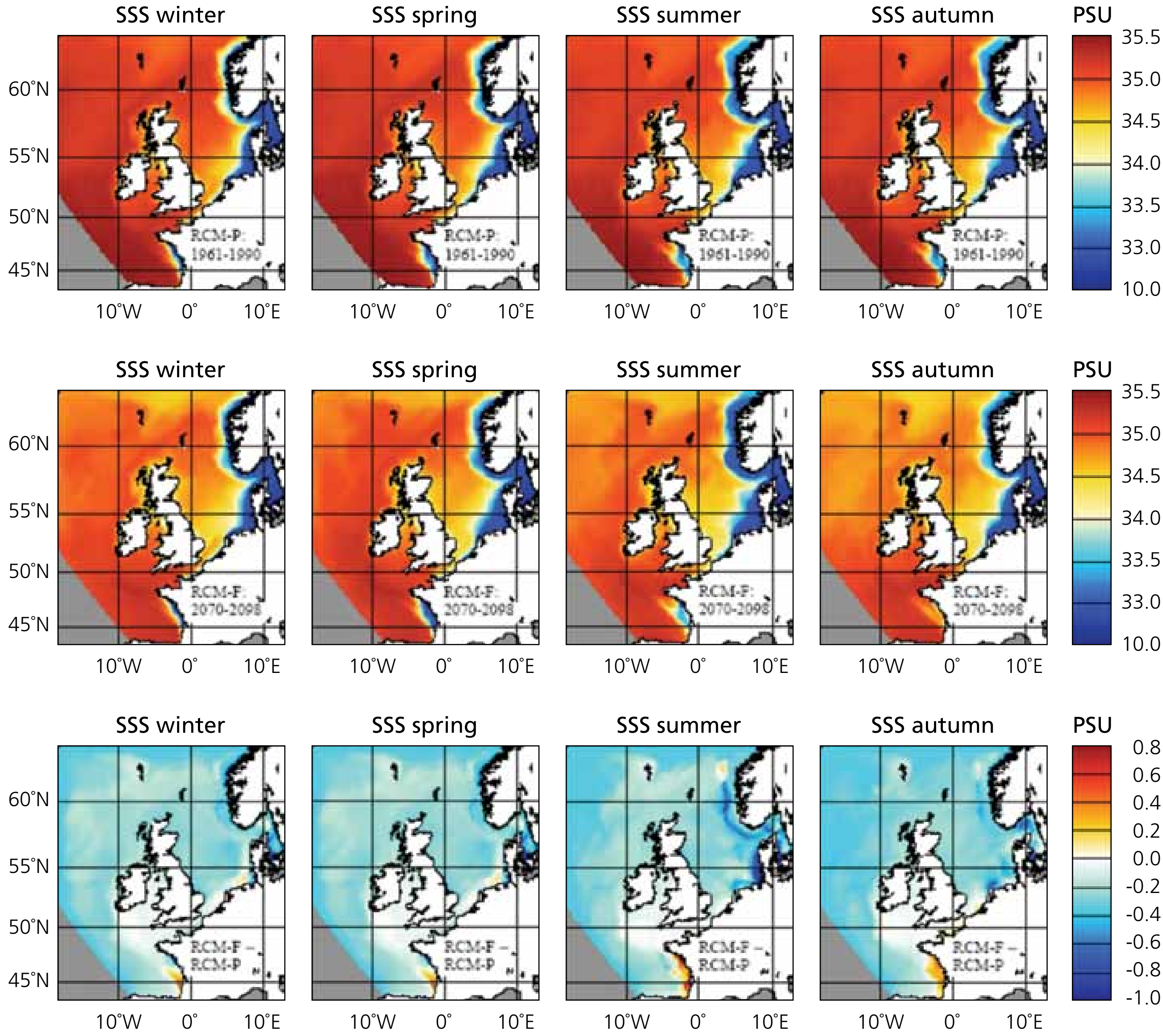


Figure 3.85 Distribution of surface salinity by season, modelled for 1961–1990 and 2070–2098 (Atlantic Margin Model, HadRCM, SRES A1B). Note the altered scale for the difference between the Past (1961–1990) and the Future (2070–2098). Courtesy of S. Wakelin, NOC.



Such factors are taken into account in modelled future scenarios, for example for the period 2070 to 2098 as illustrated in Figure 3.85 (forced by an average outer-boundary salinity in HadRCM). These plots generally show a slight freshening of the order of 0.2 in UK waters, a result of a less saline boundary and more freshwater input (especially rainfall).

However, there is less confidence in regional climate-change projections than in global projections, and less confidence for the hydrological cycle (for salinity) than for temperature.

The summary table (Table 3.4) includes an assessment of trend but not status (‘traffic-light’) because (1) no accepted criteria apply for temperatures giving significant risk of adverse effects; and (2) the UK (Government), or even the EU, cannot itself take measures to improve the status.

Temperature has risen overall since pre-industrial times by O(1 °C) with some differences between regions, but the differences are not enough to distinguish different levels of risk. The seasonal range is much greater than this change; interannual variability is somewhat greater.

Rising temperature effects appear to include northward migration of plankton species with possible impacts at higher trophic levels. Larger and faster increases in future are likely and will make adaptation (natural or managed) more difficult. Salinity is subject to natural variability in relation to circulation and freshwater inputs. There is no reason to suppose that this variability or absolute values of salinity have changed enough to have had an impact on the environment or human health. The range of salinity values is very limited, except nearshore or in estuaries. There is little basis to distinguish between CP2 Regions.

Table 3.4 Summary assessment of trends.

Parameter	*CP2 Region*	*Key factors and impacts*	*What the evidence shows*	*Trend*	*Confidence in assessment*	*Forward look*
Sea Temperature	1, 2, 3, 5	Climate change. Affects primary production, species composition	Rise in last 25 years. NAO winter influence	Upward	High	Continued rise
Sea Temperature	4, 6	Climate change. Affects primary production, species composition	Rise in last 25 years	Upward	High	Continued rise
Sea Temperature	7, 8	Climate change, North Atlantic source waters. Affects primary production, species composition	Rise from 1994 in Rockall Trough	Variable	Medium	Rise
Salinity	1	Circulation; river flows. Can affect stratification, nutrients, hence blooms	Short-term variability	Possibly upward	High	Lower values? (Low)
Salinity	2	Circulation; river flows. Can affect stratification, nutrients, hence blooms	Short-term variability	Possibly downward	High	Lower values? (Low)
Salinity	3, 4, 5, 6	Circulation; river flows. Can affect stratification, nutrients, hence blooms	Short-term variability	Not determined	High	Lower values? (Low)
Salinity	7	Circulation, North Atlantic source waters	Variable	Not determined	Medium	Lower values? (Low)
Salinity	8	Circulation, North Atlantic source waters	Variable	Overall increase in Rockall Trough since mid-1970s	Medium	Lower values? (Low)

3.2.6 Forward look and need for further work

Operational models assimilate regularly-measured data to provide day-to-day estimates of the ocean state and forecasts of its evolution. These data can include Argo and satellite imagery.

The Argo project now provides the means to monitor temperature and salinity (and velocity) in the open Atlantic adjacent to the Western European continental shelf. Argo measurements are confined to deep-water areas and thus are capable of providing only indications of conditions offshore of the UK and West European continental shelf. Nevertheless, these data have documented warming and a salinity increase since a 1990s minimum (as have ICES sections; Holliday et al., 2008). The analyses show the power of Argo data when coupled with state-of-the art assimilating models to reveal property trends and their spatial structure. The availability of Argo profile data for areas adjacent to the UK and NW Europe should be maintained so that the utility of the new analyses produced using Argo data can be evaluated. This requires continuation of the UK, other European and international partners' contributions to the Argo array.

Routine monitoring of the ocean areas between the deep sea and the continental shelf poses logistical problems: Argo floats are limited to off-shelf areas (typically > 2000 m); moored instruments are at risk from fishing activities; and ship coverage is relatively sparse. In parallel with Argo's development, similar sensors have been deployed on autonomous underwater gliders (Merckelbach et al., 2007). One such glider, operated by the National Oceanography Centre, has collected temperature and salinity data over the continental shelf and slope off West Africa (www.noc.soton.ac.uk/omf/lmm/glider/data.php). There is clear potential for such instruments to be deployed to monitor key locations around the edge of the NW European shelf; future sustained measurements of properties in shelf seas (especially where summer-stratified) and across the continental slope using autonomous ocean gliders should be considered. For forecast purposes, these data need to be transmitted in near-real time.

Satellite imagery for surface temperature has the potential to provide spatial coverage to keep model forecasts 'on track'. There is no comparable regular estimate of sub-surface temperatures from observations. Satellite imagery has yet to be proven for inferring salinity; all sources of salinity data are sparse for the purpose of constraining model forecasts. There is scope for model experiments to estimate what density, frequency and allowable time-delay in data provide the best (cost/benefit) value for predictions, forecasts and subsequent state-estimation.

Operational systems are being developed in some shelf-sea areas. Temperature is the most routine of all their measurements, and salinity is relatively routine. Nevertheless, costs are relatively high for salinity and sub-surface temperature estimates. Dependence on models (constrained by available data) appears probable in the foreseeable future for reasonably detailed estimates in time and spatially. Salinity is more difficult to model than temperature; models depend on estimates of freshwater inputs which are localized and not fully estimated.

3.3 Carbon Dioxide and Acidification

3.3.1 Key points

i. Introduction

Concentrations of carbon dioxide (CO_2) are increasing in the atmosphere. The oceans are a net sink for CO_2 substantially reducing the rate of increase in the atmosphere but this makes the oceans more acidic. Continental shelf seas play a key role in the global carbon cycle.

ii. How has the assessment been undertaken?

The assessment uses evidence from measurements, modelling of marine processes, and inverse modelling of atmospheric concentrations.

iii. Current and likely future status of carbon dioxide and acidity

- The ocean currently absorbs about a quarter of total anthropogenic emissions of CO_2 (including land use changes), critically slowing the growth of atmospheric concentrations (Section 3.3.2.1).
- Evidence suggests that the NW European shelf acts as a net sink for atmospheric CO_2, but that this sink is highly variable.
- An apparent reduction in uptake of CO_2 exceeding 50% occurred in the North Atlantic from the mid-1990s to the period 2002–2005. This may be cyclical rather than a progressive change (Section 3.3.2.2).
- Calculations based upon the Intergovernmental Panel on Climate Change (IPCC) 'business as usual' scenario (IS92a, Alcamo et al., 1995) indicate that by around 2100 the atmospheric concentration of CO_2 will have reached 800 ppm and the average pH of the surface ocean will have decreased by 0.3. Thus the acidity (active hydrogen ion content) will have doubled (since pH is on a logarithmic scale). The rate of acidification is controlled by well-understood chemical and physical processes. The probability of a significant change is therefore high if input of CO_2 to the atmosphere continues at the present rate (Section 3.3.2.3).
- Important interactions between warming trends, acidification and eutrophication are beginning to be identified (Section 3.3.2.3).
- Climate change may affect the processes leading to the natural sequestration of carbon on a scale and in a direction that is presently difficult to predict (Section 3.3.2.4).

iv. What has driven change?

Increasing atmospheric CO_2 concentrations, together with changes in seawater chemistry and in the hydrographic structure of the ocean, have changed CO_2 and pH in the ocean.

v. What are the uncertainties?

The interactions between climate change and carbon cycle dynamics are likely to be non-linear. Since marine organisms have generally evolved to perform optimally within a relatively narrow range of environmental conditions, sudden and substantial impacts on marine ecosystems and productivity are possible, due to combined effects of warming and acidification.

Comprehensive baseline measurements of pH in UK waters are not yet available, and it will therefore be some time before the rate of acidification can be accurately assessed relative to natural annual and interannual cycles. Little is known about the extent to which many biological processes are dependent on particular pH conditions.

vi. Forward look

Continued observations of the marine carbon dioxide system are essential to understand controlling processes (physical, chemical and biological) and to improve estimates of the direction and rate of future change.

3.3.2 Introduction

3.3.2.1 Background

The ocean has taken up almost half of accumulated emissions of the greenhouse gas carbon dioxide, CO_2, since the industrial revolution (Sabine et al., 2004). This has had the benefit of slowing the rate of build-up in the atmosphere, but the accumulation in the ocean makes seawater more acidic and may lead to ecosystem damage. The transfer of CO_2 to and from the ocean surface (the air to sea flux) is a chemical equilibrium process governed by Henry's Law of solubility. The direction and magnitude of this exchange is driven by the difference between atmospheric and sea-surface partial pressures of carbon dioxide (pCO_2). In the sea, pCO_2 depends on the physico-chemical conditions (particularly water temperature) at the surface and the balance of biogeochemical processes in the total water column and sediments. Consequently, sea surface pCO_2 is affected by factors such as change in sea surface temperature, mixing with deeper waters and the rate of carbon fixation by photosynthesis. The direction and magnitude of the air-sea flux varies both with location and time of year. A range of models (Orr et al., 2001, 2005) and data compilations (Takahashi et al., 2009) show that CO_2 uptake by the ocean is highest in temperate and sub-polar waters where seasonal deep vertical mixing and sub-surface water formation promote the transfer of carbon to abyssal depths. It is slower in the subtropical gyres where water is trapped at the surface for long periods. The North Atlantic is a particularly strong CO_2 sink due both to physical factors (water moving poleward at the surface, cooling and taking up atmospheric CO_2 before mixing and sinking to depth in winter) and to efficient biological uptake of nutrients and carbon. Monitoring in the North Atlantic has detected both large-scale changes in the rate of uptake from year to year and apparent trends that may be related to decadal cycles in oceanic circulation and climate. In shelf seas, CO_2 uptake may also be influenced by changes in precipitation and human activities such as land use with resultant impacts on river discharge.

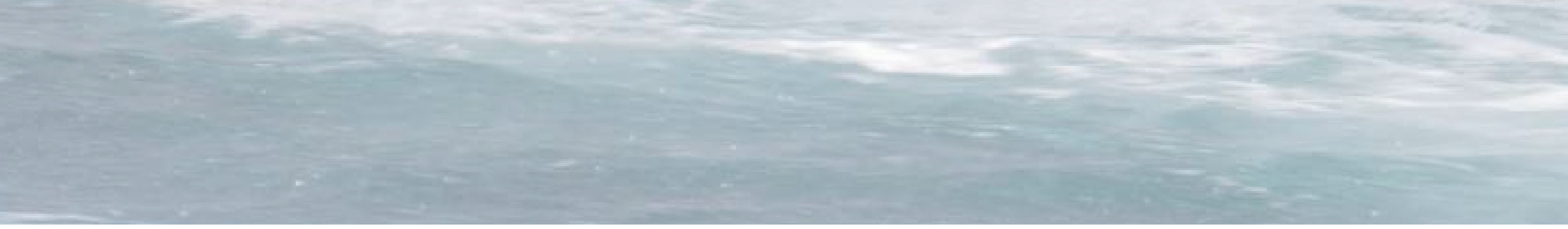
3.3.2.2 Air sea exchange of CO_2

A review of all available open ocean data for surface water pCO_2 has recently been completed by Takahashi et al. (2009). They established a climatological mean distribution for surface water pCO_2 over the global ocean with a spatial resolution of 4° (latitude) × 5° (longitude) for 2000 as a reference year. Observations made during El Niño periods in the equatorial Pacific and those made in coastal zones were excluded from the database. While about 3 million measurements of surface water pCO_2 from 1970 to 2006 are collated in the paper, the collation process demonstrates the lack of data in many areas of the ocean. A time-trend analysis of de-seasonalised surface water pCO_2 data in the North Atlantic, North and South Pacific and Southern Oceans indicates that the surface water pCO_2 over these oceanic areas is increasing at a mean rate of 1.5 µatm/y. Using this mean rate to correct observations made in different years, a global ocean database for the reference year 2000 was assembled; seasonal changes in the surface water pCO_2 and the sea-air pCO_2 difference over four climatic zones in the Atlantic, Pacific, Indian and Southern Oceans are presented. The annual mean for the contemporary net CO_2 uptake over the global ocean is estimated to be 2.2 ± 0.4 PgC/y (Le Quéré et al., 2009). The high latitude North Atlantic, including the Nordic Seas and a portion of the Arctic Sea, is the most intense CO_2 sink on a per unit area basis, with a mean of 2.3×10^6 gC/month per km^2, and is consequently, potentially one of the areas being most affected by acidification (Orr et al., 2005).

A number of time series of observations from moorings and merchant ships have established the variability of sea surface pCO_2 and air-to-sea flux from the mid-1990s to the early 2000s (Bates et al., 1996; Olsen et al., 2003; Lüger et al., 2004; Corbière et al., 2007; Schuster and Watson, 2007). The use of measurement systems on commercial ships of opportunity (SOOs) is proving to be a useful tool for detecting both the scale and variability in space and time of these fluxes (e.g. Schuster and Watson, 2007). When the processes are examined through the use of atmospheric inversion models (e.g. Patra, et al., 2005) year-to-year variability is found to be equivalent to a substantial fraction of the total sink. The sink could be expected to increase as atmospheric CO_2 rises, but increasing stratification and a slowing of the overturning circulation and decreased rates of ventilation resulting from global warming may work in the opposite direction (Sarmiento and Le Quéré, 1996; Fung et al., 2005). Determining the true scale of this variability requires that the present observational network is both maintained and expanded.

Schuster and Watson (2007) have reported that the interannual variability in the air-sea flux of CO_2 is in phase across large regions from year to year. Additionally, there has been an apparent inter-decadal decline, evident over the Atlantic. It is especially significant in the NE Atlantic with the sink reducing by more than 50% from the mid-1990s to the period 2002–2005. This decline may have been due to a decline in the rate and extent of winter-time mixing and ventilation between surface and subsurface waters due to increasing stratification. This, in turn, may be cyclical and not permanent, for example the climate related oscillations such as the North Atlantic Oscillation may also be influencing the changes that have been seen in the North Atlantic.

Observations made around and across the North Atlantic have been linked through the International Ocean Carbon Coordination Project (IOCCP). Of particular importance has been the contribution of data from the EU FP7 project CarboOcean. Observational activities were most extensive in 2005, and ended in late 2008. A team led by Andrew Watson (University of East Anglia, UEA) with support from CarboOcean and the NERC CASIX (Centre for observation of Air-Sea Interactions and fluXes) project has related the ship of opportunity observations of pCO_2 with hydrographic and meteorological data and satellite observations. This data synthesis was used to constrain the estimate of air-sea CO_2 exchange across the North Atlantic, and statistically test its accuracy; it was found to have a precision of ~10% in 2005 (Watson et al., 2009). The ability to make surface ocean observations is critical because such information can be used with knowledge of atmospheric changes to estimate regional-scale fluxes from land, potentially with greater accuracy than 'direct' land-based methods. Presently there is considerable uncertainty about how the ocean observational network can be maintained.



3.3.2.3 pH and acidification

Based on the IPCC 'business as usual' scenario for CO_2 emissions (IS92a, Alcamo et al., 1995), it is predicted that the acidity of the surface ocean will have doubled by 2100 (Orr et al., 2005). That is because dissolving CO_2 gas in water releases hydrogen ions, increasing acidity and reducing pH. Such acidification is a major threat to marine resources (Raven et al., 2005; IPCC, 2007b; Turley et al., 2007), with impacts on ecosystem function across the spectrum from molecular processes to food web dynamics affecting large organisms. Few measurements of pH in UK marine waters, suitable for use as reference/baseline measurements, were made prior to 2008. To fulfil this need, observations must be relatively long term, of high temporal and spatial frequency, and accurate enough not only to allow for valid statistical interpretation but also to characterise fully the suite of processes that modify *in situ* pCO_2. The lack of observations means there is a serious gap in the evidence base for developing policy responses on sustainable marine ecosystems. It is an important consideration that the measurement of change in the acidity of a body of water has to be measured relative to natural variability. Observations and output from ecosystem models (e.g. Blackford and Gilbert, 2007) clearly indicate that the annual cycle of changing water temperature and biological production imparts a far greater variability to sea water pH compared with the predicted year on year increases in the acidity due to the increased uptake of CO_2 from the atmosphere. These factors require that a fully documented baseline data set is collected using the best available means and that observations are made in a way that seasonal changes are scaled so that they can be taken into account in future assessments.

The concentration of active hydrogen ions in water is expressed as a pH value. This is a key chemical variable because the association of hydrogen ions with other atoms and molecules changes their reactivity. Species such as trace metals will tend to be more soluble at lower pH (higher acidity); depending on the metal this may benefit biological production or cause toxic effects. Primary biological production tends to be limited by the supply of dissolved nitrogen compounds. The balance of components in the nitrogen cycle (N_2, NO, N_2O, NO_2, NO_3, NH_4) will change as pH changes, as the rates of bacterial activity that control the inter-conversion will change. Productivity may also be changed because a lower pH will favour the existence of ammonium over ammonia in solution, ammonium being more easily assimilated by plankton than ammonia. Such effects may be most marked in nutrient-rich eutrophic waters. The likely scale of such effects needs to be investigated more closely because any enhanced productivity will tend to counteract a decrease in pH as hydrogen ions are consumed during primary production. Another effect of increased CO_2 is the lowering of the carbonate saturation state (Ω). Such CO_2-related changes in the oceanic carbonate system have already been detected (Bates et al., 2002; Gruber et al., 2002; Dore et al., 2003; González-Dávila et al., 2003). These could have profound impacts on marine organisms and ecosystems (Riebesell et al., 2000; Cicerone et al., 2004); in particular, species with carbonate shells or exoskeletons such as molluscs, corals or calcareous algae (Orr et al., 2005). The majority of marine animals have planktonic larval stages and it is the processes of reproduction, larval development and larval survival that are most likely to be compromised by this stress (Fernand and Brewer, 2008).

Seasonal changes in the balance between biological production and respiration/decay removes and then returns CO_2 to solution. This causes the pH of the water to rise and then fall. Results from the POLCOMS-ERSEM numerical model (Blackford and Gilbert, 2007, discussed in Section 3.3.4) suggest that in highly eutrophic areas of the North Sea, such as the plume of the River Rhine, the cycle in pH could be as high as one pH unit. The net effect on the pH system will depend on the degree to which the production-decay cycle of an area is in balance; i.e. whether it is dominated by new photosynthetic production (autotrophic production) which removes CO_2 or the decay of existing organic matter that releases CO_2 into solution (heterotrophic production). Estimates of this trophic balance in the southern North Sea (Smith et al., 1997; Hydes et al., 1999) suggest that it tends to be a net heterotrophic system, hence efforts to reduce eutrophication may also reduce the accumulation of CO_2 by reducing the excess respiration in the system.

3.3.2.4 Natural carbon sequestration

Within the global carbon cycle, the so-called biological carbon pump (BCP) is a large component, responsible for transferring approximately 10 PgC/y from the atmosphere to the ocean's interior (Boyd and Trull, 2007). This is approximately five times the ocean's net uptake of CO_2. This flux mainly occurs via the sinking of small particles that contain organic material derived from phytoplankton production in the sunlit upper ocean. As it sinks, a fraction of this material decays and dissolves, and its constituent elements, including carbon, are mixed back into surface waters. The sinking of particles creates a surface water deficit in dissolved CO_2 that encourages the invasion of atmospheric CO_2 and so complements the solubility pump. The biological pump is independent of the enhanced solubility pump, which is currently occurring due to increased atmospheric CO_2 levels. However, it is linked to the calcite counter-pump. The growth of calcareous phytoplankton causes the release of CO_2 to the ocean, but the heavier shell material formed can aggregate with other plankton detritus and enhance the downward organic carbon flux (Klaas and Archer, 2002). The timescale over which biologically-sequestered carbon remains in the ocean is driven by the depth of mineralisation of organic matter and the relative mineralisation depth scales of carbon and the major plant nutrients that are primarily supplied to the surface ocean by winter mixing and upwelling of deep water (Christian et al., 1997).

The biological carbon flux is not directly related to increased atmospheric concentrations of CO_2. In contrast with terrestrial plant production, oceanic plant (phytoplankton) production is not limited by CO_2 but is controlled by the supply of mineral nutrients, such as nitrate, phosphate and iron, and by physical factors such as irradiance and mixed layer depth. All these factors will be affected by climate change (Sarmiento et al., 2004). Thus the supply of nutrients is sensitive to changes in mixed layer depth, atmospheric circulation patterns and anthropogenic inputs (Bopp et al., 2001). The size of the BCP within the current global carbon cycle means that even small changes could significantly enhance or reduce the ability of the ocean to sequester CO_2. The present state of knowledge is that it is clear that change is possible but the direction of the change is uncertain. From this has arisen the idea that the ocean could be manipulated (fertilised, by the addition of artificial nutrients and/or the redistribution of oceanic nutrients) as means of increasing the drawdown of CO_2 into the ocean.

This is seen as a process that could be exploited commercially. It is critical that the scientific community maintains an active and significant programme of research into the BCP to provide the expertise required to comment critically on and evaluate such proposals and to anticipate potentially damaging feedbacks. Future research should focus on processes most susceptible to the change and on those elements of the BCP that are least understood. These include (1) the role of mineral ballasting of downward carbon flux, (2) the depth of organic carbon mineralization, (3) the factors controlling organic carbon mineralization, and (4) the relationship between the limiting micronutrient such as iron and the functioning of the BCP in areas such as the Southern Ocean where residual nitrate concentrations are high and plant biomass levels are low (Boyd and Trull, 2007; Pollard et al., 2009).

3.3.3 Existing data sets for UK and neighbouring waters

3.3.3.1 Background

Data on the components of the dissolved carbonate system (pCO_2, pH, alkalinity and total dissolved inorganic carbon - DIC) are available from the published literature and elsewhere for the NE Atlantic and NW European shelf seas, and new data are being collected nationally (through the NERC-funded CARBON-OPS project – an operational UK air-sea carbon flux observation capability) and by EU programmes such as CarboOcean and EPOCA (European Project on Ocean Acidification). The Department for Environment, Food and Rural Affairs (Defra) currently funds the DEFRApH project (ME4133, 2008-2010) which is making new measurements in key areas round the UK. In addition DEFRApH is continuing work begun in Defra contract ME2109 (Turley et al., 2007) searching for relevant existing and new data sets produced elsewhere. These are being assembled and critically assessed. This assessment will be included as part of the DEFRApH report.

Currently available data sets are summarised in the rest of Section 3.3.3. In cases where only pCO_2 was measured, pH was estimated by calculating alkalinity from its relationship with salinity and sea surface temperature (Lee et al., 2006) in locations where this is possible. pH, DIC, and pCO_2 have been calculated following Lewis and Wallace (1998) using the constants of Mehrbach et al. (1973) and Dickson and Millero (1987).

3.3.3.2 MV *Santa Maria* data, UEA, 2002–2006

Relevant data, including one carbon parameter and salinity, are available from July 2002 onwards, collected during CAVASSOO (Carbon Variability Studies by Ships of Opportunity, http://lgmacweb.env.uea.ac.uk/e072/welcome.htm, contract number EVK2-CT-2000-00088) and CarboOcean (Marine carbon sources and sinks assessment, www.carboocean.org, contract number 511176-2), on board MV *Santa Maria* trading between Le Havre (France) or Portsmouth (UK) and the Caribbean. This dataset is assembled from 13 return-crossings of the Atlantic per year. Principal Investigators (PIs): Ute Schuster and Andrew Watson, UEA.

3.3.3.3 P&O *Pride of Bilbao*, National Oceanography Centre, 2005 and 2006

Data are available from September 2005 to July 2006, collected during the FerryBox project (www.ferrybox.org, European Commission contract no: EVK2-CT-2002-00144), on board *Pride of Bilbao* sailing between Portsmouth (UK) and Bilbao (Spain). The data set will be added to during DEFRApH, when samples will be collected monthly except for January (when the ship is out of service). PI: David Hydes, National Oceanography Centre (NOC).

3.3.3.4 MV *Prince of Seas*, 1994 to 1995

Data are available from 1994 and 1995, collected during UK DoE contract PECD/7/12/143, sailing between the UK and the Caribbean. PIs: Nathalie Lefevre and Andrew Watson, UEA.

3.3.3.5 PML/Dartcom systems (Carbon-Ops project)

Data are available from 2007 onwards from systems fitted to each of NERC's research vessels. Data are transferred from the ships to the British Oceanographic Data Centre (BODC) (www.bodc.ac.uk/carbon-ops). Data are being contributed to the DEFRApH study from weekly surveys off Plymouth and from eight surveys a year in Liverpool Bay. PI: Nick Hardman-Mountford, Plymouth Marine Laboratory.

3.3.3.6 Tamar Estuary data

Data on Tamar Estuary alkalinity were collected sporadically in the 1990s, between Plymouth Sound and the fresh water of the River Tamar. PI: Tony Bale, Plymouth Marine Laboratory.

3.3.3.7 Additional data

The data sets summarised in Table 3.5 provide additional information for waters around the UK and elsewhere in European shelf seas. These data are available from the published literature and through direct contact with the scientists who carried out or are carrying out the work.

3.3.4 Baseline understanding and prediction of future states from modelling

3.3.4.1 Introduction

Given the complexity of the carbonate system on the shelf and the inability of observational programs to characterise fully the spatial-temporal variability of UK regional seas, model systems have an important role in both gap filling and predicting future trends. However, it is important to remember that the utility of models depends on the extent to which they have been evaluated in terms of their accuracy, and an understanding of why and where the models and data deviate.

Building on existing expertise, a UK modelling capacity has been developed that couples hydrodynamics, ecosystem processes, terrestrial inputs and the carbonate system (Blackford and Gilbert, 2007). This model system has reached a level of maturity where it can successfully extrapolate information into the future and estimate conditions in areas where *in situ* data have not been collected. Thus the model can replicate (nowcast and hindcast) the carbonate system for UK shelf and marginal seas (Figure 3.86), and also forecast the system (eventually including ecological impacts) for given emission and climate change scenarios.

3.3.4.2 Model system synopsis

The model system couples the carbonate system (HALTAFALL; Ingri et al, 1967), the marine ecosystem (ERSEM; Baretta et al., 1995; Blackford et al., 2004) and the POLCOMS model (Holt and James, 2001) giving a three-dimensional representation of the hydrodynamic system of the NE Atlantic.

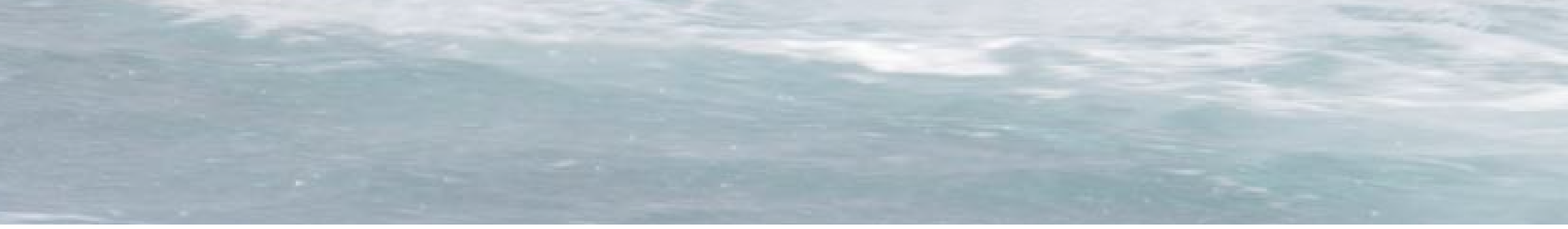


Table 3.5 Summary of data sources relevant to the study of acidification of UK marine waters.

Reference	*Time*	*Parameters*	*Location*
PI: Michel Frankignoulle, University of Liege, Belgium (Frankignoulle, 1988)	1985	pH measured pCO_2 measured Alkalinity measured	North Sea, Shetland Islands
PI: Stephan Kempe, University of Hamburg, Germany. (Kempe and Pegler, 1991)	1985 and 1986	pH measured Alkalinity measured DIC measured pCO_2 calculated	North Sea, three water masses: North Atlantic (enters North Sea from the NW), Skagerrak (outflow of the Baltic Sea), German Bight (influenced by European rivers)
PI: Mario Hoppema, Alfred Wegner Institute, Germany. (Hoppema, 1991)	1987	TCO_2 measured Alkalinity measured pH measured surface salinity measured pCO_2 calculated	North Sea: eastern part of the Southern Bight
PI: Michel Frankignoulle. (Frankignoulle et al., 1996)	1992 and 1993	pH measured Alkalinity measured pCO_2 calculated	English Channel and Southern Bight of the North Sea
PI: Michel Frankignoulle. (Borges and Frankignoulle, 1999)	1995 and 1996	pH measured pCO_2 measured/calculated Alkalinity measured Oxygen measured	Belgian and southern Dutch coasts
PI: Michel Frankignoulle. (Frankignoulle et al., 1998)	1992 to 1997	pH measured pCO_2 calculated before 1995, then measured	European estuaries
PI: Michel Frankignoulle. (Frankignoulle and Borges, 2001)	1993 to 1999	pH measured pCO_2 calculated before 1995, then measured	European continental shelf: Galician Sea, Bay of Biscay, Armorican Sea, Celtic Sea, English Channel, North Sea
PI: Helmut Thomas, Netherlands Institute of Sea Research. (Bozec et al., 2005). Thomas et al. (2005b).	2001–2002	TCO_2, Total alkalinity, pCO_2 measured Oxygen measured Nutrients measured Chlorophyll a measured	North Sea

HALTAFALL provides an iterative method to determine chemical speciation, using two parameters selected from total inorganic carbon (a state variable in the ERSEM ecosystem model), total alkalinity (TA), pCO_2 or pH, allowing calculation of the other two variables. Currently two regime-dependent relationships are used to derive TA from salinity: for salinity > 34.65, the relationship reported by Bellerby et al. (2005) for North Atlantic waters, ($TA = 66.96 \cdot S - 36.803$); for salinity < 34.65 an approximation from Borges and Frankignoulle (1999) is used ($TA = 3887.0 - 46.25 \cdot S$). The calculations utilise the seawater pH scale, with coefficients according to Weiss (1974), Dickson and Millero (1987), Hansson (1973) and Millero (1979). Air-sea exchange of CO_2 is calculated using the parameterisation of Nightingale et al. (2000) acting on the derived partial pressure of CO_2 in the water and the parameterised atmospheric concentration.

The European Regional Seas Ecosystem Model (ERSEM) is a complex plankton functional type (PFT) model developed in the context of the North Sea and is applied to the area shown in Figure 3.86. Figure 3.87 illustrates the components of the model (Baretta et al., 1995; Blackford et al., 2004). The POLCOMS hydrodynamic model is a three-dimensional baroclinic circulation model in this case set up for the UK shelf seas, taking boundary conditions from wider-area versions of the same model (Holt and James, 2001). Dissolved inorganic carbon (DIC) concentrations for the main regional rivers are taken from Pätsch and Lenhart (2004). For rivers with no specific data, the budget calculations in Thomas et al. (2005a) are used to derive a DIC load.

Figure 3.86 The full area covered by the HALTAFALL-ERSEM-POLCOMS model system is illustrated here presenting data for net annual primary production. Courtesy of J. Blackford, PML.

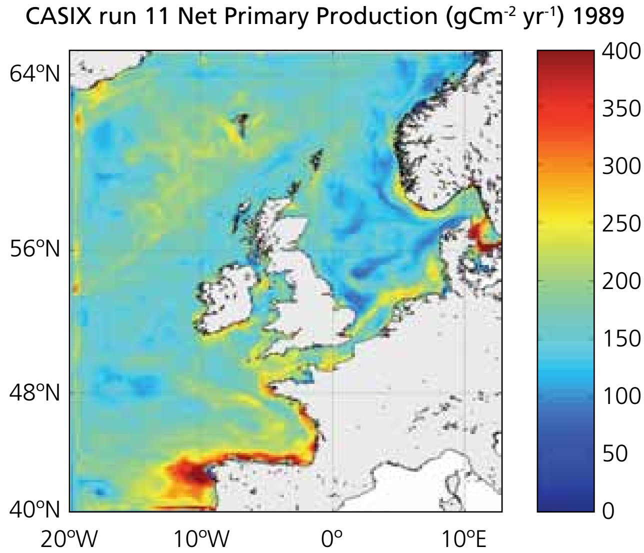
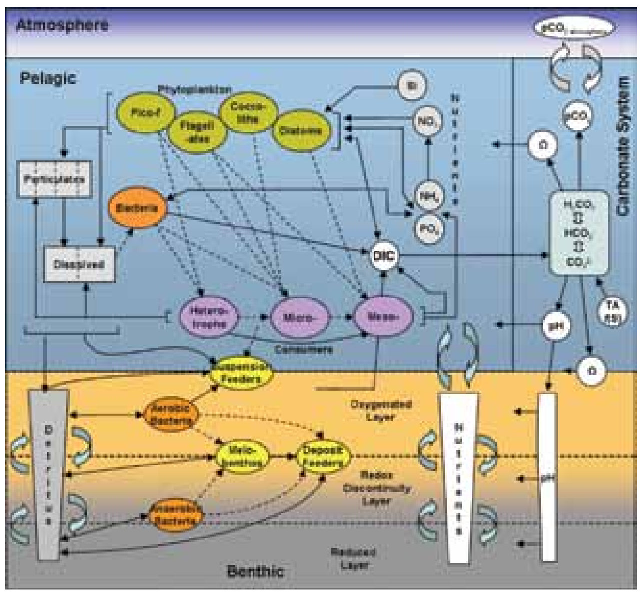
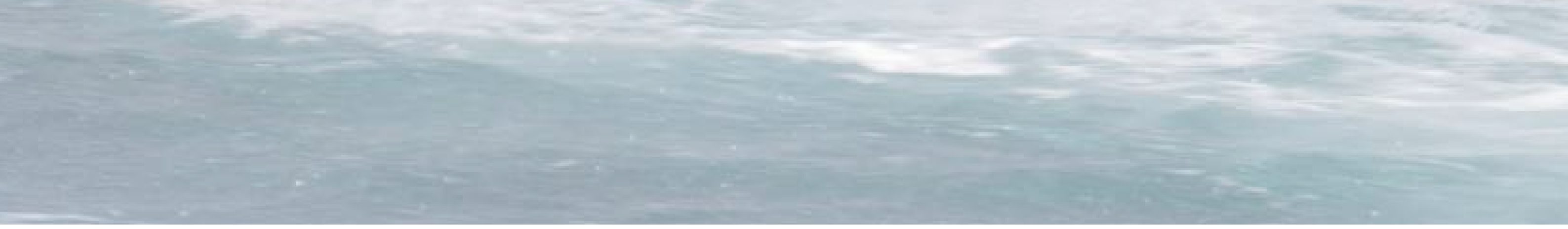


Figure 3.87 Schematic of the model system derived using HALTAFALL, ERSEM and POLCOMS models. Courtesy of J. Blackford, PML.





3.3.4.3 Evaluation

The ERSEM-POLCOMS model demonstrates reasonable skill in reproducing regional observations (Holt et al., 2005; Lewis et al., 2006; Allen et al., 2007). Despite some specific drawbacks the ERSEM-POLCOMS North Sea models are generally considered fit-for-purpose and are cited as the best validated of all regional modelling attempts (Moll and Radach, 2003). The carbonate-ERSEM model is initially validated by Blackford and Gilbert (2007).

The development of this model system is an ongoing process, benefiting from improvements in hydrodynamic, optical and ecosystem model descriptions. Currently the key data sets for evaluation of the carbonate system are:

1. Publicly available pH data from the Dutch 'Waterbase' database, maintained by the Dutch National Institute for Coastal and Marine Management (RIKZ) and the Dutch Institute for Inland Water Management and Waste Water treatment (RIZA) www.waterbase.nl, covering the southern North Sea.
2. The carbonate system data set generated by the CANOBA (Carbon and Nutrient Cycling in the North Sea and the Baltic Sea) project in 2001–2002, courtesy of Helmuth Thomas (NIOZ, Netherlands).
3. pCO_2 data from the CAVASSOO program supplied courtesy of Andrew Watson, UEA, relating to the English Channel.
4. Alkalinity and dissolved organic carbon data supplied by David Hydes from the NOC Ferrybox program, also relating to the English Channel.

Figures 3.88 and 3.89 compare model output with pCO2 data measured from ships of opportunity during the CAVASSOO and FerryBox projects. In the English Channel the model is generally producing more seasonal variability than shown in the data, but it represents the mean condition well. Essentially the model over-estimates winter levels of pCO_2, which could be due to excessive respiration in the modelled biology, although a range of additional factors could also be contributing. Without additional data describing concurrent biochemistry it is difficult to be conclusive. A longitudinally resolved analysis identifies a tendency to excessive pCO_2 at around 6° west. This probably derives from over-estimation of frontal structures in the region causing excessive production.

Figure 3.88 Comparison of model output for pCO_2 with CAVASSOO data (English Channel), seasonally resolved. Blue line represents the model mean; the grey area represents model variability. Courtesy of J. Blackford, PML.

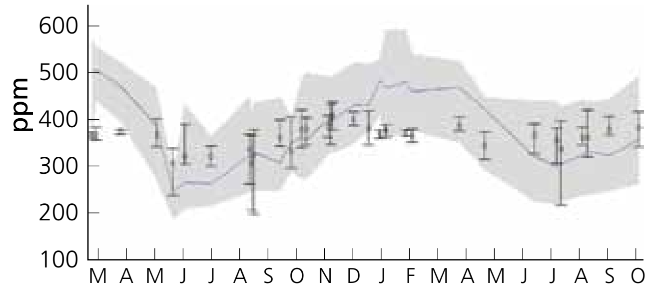
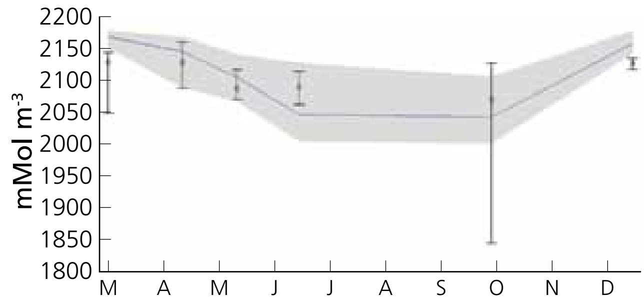


Figure 3.89 Model comparison (shaded) with Ferrybox dissolved inorganic carbon data (circles and range bars). Courtesy of J. Blackford, PML.



Nevertheless, the model does reproduce the correct mean and longitudinal trend. Similarly, a comparison with data from the North Sea region (Table 3.6) shows the bulk properties of the model system to be correct; however, in some places and at some times, in particular associated with coastal systems, the model exhibits too much variability.

Further advances in improving fit for carbonate system parameters will require data sets that characterise not only the carbonate system but also its physical and biological drivers. These initial studies identify the improved treatment of coastal processes (river loads, optical properties and total alkalinity parameterisation) as the key model refinements required. However, it is clear that the model captures the essential bulk properties of the carbonate system when compared with available data and can be considered fit for purpose.

3.3.4.4 Presentation of the evidence: Model now-casts and forecasts

Figures 3.90 and 3.91 illustrate current predictions of pH and carbonate (aragonite) saturation state for the UK shelf waters, as generated by the model for an atmospheric CO_2 concentration of 1000 ppm (expected to

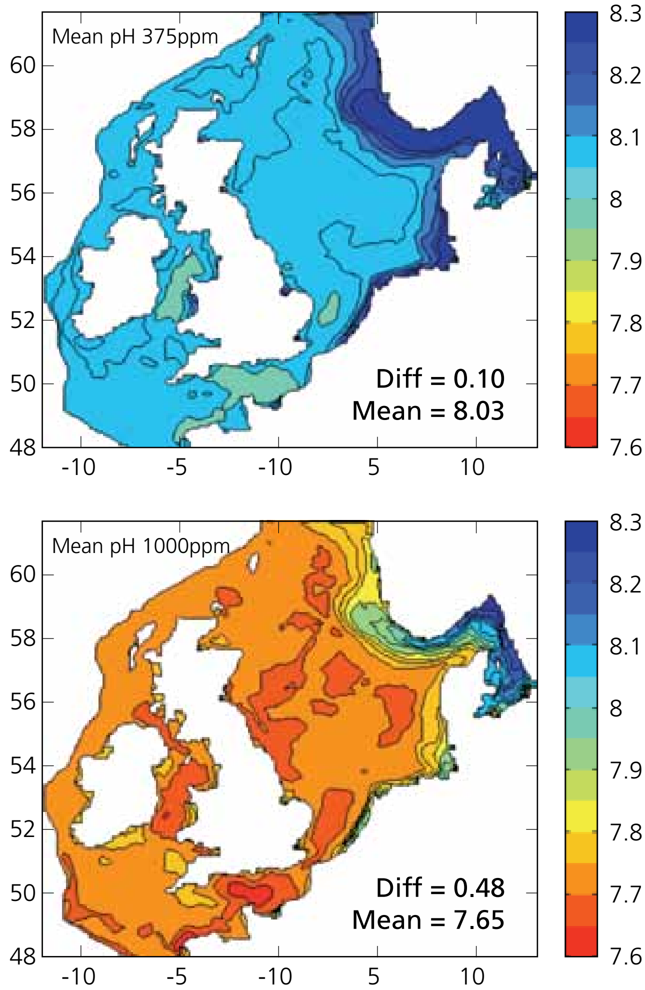
Table 3.6 Comparison of model results against CANOBA data (Thomas et al., 2005a,b), illustrating scores for a variety of evaluation metrics. r is the correlation coefficient (a measure of the tendency for model and observations to vary together, r = 1 is optimal), bias and rmse (root mean squared error) are both measures of the discrepancy, (0 is optimal) and model efficiency is a measure of how well the model predicts relative to the average of observations (ME = 1 is optimal) (see Stow et al., 2009). The variables tested are DIC: dissolved inorganic carbon; TA: total alkalinity; pCO2: the partial pressure of CO_2 in water.

	Mean of data	*Mean of model*	*Percentage bias*	*r*	*rmse*	*Efficiency*
February						
DIC	2125.1	2149.9	-1.168	0.527	27.16	-3.397
TA	2301.5	2310.9	-0.406	0.515	12.904	-0.776
pCO_2	~	~	~	~	~	~
May						
DIC	2112.4	2124.5	-0.572	0.655	43.211	-1.056
TA	2313.1	2310.5	0.113	0.486	13.848	0.206
pCO_2	317.5	292.2	-7.968	0.015	119.441	-6.288
August						
DIC	2108.3	2102.8	0.265	0.787	36.801	0.481
TA	~	~	~	~	~	~
pCO_2	337.2	342.8	1.647	0.632	50.753	0.209
November						
DIC	2122.7	2136.7	-0.661	0.685	26.003	0.25
TA	2303.5	2310.9	-0.323	0.371	12.078	-0.563
pCO_2	404.4	367.0	-9.248	-0.733	58.383	-0.717

be reached by 2100 under IPCC 'business as usual' scenarios). The evaluation suggests that results for areas near coasts and hydrographic boundaries, especially the Baltic outflow, are less robust than for offshore waters.

The model predictions indicate that aragonite under-saturation will become the norm for shelf waters. Most waters will be under or close to saturation throughout the year. In some areas in phytoplankton bloom periods during May to July, biological drawdown of CO_2 may temporarily create limited areas of over-saturation in which calcification may still be possible (see Figure 3.90). However the extent and duration of these features is highly uncertain, due to the high variability in biological and terrestrial signals in coastal areas. Currently, the extent to which calcification in different types of organisms is directly dependent on the saturation state in the water is poorly understood. Such dependency is most likely for corals, which induce calcification in vacuoles of seawater. For other organisms, such as coccoliths, calcification occurs within the cell, so the effect may be modulated by the efficiency of transport through the cell wall. Knowledge of how organisms control their calcification is needed before this part of the ecosystem-CO_2 interaction can be incorporated into the models.

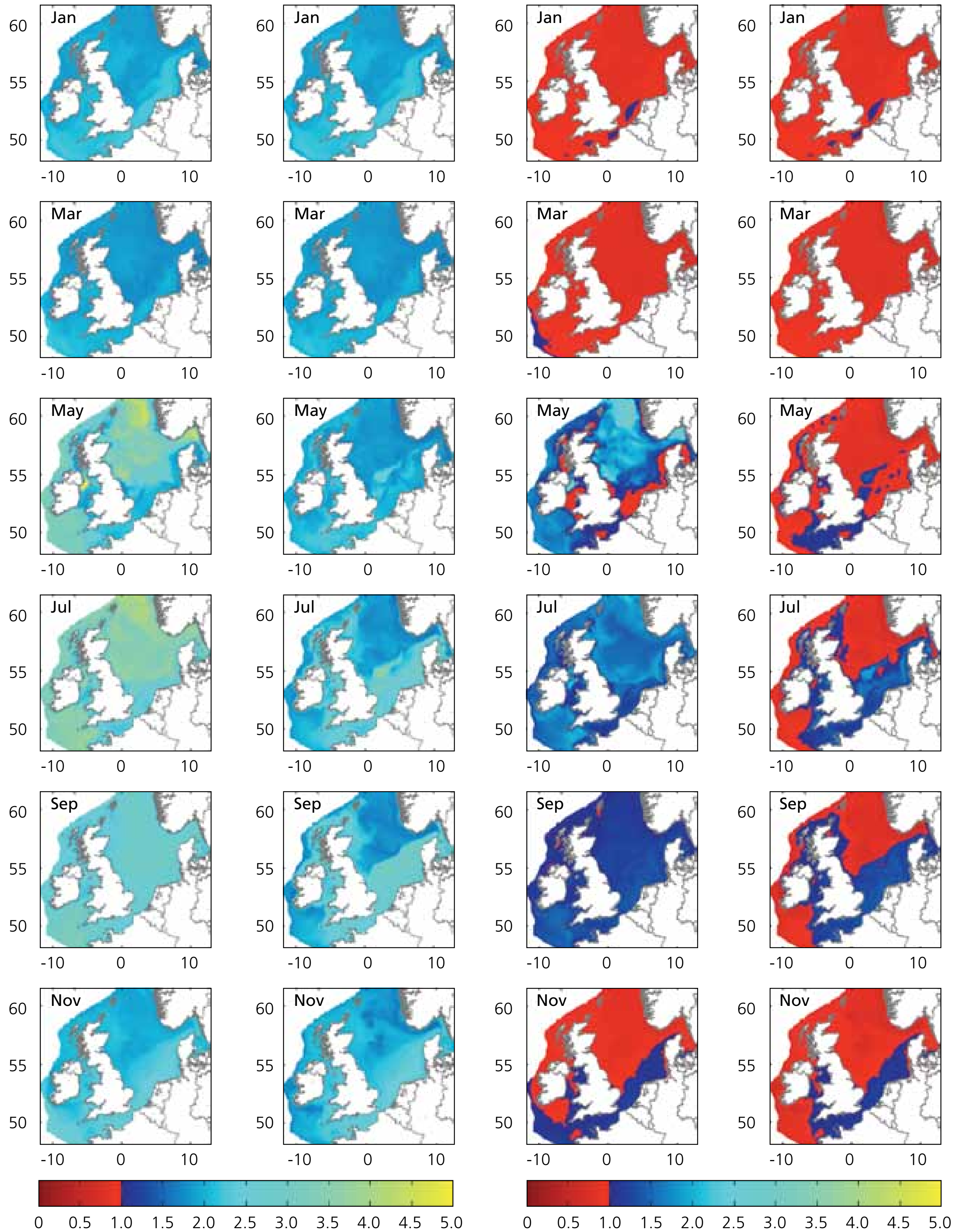
Figure 3.90 Now-casts and forecasts of surface pH in shelf seas around the UK for atmospheric CO_2 concentrations of 375 ppm and 1000 ppm. The regional annual mean pH and the difference from pre-industrial levels are shown. Courtesy of J. Blackford, PML.

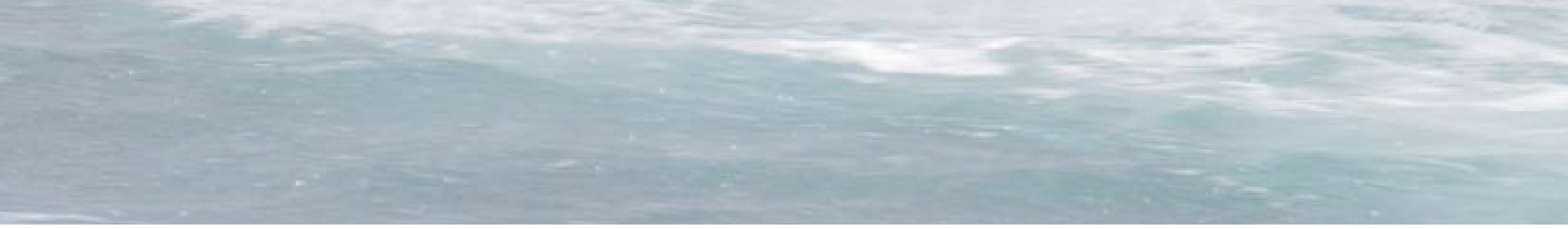


3.3.5 What the evidence tells us

Calculations based on the IPCC 'business as usual' scenario (IS92a, Alcamo et al., 1995) show that by around 2100 the additional CO_2 will cause the acid content of the global ocean's surface to double, equivalent to decrease in pH of 0.3 units (Orr et al., 2005). The extent of acidification is controlled by well-understood chemical and physical processes and the eventual amount of acidification is consequently determined by the amount of CO_2 in the atmosphere. The rate at which marine acidification takes place depends on the rate of release of CO_2 to the atmosphere and on local conditions at the sea surface. Different models predict relatively small temporal and regional differences compared to the scale of the overall change that will take place (Orr et al., 2005). The probability of a significant change is therefore high if input of CO_2 to the atmosphere continues at the present rate which is close to the IPCC 'business as usual' scenario.

Figure 3.91 Initial now-casts and forecasts of aragonite saturation state (left two columns, now-cast at atmospheric CO_2 concentrations of 375 ppm; right two columns at 1000 ppm, columns 1 and 3, surface waters, columns 2 and 4, bottom waters). Values under 1.0 (in red) represent undersaturation. Courtesy of J. Blackford, PML.





The ocean and shelf seas take up a substantial fraction of the CO_2 released to the atmosphere each year. Work on the US west coast has identified areas where pH has fallen more rapidly than expected (Feely et al., 2008; Wootton et al., 2008). This is due to a combination of local circumstances, in particular the upwelling of water with a high content of CO_2. In open ocean waters the amount taken up shows high year-to-year variability (Schuster and Watson, 2007; Watson et al., 2009). It is not known to what extent observed variation can be explained by natural cycles in the ocean or may be being forced by climate change. A programme of sustained observations is essential in order to determine causes of this variability.

An international effort based on using ships of opportunity has created a network in the North Atlantic which in 2005 provided sufficient observations for the air-sea flux to be determined to within 10%. This information taken together with air measurements allows the land flux to be estimated to a degree of precision that cannot be achieved through land based measurements (land based sources and sinks are much more varied and variable than those in the ocean). This programme of observations must be maintained at least to the level of activity that was achieved in 2005.

Baseline measurements of pH against which changes in UK waters can be judged are not yet available. There are few high quality, directly-measured data on pH for UK marine waters. At present pH is assessed most reliably by calculation following the measurement of total alkalinity and total dissolved inorganic carbon. Good-quality time-series data are becoming available in some key areas through the DEFRApH project (ME4133: Defining the degree of acidification (pH) of UK waters and potential future changes). Small shifts in the natural cycle of organic matter production in the ocean, driven by climate change, could significantly affect the ocean sink for CO_2. More research is needed before it will be possible to predict the most likely direction of such changes. This research is also needed to determine if the ocean could be forced to absorb more CO_2 by human intervention.

The trend towards increased CO_2 concentrations and reduced pH represents a threat to marine organisms and ecosystems. It is not known if the changes in pH that have occurred to date have been ecologically significant in UK waters, but future changes are much more likely to be. Presently there is insufficient information to predict if future impacts will be different in different regions.

There is strong evidence that climate and ecosystems can change abruptly within periods of a few years (generating so called 'regime shifts'), with species ranges and population dynamics affected largely by temperature-induced changes. The synergies of ocean climate warming and carbon cycle dynamics are likely to be non-linear. With environmental temperature changes, good evidence supports the idea of thresholds beyond which changes happen rapidly. This reflects species niche concepts. Since temperature and pH are both fundamental constraints on biochemistry, and since evolution has adapted marine organisms to perform optimally within restricted ranges, there may well be quite sudden and dramatic effects in marine ecosystems and productivity due to combined effects of warming and acidification (see Table 3.7 for indicators of acidification in UK waters).

Table 3.7 Indicators for acidification of UK waters.

Parameter	*Region*	*Key factors and impacts*	*What the evidence shows*	*Trend (right direction?)*	*Confidence in assessment*	*Forward look*
pH	CP2 Regions 1 to 8	Increasing atmospheric CO_2 levels, increasing solubility of aragonite and calcite, and decreasing pH. Affects plankton and shelled organisms	Lack of baseline pH data in most regions. pCO_2 data show the system is highly variable and influenced by interannual and possibly decadal changes. Synergistic effects with climate change may accelerate impacts	Lower (no)	Medium	Further decrease in pH (i.e. increase in acidity)

3.3.6 Forward look

3.3.6.1 pCO_2 monitoring

A worldwide ocean-carbon monitoring system has been identified as an essential part of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS).

The ability to extensively monitor the air-sea flux of CO_2 across the North Atlantic is critical because the flux assessments that they lead to can be used with knowledge of atmospheric changes to provide estimates of fluxes from land. Key parts of the observational network involved in the assessment for 2005 were funded by the CarboOcean project, the observational phase of which ended in 2008. Presently there is considerable uncertainty about how the observational network can be maintained. A European framework for co-ordination of both terrestrial and marine observation is being developed (ICOS; Integrated Carbon Observation System) but this requires that individual observing components are funded nationally.

3.3.6.2 DEFRApH monitoring

DEFRApH (ME4133) is a Defra-funded study to define the present state of UK waters with respect to potential changes in the degree of acidification (pH) of these waters. It combines collection of new data over two years, a review of pre-existing information and numerical analysis. The project will run for 30 months and started in August 2008. It will provide the basic data set against which results from a future monitoring programme would be referenced. DEFRApH will produce a statistical description of the variability seen in the new data. Estimates of likely future changes will be based on this analysis of the factors driving changes in pH.

Based on the work carried out and knowledge of ongoing developments in measurement technology, DEFRApH will make recommendations for a future statistically robust programme for monitoring the acidity of UK waters working within the UK Marine Monitoring Assessment Strategy (UKMMAS) framework (i.e. the Ocean Processes Evidence Group, OPEG; and the Clean and safe Seas Evidence Group, CSSEG).

3.3.6.3 DEFRApH modelling

To characterise behaviour beyond the observational sites to a full consideration of UK shelf waters, the ERSEM-POLCOMS based 3D dynamic ecosystem model (Blackford and Gilbert, 2007) can provide the required assessment. The likely accuracy of this extrapolation will be determined by comparison of the output from the ERSEM-POLCOMS model and the new data on pH provided by DEFRApH.

Under the DEFRApH project further evaluation will be undertaken with updated model systems. Funding from European framework and UK national programmes will contribute to general and carbonate-specific model improvement over the next few years. In particular, programmes will be looking at how different drivers such as ocean acidification, climate change, modifications in fishing pressures and pollution may interact to modify ecosystem responses. Comprehensive surveys of the region, similar to the CANOBA programme in the North Sea (Thomas et al., 2005a,b), in combination with long-term or high-frequency measurements as identified under DEFRApH, are key to improving modelling capability.

3.3.6.4 Related projects

Work in DEFRApH complements that also being carried out under the EU projects CarboOcean and EPOCA (European Project on Ocean Acidification http://epoca-project.eu) and the international effort to determine the role of the ocean in the anthropogenic CO_2 cycle co-ordinated by the IOCCP (International Ocean Carbon Coordination Project).

The UK is contributing to international programmes on ocean acidification and is funding work on pH monitoring in UK sea shelves and open ocean regions. The Department of Energy and Climate Change (DECC) is co-funding with Defra a NERC research programme starting summer 2010. It will look at the mechanism of ocean acidification and its potential impacts in a range of ecosystems. The UK has also recently put forward a proposal for an IPCC special report on ocean ecosystems including the impacts of ocean acidification.

3.4 Circulation

3.4.1 Key points

i. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) gives warm water flow ('North Atlantic Drift') past the west of the UK, strongly influencing UK climate by warming the prevailing westerly airflow. Circulation is important to distributions of salt, of deep-ocean heat and hence regional climate, of pollutants and of many species carried by the flow during their lifecycle. Currents affect offshore operations and habitats. In UK shelf seas, the instantaneous observed current comprises an important tidal contribution, and contributions due to winds and to flows driven by differences in density (arising from seasonal heating and salinity differences between locations). 'Residual' flow (after averaging out oscillatory tidal flow) is dominated in many areas by flows forced by winds and by differences in density. Tides, density and winds all change on various timescales, so that observed and residual flows can be very variable. Wind forcing is the most variable factor; transports of water in one storm can be significant relative to a year's integrated transport (e.g. in the Irish Sea). Currents vary strongly with location. Notable persistent flows are polewards along the upper continental slope; from the Atlantic onto the continental shelf around Scotland and into the northern North Sea; and northwards through the Irish Sea to form the relatively fresh northward Scottish Coastal Current west of mainland Scotland (see Sections 3.4.2.2, 3.4.2.6, 3.4.4).

ii. How has the assessment been undertaken?

Long-term circulation in UK waters has mostly been inferred from distributions of tracers, tracks of drifters and floats, or from numerical hydrodynamic models. Data also come from current-meter measurements (there are a few long-term mooring arrays) and from submarine cables. Circulation can be inferred from hydrographic sections, for components with time-scales longer than a day. HF radar gives spatial coverage for surface currents within a limited range (Section 3.4.2.3). There are no criteria for status and there is no baseline.

iii. Current and likely future status of circulation

- Five sections from 1957 to 2004 suggest AMOC decline but this is within the range of large variability on time-scales of weeks to months. An overall trend has not been determined from the continuous measurements begun in 2004 (new data since *Charting Progress*; Defra et al., 2005). (Section 3.4.4.1).
- Deep outflows of cold water from the Nordic seas are likewise too variable to infer any overall trend (Section 3.4.4.1).
- Strong North Atlantic flow eastwards towards the UK may correlate with positive North Atlantic Oscillation (NAO) Index (i.e. prevailing westerly winds). Enhanced along-slope current around the UK may correlate with a negative NAO Index (Section 3.4.4.1).
- Climate models' consensus makes it very likely that AMOC will decrease over the next century, but not 'shut down' completely (Section 3.4.5).

- Similar spatial and temporal variability (arising from complex topography and variable forcing) is likely in future (Sections 3.4.4.2 to 3.4.4.7, 3.4.5).

iv. What has driven change?

Circulation is directly dependent on forcing by tides, winds and spatial differences in density.

v. What are the uncertainties?

Relative to spatial variability, measurements are generally sparse. This lends importance to developing models. Temporal variability complicates the inference of changed conditions unless several years' data are available. Instabilities generating meanders and eddies at irregular intervals are a large part of variability over the continental slope and nearby ocean.

vi. Forward look

There is a need for long-term data to elucidate climate-change signals from background variability. The RAPID monitoring to 2014 needs complementary measurements, especially at higher latitudes, to help understand how changes in the AMOC are relayed from place to place and possibly to establish proxies for easier monitoring. In UK shelf seas, measurements are sparse relative to currents' variability; reliance will be placed on models for most distributional information. In view of the importance of currents, better prediction of short-term variability in circulation is needed; this entails model validation and development of observational networks.

3.4.2 Introduction

3.4.2.1 Types of current

Tides (surface elevations and currents or 'streams') are generated by the varying gravitational attraction of the Moon and the Sun. In the North Atlantic Ocean, tides are predominantly semi-diurnal (two tides a day); in the relatively shallow (< 200 m) UK shelf seas, tides are amplified to give a macro-tidal (> 4 m) regime around much of the UK (particularly large elevations, > 10 m range, occur in the Bristol Channel). Strong tidal currents occur in the southern North Sea, in some areas of the Irish Sea, and in constrictions between islands and around headlands, for example the Pentland Firth.

Meteorologically forced 'surge' currents are due to variations in wind stress and atmospheric pressure. Wind stress is most effective in shallow water whereas the pressure effect is independent of depth. Surge currents have timescales of hours to days according to storm duration, water depth and the extent of the storm. Winds that drive surface waters offshore may induce 'upwelling' of replacement water from below.

Density currents are driven by density gradients due to changes in temperature and/or salinity, arising from the net flux of heat through the sea surface, freshwater inputs from rivers and the atmosphere, and different mixing regimes according to water depth and tidal-current strength. Intense cooling and hence dense-water formation may induce local sinking or 'convection'.

3.4.2.2 Circulation

The net movement of water, the circulation, is driven by 'residual' currents which arise from a combination of net tidal action, mean meteorological forcing and the mean density distribution. (Upwelling and convection are components of vertical or 'overturning' rather than lateral circulation.) Traditionally, there has been a tendency to think of circulation as a smooth, wide constant flow, perhaps because such characteristics are most amenable to measurement (see Section 3.4.2.3). In reality, and especially in UK waters, most elements of circulation vary strongly on short (daily and monthly) timescales or short spatial scales.

3.4.2.2.1 Short-term circulation

Tidal currents are primarily oscillatory and contribute little to daily mean circulation, except where currents are strong and spatially variable, such as the southern North Sea or headlands such as Portland Bill.

During winter in UK shelf seas, the net movement is likely to be determined by the last storm, because surge currents typically exceed density currents and daily-mean tidal currents. Thus daily or monthly mean circulation may even be the reverse of the long-term pattern. An example is flow through the North Channel (Knight and Howarth, 1999); the two largest daily mean flows in February 1994 amounted to 20% or more of the year-long transport along the Channel.

> Animation of flows with reversal through a tidal cycle in Liverpool Bay; available at: http://chartingprogress.defra.gov.uk/resources/. Courtesy of A. Lane, National Oceanography Centre.

> Animation of surge levels around UK for 8-9 November 2007 storm (surge) event; ; available at: http://chartingprogress.defra.gov.uk/resources/. Courtesy of K Horsburgh, National Oceanography Centre.

3.4.2.2.2 Seasonal mean circulation

The seasonal mean circulation is mainly due to the strong seasonality in surge and density currents: storms mainly occur in winter, river discharge has an annual cycle and solar input varies seasonally.

Each year, from about May to October, large areas of UK waters stratify as surface waters are warmed. Below the (relatively sharp) seasonal pycnocline, colder bottom water remains from the previous winter. However, the water column remains vertically mixed by tidal stirring all year where the water depth is relatively shallow (typically less than 50 m and nearer to shore) and/or depth-averaged tidal currents are large (Simpson and Hunter, 1974). Between the stratified and mixed areas is typically a sharp horizontal temperature (and/or salinity) gradient with a horizontal scale O(10 km). Because the cold bottom water is largely static (friction tends to bring the velocity to zero at the sea bed), the corresponding density gradient is expected to drive a near surface geostrophic jet or 'thermal wind' above the region of maximum horizontal density gradients; the flow direction is cyclonic with the dense bottom water to the left of the direction of flow (northern hemisphere; Hill et al., 2008).

For a typical horizontal density gradient 0.4 kg/m^3 per 10 km, the jet velocity is 0.2 m/s at 50 m above the bed resulting in a typical transport of the order of 10^5 m^3/s, an important (albeit localized) contribution to persistent transports from late spring to autumn (Hill et al., 2008).

Such flows can transport water over many hundreds of kilometres in areas of the North Sea, Celtic Sea and Irish Sea (see Section 3.4.4). The timing of the onset of this seasonal circulation in April or May is dependent on wind mixing, surface heat fluxes and freshwater input and may vary between years by up to a month (Brown et al., 1999, 2003).

An animation of the evolution of surface to seabed temperature differences, and hence thermal fronts, available at: http://chartingprogress.defra.gov.uk/resources/. Courtesy of J. Holt, NOC.

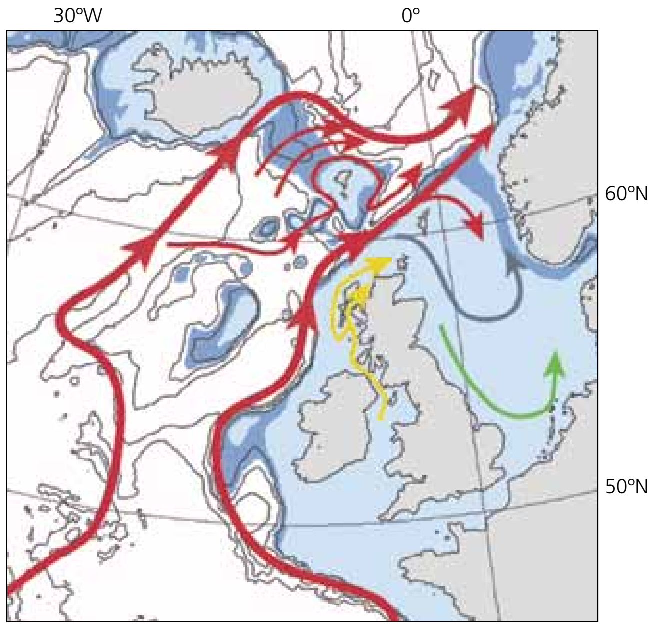
The seasonal mean circulation varies through depth: jets are stronger near the surface, and the relative contributions from surge or density currents may vary with depth. This is illustrated in Section 3.4.4.5 (see Figure 3.100 showing an 'estuarine / coastal' type circulation: flow near the bed is towards the coast and flow near the surface is away from the coast). The prime driving force is density for both the outflow and the inflow, although the near-surface is more affected by the wind (M.J. Howarth, NOC, pers. Comm., 2009).

3.4.2.2.3 Long-term mean circulation

When averaged over some years, the long-term or 'climatological' mean circulation indicates some persistent features in UK waters (see Figure 3.92). However, there are large uncertainties in estimating the magnitude of mean circulation, and most regions have significant inter-annual variation (see Sections 3.4.2.3 and 3.4. 4).

'Flushing time' is a concept describing the average time needed to completely replace the waters in a region. However, it depends on the circulation and on the amount of mixing; hence flushing time is not easy to estimate and hides large local variations. For example, the volume of water that enters and leaves the North Sea each year is approximately the entire volume of the North Sea basin (Huthnance, 1997). However, most of this (red and blue arrows in Figure 3.92) only passes through the northern North Sea, which therefore has a flushing time of ~ 1 year or less, whereas flushing time in the central North Sea is thought to be several years.

Figure 3.92 Circulation of surface waters in the North-East Atlantic. Red arrows represent the flow of warm, salty Atlantic waters along the continental slope and further west, while the yellow, blue and green arrows represent the flow of coastal waters. The yellow arrow indicates the path of the Scottish Coastal Current, while the blue arrow indicates the inflow of mixed coastal/oceanic water past Fair Isle (the Fair Isle Current) and the green arrow indicates average anti-clockwise flow in the southern North Sea. Supplied from Scotland's Seas: Towards Understanding their State *(Scottish Government, 2008). Courtesy of S. Hughes, Marine Scotland.*



3.4.2.3 Measuring circulation

Long time-series of observed currents are sparse, hindering the determination of long-term circulation and its variability. Long-term circulation in UK waters has mostly been inferred from distributions of tracers (e.g. salinity or radionuclides), tracks of drifters and floats, or from numerical hydrodynamic models, optimised with any available observations.

Observational data on circulation come from current-meter measurements, drifting buoys and floats, submarine and telephone cables (to measure induced voltages across channels) and distributions of 'tracers' such as salinity and radionuclides, for example, caesium-137 and technetium-99 (Kershaw et al., 2004). Circulation can also be inferred from hydrographic sections, albeit only for components with time-scales longer than a day and leaving an arbitrary depth-independent component to be determined by other constraints. However, accurate estimation from measurements needs strong and persistent circulation. In the presence of strongly time-varying currents, it is difficult to infer a relatively weak long-term circulation from current meters and Acoustic Doppler Current Profilers (ADCPs), whose point locations may also be unrepresentative. HF radar gives fuller spatial coverage for surface currents within a limited range (typically 50 to 100 km) of its transmitters and receivers ashore. Wider coverage of surface currents can be given by satellites: (1) altimetry can measure surface slopes to infer surface currents, however, measurements are degraded within O(10 km) of the coast and are everywhere infrequent so that only variability on time-scales of weeks is resolved; (2) the movement of features in colour or infra-red imagery can be tracked – evidently the outcome is degraded by the unknown development of the features themselves and by the infrequency of clear images. The motion of floats and drifters is often difficult to interpret in continental shelf seas because of the usual short time of deployment and observation; surface floats are also partly driven by the wind, so that they do not simply track the bulk current. Tracers can help to determine circulation patterns rather than current speed.

Descriptions of the monitoring networks which regularly measure currents and circulation are given in the UK Directory of Marine Observing Systems (www.ukdmos.org). These include RAPID arrays for the North Atlantic circulation, moorings on the West Shetland slope for Atlantic water transport past northern Scotland, a mooring in Tiree Passage, two moorings and HF radar in Liverpool Bay, but little else on a regular basis. This is a sparse array relative to the spatial scales of circulation patterns.

3.4.2.4 Models

Charting Progress expressed caution regarding the use of numerical models to predict circulation; inevitably, different models may best reproduce (hindcast) observations in different contexts (Jones, 2002). Insufficient resolution and unsuitable advection schemes were a factor in some comparisons, for example Smith et al. (1996) and NOMADS2 (Delhez et al., 2004); in deeper waters and over steep slopes, effects due to density differences can be important and difficult to model.

More recently, Holt et al. (2005) have assessed uncertainties in a coupled hydrodynamic–ecosystem model of the northwest European continental shelf. The three-dimensional baroclinic circulation model POLCOMS had ~ 7 km horizontal resolution and 20 's-levels' in the vertical. POLCOMS was coupled with the European Regional Seas Ecosystem Model representing the functioning of the ecosystem with 52 state variables. The period August 1988 to October 1989 of the North Sea Project was simulated. Tidal currents and elevation, and sea surface temperature, were well modelled, with root mean square (RMS) errors of less than 0.4 standard deviations of the data. However, residual current speed and salinity had RMS errors similar to the standard deviation of the data. Improving the comparison for residual currents and salinity requires improvements in the model (forcing and formulation) and in observational data (quantity and quality). Nevertheless, the resolution was found sufficient to model complex biophysical interactions in the horizontal (e.g. enhanced production at fronts) and in the vertical (e.g. mid-water production modulated by the spring–neap cycle). The assessment also suggests what data assimilation might prove most fruitful.

3.4.2.5 The significance of circulation

The heat capacity of the seas is large relative to the atmosphere, thus the ocean can store and transport large amounts of heat; the world's ocean circulation is critical in the global climate system. A meridional (tropics to poles) transport of energy is required for the Earth system to be in global radiative balance; some 30% to 50% of this meridional energy transport is in ocean currents at mid-latitudes and a higher proportion at lower latitudes (Bryden and Imawaki, 2001).

In particular, the Atlantic Meridional Overturning Circulation (AMOC) comprises the large-scale surface and subsurface circulation of the Atlantic basin, including regional currents such as the Gulf Stream and the North Atlantic Drift. The system is responsible for transporting large amounts of heat into the North Atlantic region (Ganachaud and Wunsch, 2000), much of which is transferred to the atmosphere, and then advected into NW Europe. This relatively warm surface water enhances the inherent moderating effect that the North Atlantic Ocean has on the climate of NW Europe and the sub-Arctic. Climate model simulations suggest that without the presence of the AMOC, mean annual temperatures in the UK, for example, may be 2 to 4 °C cooler than is otherwise the case, in particular with much colder winters (Vellinga and Wood, 2002).

The potential of the AMOC to undergo a partial or (less likely) a total slowdown is of serious concern given the capacity for the associated cooling to offset some (or in the extreme case, most) of the projected global warming for the UK and wider North Atlantic region. This has obvious direct societal implications with respect to the planning and implementation of climate change adaptive measures. Implications for the UK's seas, and those directly adjacent, are equally serious, with changes in circulation patterns and heat and salinity transport likely to have marked biological effects (see Schmittner, 2005 for example).

Circulation is an agent for flushing of sea areas (and pollutants). It brings Atlantic water on to the shelf; the extent of this influence is limited regarding heat content (hence temperature), but more extensive for salinity and other constituents less subject to exchange with the atmosphere. Ultimately, Atlantic water is the main source of UK shelf-sea nutrients, for example. The circulation also advects carbon from the shelf to the Atlantic.

Locally, cooling water may be a significant contributor to circulation and may exploit coastal flows to disperse the heat. A modern coastal power station discharges heat of the order of 3 GW; assuming excess temperature of 2 °C, this represents a flow of order 400 m^3/s, larger than any UK river's average and comparable with alongshore tidal flow in the first kilometre offshore.

Circulation patterns control the overall movement and distribution of passive objects (eggs, larvae, nutrients, contaminants, flotsam, sediments). Hátún et al. (2009) attributed biogeographical shifts in the NE Atlantic to exchanges of sub-arctic and sub-tropical water masses. Some species exploit the circulation, for example herring, in order to transport larvae from spawning grounds to nursery areas (Turrell, 1992). The flow off NE England provides a direct pathway for material and fish larvae from coastal regions to the northern Dogger Bank and central North Sea (Brown et al., 1999). Density-driven currents provide a continuous transport route from the French coastal region via the Celtic shelf and west of Ireland to the Scottish shelf, potentially a 'conveyor belt' for contaminants and plankton (Hill et al., 2008). On a smaller scale, dispersal of herring larvae in the Blackwater Estuary is dependent on circulation in the area (Fox and Aldridge, 2000). To summarise, advection of marine nutrients, plankton and animals is a critical factor in the lifecycles of many marine species. Movements of objects depend on their density – if neutrally buoyant or dissolved, they move with the water circulation; if particulate or heavier than water, they tend to sink and move less far, with a bias towards the direction of fastest flow; floating objects are driven by winds as well as the water circulation. Areas of retention (material not being advected away) are often characterised by deposition of soft organic sediment, while frontal regions are associated with greater productivity. Frontal boundaries between eco-regions are important when considering the division of shallow seas into biologically relevant management units (applying an ecosystem approach to the sustainable use of marine resources; Hill et al., 2008).

3.4.3 Progress since *Charting Progress*

In the open Atlantic Ocean, there are now more Argo profiling floats (which give an indication of circulation from their changing reporting positions), and the RAPID array (especially across 26° N) is giving an estimate of the time-varying meridional overturning circulation. In addition to the 26° N array, RAPID is also funding field work at 38° to 39° N southwest of Cape Cod (six bottom pressure recorders in collaboration with Woods Hole Oceanographic Institution), and at 42° to 43° N off Nova Scotia (moorings comprise combinations of bottom pressure recorders, ADCPs and CTD sensors in partnership with Bedford Institute of Oceanography, Canada). These latter arrays aim to record the variability of bottom pressure across the Atlantic deep western boundary, to provide a robust estimate of the variability of the AMOC itself (Bingham and Hughes, 2008). One-year time series of bottom pressure from the Nova Scotia array became available at the end of 2009.

The Irish Sea Observatory was established in the eastern Irish Sea in 2002; there are now several years of data to provide estimates of interannual variability; a second site (also with current measurements) was started in 2005; HF radar for surface currents has also been running since 2005. HF radar is able to monitor surface currents hourly or more frequently, with spatial resolution of the order of 1 km out to a range of the order of 100 km, but few systems are operational. Drifters have provided further insight into aspects of shelf-sea circulation as described by Hill et al. (2008). Gliders are a recent development for hydrography with less dependence on ships; they are not yet in routine use but can give an indication of circulation from their changing reporting positions.

Model development has continued, in particular with finer resolution ~ 1.8 km over the UK shelf area (out to the shelf break); this is fine enough to resolve features associated with stratification in summer and in regions of freshwater influence. Forecasts using a 3-D hydrodynamic model (POLCOMS) are now operational at the Met Office National Centre for Ocean Forecasting (NCOF). The UK shelf area is also modelled by several other countries. Models which have been published and well validated are those of MUMM (Brussels, Belgium), BSH (Hamburg, Germany), Ifremer (Brest, France), IMR (Bergen, Norway), Mohid (Portugal) and the Marine Institute (Galway, Ireland). Most of these are run operationally using data assimilation. Nevertheless, strong variability in currents (spatial and temporal) presents a modelling challenge and makes them a poor indicator of any trends in the state of UK seas.

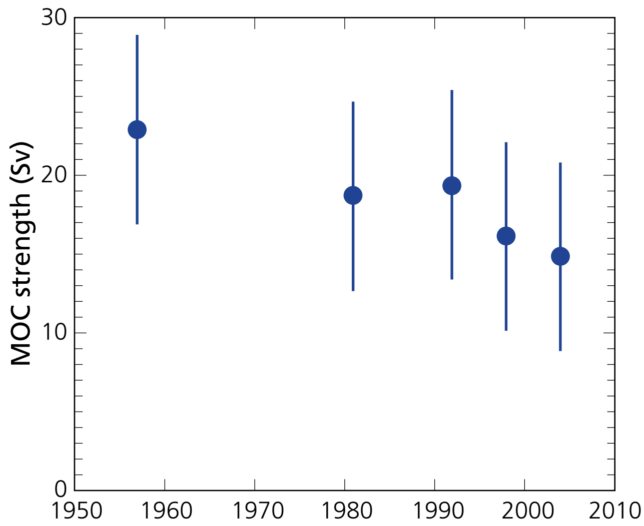
3.4.4 Presentation of the evidence

3.4.4.1 North Atlantic circulation

The AMOC (Sections 3.4.2.5, 3.4.3) has been estimated from a hydrographic section along 26° N completed in 2004. This updated ship-based estimate of AMOC strength has been compared with previous estimates spanning the past five decades (Bryden et al., 2005). The analysis, based on six-week 'snapshots' of the circulation obtained during each cruise, indicates that AMOC strength has declined by around 30% since 1957 (Figure 3.93).

Closer inspection of the circulatory components that comprise the AMOC reveals little change in the actual northwards transport of water associated with the Gulf Stream at the ocean surface (in 1957 to 2004), but an enhanced southwards recirculation of water in the upper 1000 m of the ocean by the subtropical gyre. The

Figure 3.93 Estimates of the strength (dots plus error bars) of the Atlantic Meridional Overturning Circulation at 26° N from five ship-based transects (Bryden et al., 2005), 1957 to 2004. Courtesy of NOC.



effect is to reduce the amount of water entrained into the North Atlantic Drift. The AMOC deep returning limb, comprising dense cold water formed in the Arctic and flowing southwards, is found at 26° N to have declined by ~ 8 Sverdrups (Sv; 1 Sv = 10^6 m3/s; Table 3.8), further implying a slow-down in the overall circulation.

Following the deployment of the RAPID mooring arrays, continuous daily estimates of the AMOC strength at 26° N are now available from spring 2004. Detailed analysis of the first year's full time series, April 2004 to April 2005, reveals an observed annual mean AMOC strength of 18.7 Sv (Cunningham et al., 2007; Kanzow et al., 2007). Also evident are sizeable high-frequency variations (the standard deviation of the daily series is 5.6 Sv). An extended time series spans 3.5 years (April 2004 to September 2007; Figure 3.94); this shows similar levels of variability and an annual mean AMOC strength for the entire period of 18.5 Sv (± 4.9 Sv). Given the brevity of the time series to date, no attempt is made to comment on any linear trend.

Table 3.8 Transport estimates of Lower Atlantic Deep Water (originating in the Arctic basin and occupying 3000 to 5000 m depth) across 26° N. Units are Sverdrups (1 Sv = 10^6 m^3/s of water crossing 26° N). Negative units indicate a southwards transport. Source Bryden et al. (2005).

Year	*1957*	*1981*	*1992*	*1998*	*2004*
Transport strength (Sv)	-14.8	-11.8	-10.4	-6.1	-6.9

Figure 3.94 Continuous Atlantic Meridional Overturning Circulation strength from the RAPID monitoring array at 26° N, April 2004 to September 2007. Data are expressed in Sverdrups (1 Sv = 10^6 m^3/s). A low-pass filter has been applied to the daily strengths, suppressing much of the variation on time scales less than 10 days. Courtesy of S. Cunningham et al., NOC.

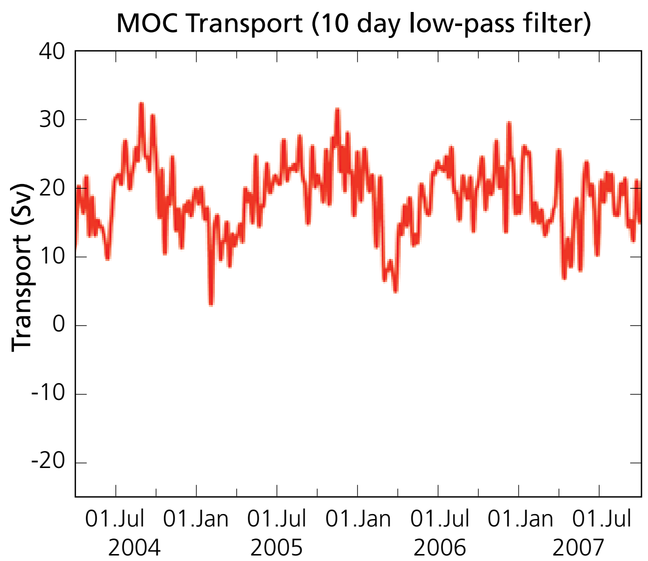
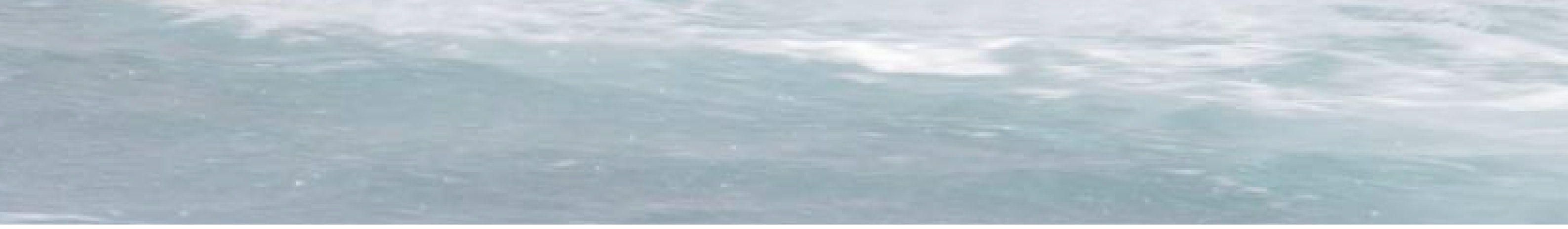


Figure 3.92 illustrates the broad circulation of surface waters around the UK. Warm, salty Atlantic waters flow along the continental slope and further to the west (shown in Figure 3.92 by red arrows). In addition to the surface circulation, deeper flows return water to the Atlantic from Nordic seas; cold dense bottom water ultimately forms the main return limb of the AMOC. Deep 'overflow' water locations include Denmark Strait and the Faroe Bank Channel (prior to this the deep water flows south-westwards through the Faroe-Shetland Channel and is diverted north-westward by the Wyville-Thomson Ridge). There are also intermittent overflows across the Wyville-Thomson Ridge.

Some regularly updated time series describe these outflows of deep water from Nordic seas into the subarctic Atlantic basin. Outflow through the Faroe Bank Channel contributes approximately 2 Sv; updated measurements here are provided by Østerhus et al. (2008). These data are continuous from 1995 to 2005 and reveal sizeable inter- (and intra-) annual variability but do not point to any secular change indicative of a major change in AMOC strength.

A slightly larger flux of cold, dense deep water exits the Greenland-Iceland-Nordic Seas via the Denmark Strait, east of Greenland and to the west of Iceland. New data sets assembled here include those by Macrander et al. (2005), based on measurements made at the narrowest point of the channel, and a lengthier record maintained by Dickson et al. (2008) slightly further south. The Macrander et al. (2005) analysis reveals a 20% decrease in deep-water transport through the period 1999 to 2003. The Dickson et al. (2008) record encompasses data from 1996 to 2005 and reveals sizable, additional interannual variability around the Macrander et al. (2005) feature, but no overall trend in transport. The mean flux estimate of deep water transport through the Denmark Strait during the 1996 to 2005 period was 4.0 Sv (± 0.4 Sv).



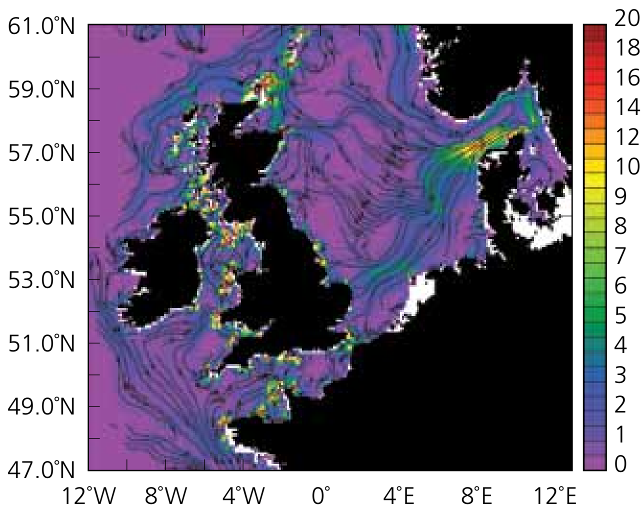
Interannual changes in the North Atlantic Current and the Subtropical Gyre transport during 1992 to 2002 were found by Pingree (2002) to correlate with the winter NAO Index. Pingree found maximum flow conditions in 1995 and 2000 when NAO was positive and at a minimum in 1996 to 1998 with NAO-negative winters. Conversely, years of extreme negative winter NAO Index correlated with enhanced poleward flow and anomalous winter warming along the west European continental slope (see Section 3.4.4.7), as measured in 1990, 1996, 1998 and 2001. One explanation is that negative NAO Index associated with weak westerlies reduces the wind-stress curl driving the Subtropical Gyre; in turn, geostrophic balance in the Gyre implies a raising of sea-level at the southern end of the west European continental slope, driving enhanced poleward flow along the slope (Pingree, 2002). An alternative explanation was proposed by Hatun et al. (2005) and is backed up by the observations of warmer water along the shelf edge (Holliday et al., 2008): that tropical gyre water replaces the Subtropical Gyre as the gyre weakens and moves westward. The two mechanisms can work together.

3.4.4.2 Circulation in UK waters

As discussed in Section 3.4.2.1, circulation is variable in time and space and it is therefore difficult to describe any generally persistent circulation patterns in UK waters. There are only a few regions where the long-term circulation has been convincingly measured (usually from the distribution of tracers), for example the north-eastward flow of the North Atlantic to the west of Ireland and Scotland, some aspects of flow in the North Sea, the north-eastward flow from Dover Strait into the North Sea and the mean flow northwards through the Irish Sea (see Figure 3.92). UK shelf-sea circulation is strongly affected by density-driven coastal currents and jets (Section 3.4.2.2) and by winds which can lead to significant changes and even a reversal of the general pattern for short periods.

Figure 3.95 shows time-mean circulation from the CS3X model used for UK operational storm-surge forecasting; it is two-dimensional (depth-integrated) with a resolution of 1/6° longitude by 1/9° latitude. The time-mean is from 1st September 1957 to 31st August 2002; the model is forced by ERA-40 (the duration and forcing are updates on *Charting Progress*). The scale picks out weak, interesting structures and strong, localised currents. However, the model cannot show density-driven flows, and lacks forcing by the oceanic steric height which gives poleward forcing at shelf-sea depths; this model's Celtic Sea time-mean flow to the south-east disagrees with other evidence.

Figure 3.95 Residual currents, for the period 1957 to 2002, from the CS3X model used for UK operational storm-surge forecasting. Speed is illustrated by shading (pixel-by-pixel, units 0.01 m/s, showing the speed at each grid cell). Note the bi-linear scale (0-10 in 0.5 units; 11-20 in 1 unit intervals). Streamlines show direction (where speed > 0.005 m/s). Courtesy of C. Wilson, NOC.



Seasonal circulation is shown in Figures 3.96 and 3.97. Figure 3.96 uses a 45-year run of the POLCOMS (3-D) model with a resolution of ~ 12 km (which has been tested by comparison with UK LOIS Shelf Edge Study drifters for 95/96; see for example, Burrows et al., 1999). Figure 3.97 shows three-month averages of near-surface currents in 2001, using POLCOMS (3-D) with a resolution of ~ 1.8 km and 32 vertical 'levels' (Holt and Proctor, 2008).

Figure 3.96 Seasonal mean current for the period 1960 to 2004 from the Atlantic Margin Model version of POLCOMS. (a) January-March; (b) April-June; (c) July-September; and (d) October-December. Courtesy of J. Holt, NOC.

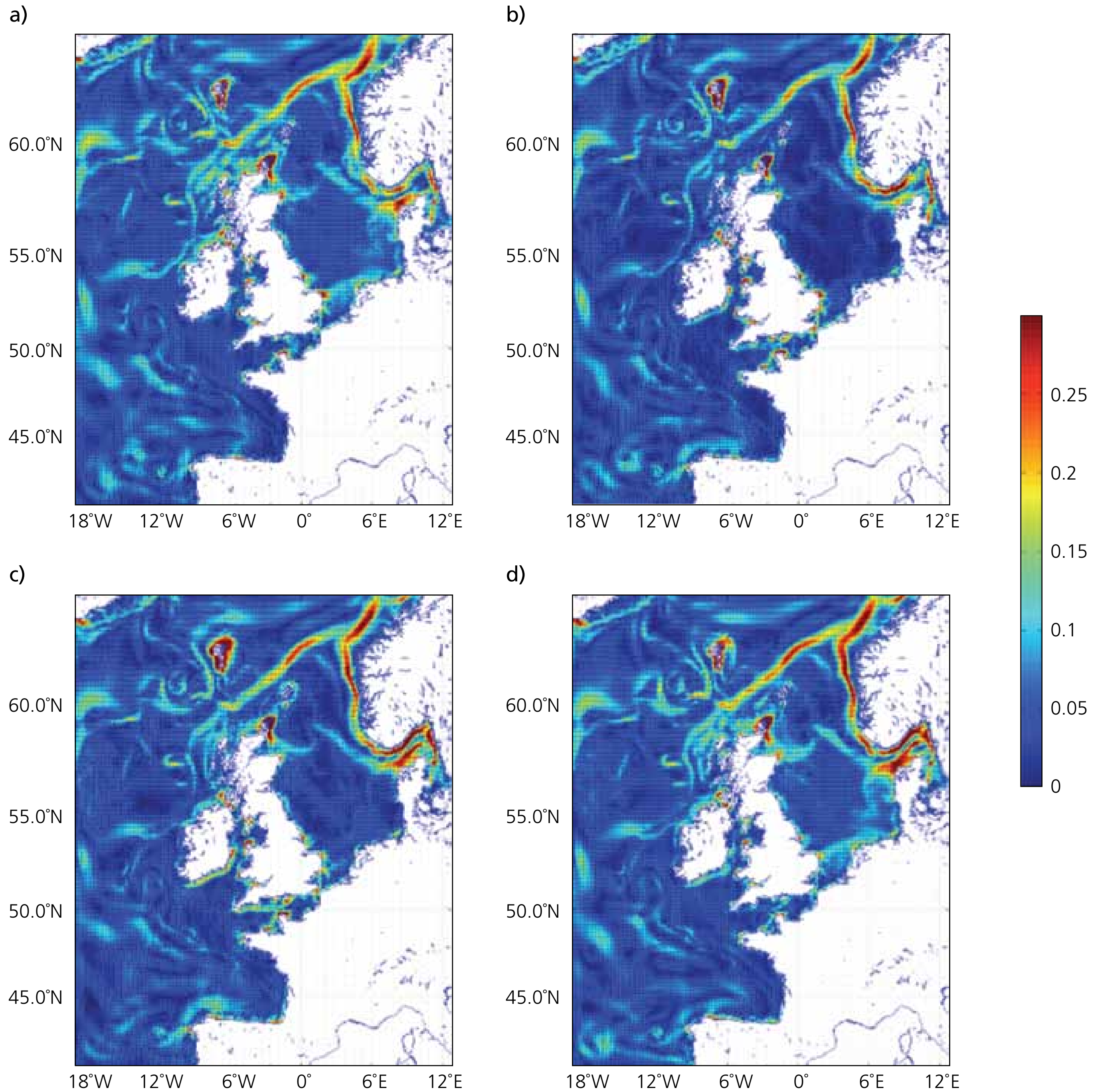
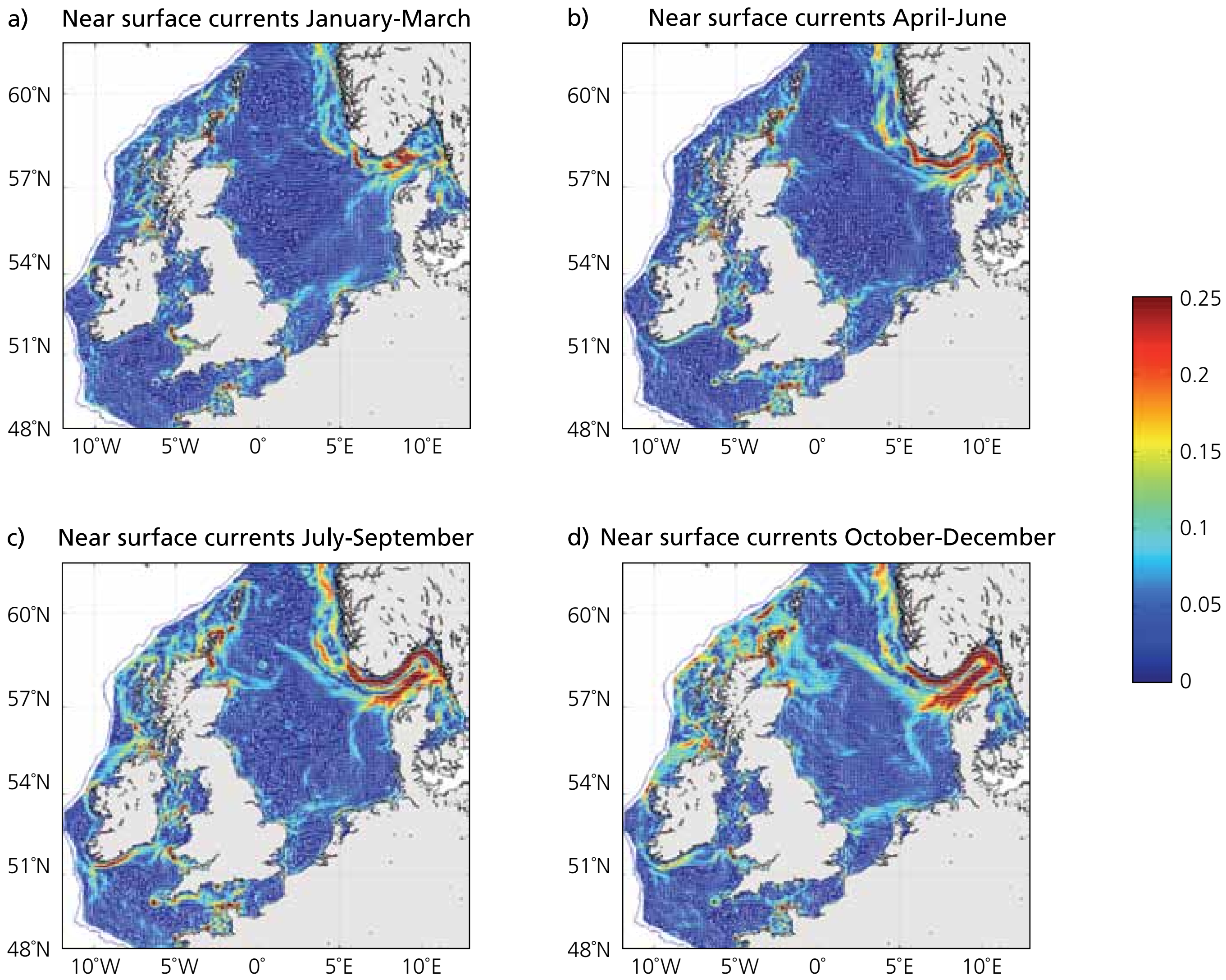


Figure 3.97 Modelled near-surface currents for 2001 with a ~ 1.8 km resolution version of POLCOMS. (a) January-March, (b) April-June, (c) July-September and (d) October-December respectively. Courtesy of J. Holt, NOC.



The figures show year-round mean flows locally around prominent headlands (and the Norwegian Coastal Current is present all year). The simulated mean flows are least in the period January to March. Other seasons show additional, typically filamentary flows, especially in the English Channel, Irish Sea and west and north of Scotland (and a stronger Norwegian Coastal Current). These flows are typically associated with the boundaries of seasonally-stratified waters (Hill et al., 2008).

Transports as found by 154 satellite tracked drifting buoys (mostly drogued at 20 to 30 m below the sea surface) between 1994 and 2005 are illustrated in Figure 3.98. These show some concentration and persistence near tidal-mixing fronts (see Section 3.2: Temperature and Salinity; also Hill et al., 2008) as reinforced by superposition of the summary tracks on modelled temperature gradients (Figure 3.99).

Figure 3.98 Summary of 154 tracks of drifting buoys (from Hill et al., 2008).

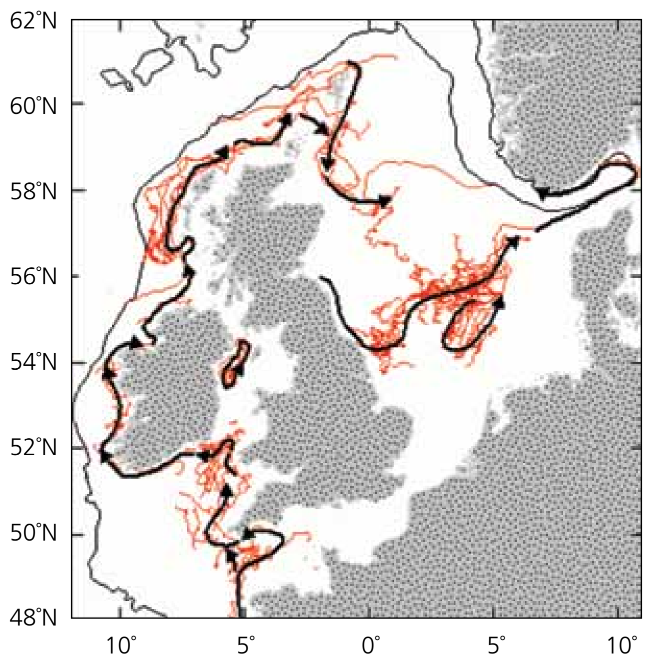
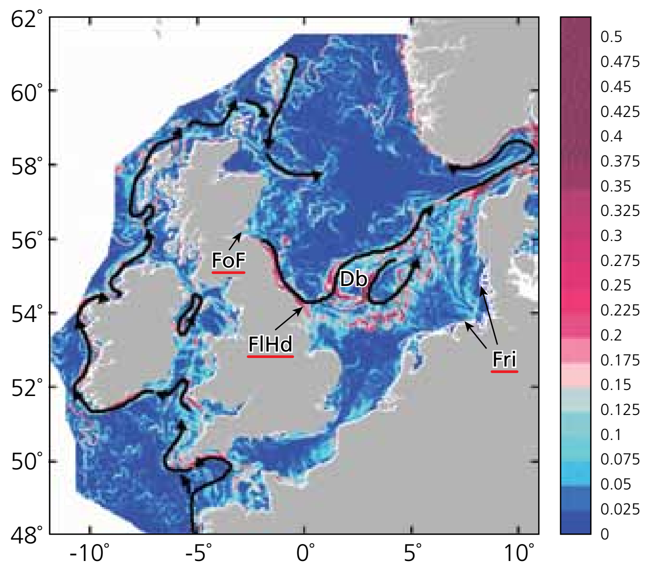


Figure 3.99 Horizontal near-bed temperature gradients (°C per km) from a 3-D model (Holt and Proctor, 2008) with observed summary drifter tracks overlaid (from Hill et al., 2008). Db – Dogger Bank, Fri – Frisian Islands, FlHd – Flamborough Head, FoF – Firth of Forth.



3.4.4.3 North Sea

More than 1 Sv of Atlantic-origin water flows into the northern North Sea, but does not penetrate great distances south. Much flows along the western slope of the Norwegian Trench, recirculates in the Skagerrak and flows out along the eastern side of the Trench underneath the Norwegian Coastal Current (NCC). A smaller inflow of mixed Atlantic and shelf water (including some from the Scottish Coastal Current, see Section 3.4.4.7) enters around Shetland and between Shetland and Orkney. However, most of this flow is guided eastwards to the Norwegian Trench by the ~ 100 m-depth contour; only a small part flows southwards along the coast of Scotland and England. Less than 10% of inflow to the North Sea enters via the English Channel. Thus most of the transport in the circulation is concentrated in the northern part of the North Sea and in the region of the Norwegian Trench; the one main outflow from the North Sea is ~ 1.3 to 1.8 Sv along the eastern side of the Norwegian Trench (Howarth, 2001). Holliday and Reid (2001) correlated increased oceanic inflows into the North Sea, in 1988 and 1998, positive NAO and strong northward transport of anomalously warm water in Rockall Trough (Section 3.4.4.7). Although there may be linkage by the slope current and/or local winds, however, causality was not determined.

Tides enter from the Atlantic Ocean, primarily north of Scotland, and progress anticlockwise around the North Sea. Thus tides form the dominant motion in the western and southern parts of the North Sea around to Denmark. Tidally-generated residual currents are relatively small, but are responsible for significant mean circulation in the western and southern parts, especially locally around sandbanks and other features. Wind is the dominant source of energy in the northern and eastern parts (Rodhe, 1998). Wind-driven currents are induced by mostly south-westerly and westerly winds. Surges travel anticlockwise like the tides: southwards along the UK coast and then north-eastwards along the coast of continental Europe. Density-driven currents are important locally in outflows from estuaries (and from the Baltic), and in association with features of summer stratification.

The resulting overall pattern of the mean circulation in the North Sea is broadly anticlockwise around the coasts, with weak and varied circulation in the centre. The mean coastal flow is southward past Scotland and England, into the Southern Bight where there are inputs of salty water through Dover Strait and of fresh water down the main rivers, and on to the German Bight, flowing northward past Denmark in the Jutland current to join the Norwegian Coastal Current in the Skagerrak (Rodhe, 1998; Howarth, 2001). However, this broadly anticlockwise circulation can be reversed by easterly winds (occurring mostly in spring and summer).

Most of the central and northern North Sea becomes thermally stratified during April/May, due to increasing solar heat input, with a well-mixed layer about 30 to 40 m deep (Howarth, 2001). In autumn, surface heat loss causes the surface mixed layer to cool and deepen until the bottom is reached in October-December. In contrast, tidal energy in southern and shallow coastal regions is strong enough to keep the water column well mixed most of the year. Some coastal regions stratify because of freshwater river discharge; the fresher water tends to form a thin surface layer, up to about 30 km wide, which stays close to the coast (Howarth, 2001). Off Sweden and Norway, the Baltic Sea outflow forms low-salinity water in the Norwegian Coastal Current, which is typically broader. A summer front in the central North Sea separates the thermally-stratified water to the north from the well-mixed water to the south. The front (Figure 3.99) is off Flamborough Head, bifurcates around Dogger Bank and passes to the north of the Frisian Islands (Howarth, 2001). Some fronts in the southern North Sea are related to freshwater from rivers, but most are tidal fronts (Rodhe, 1998).

An associated persistent and narrow (10 to 15 km) near-surface flow extends continuously for ~ 500 km along the ~ 40 m depth contour from the Firth of Forth to Dogger Bank (Figures 3.97 and 3.99). It is an example of flow associated with a strong bottom front bounding dense bottom water isolated below the summer thermocline (Section 3.4.2.2; Hill et al., 2008). This flow is the main component of the (otherwise very weak) summer circulation in the central North Sea.

The flushing time, for the complete renewal of the water, is about one to three years (Simpson, 1998). *Charting Progress* tabulates mean transport across sections in the North Sea for the period 1987 to 1993 from three numerical models (typical values 1 to 1.6 Sv into and out of the northern North Sea at 59.5° N).

3.4.4.4 English Channel and Celtic Sea, including the Bristol Channel

Along the English Channel, mean circulation is from west to east, driven by winds (prevailing south-westerlies), non-linear tides (due to strong tidal forcing from the Atlantic) and density currents. The latter are primarily due to freshwater discharge from rivers. Much of the Channel has strong tidal flow and is well mixed, however, a tidal mixing front occurs in the western Channel where the stratified waters bordering the Celtic Sea meet the well-mixed regime; summer time flows at the edge of the region are anticlockwise (i.e east to west). Net west-to-east flow in the bulk of the Channel has been modelled (Salomon and Breton, 1993; Salomon et al., 1993) and confirmed from distributions of radionuclides released from the nuclear fuel reprocessing plant at Cap de la Hague on the NW French coast (Guegueniat et al., 1995). Prandle et al. (1993a) estimated net flux north-eastwards through Dover Strait as 0.11 Sv. However, long-term net flow patterns are complex, including for example an anticlockwise gyre off Cap Gris Nez (Prandle and Player, 1993) and other gyres in bays, off headlands and around the Channel Islands (e.g. Mardell and Pingree, 1981; Pingree and Maddock, 1985; Salomon and Breton, 1993).

In the Celtic Sea, Pingree and le Cann (1989) analysed an extensive set of current meter data and found a generally weak mean circulation, albeit tidal currents are strong. During winter (November to April) the Celtic Sea is vertically mixed and residual circulation is largely controlled by wind forcing. In summer, most of the Celtic Sea has strong thermal stratification (where tidally-generated turbulence is insufficient to mix the solar heat input (near the surface) throughout the water column). Then summer circulation is dominated by anticlockwise jets associated with bottom fronts bounding a cold saline pool (Brown et al., 2003; Hill et al., 2008; see Figure 3.99). On the eastern side of St George's Channel, a jet transports water northwards from the mouth of the Bristol Channel towards the Irish Sea. Tides induce local circulation around the Scilly Isles (Pingree and Mardell, 1986).

In the Bristol Channel, tidal currents are strong but residual flows are weak and the estimated flushing time is 150 to 300 days (OSPAR, 2000). Prevailing south-westerly winds drive a flow northwards along the Cornish coast. Along the northern coast of the Bristol Channel, between Carmarthen Bay and Nash Point, flow is also into the Channel. As wind piles up water in the Channel, however, an adverse pressure gradient is created, driving a depth-mean flow westwards along the central axis of the Bristol Channel. This flow is then steered northward around St David's Head and into the Irish Sea. Density gradients also contribute to the weak circulation; when freshwater input is large, these flows are significantly enhanced, although no direct measurements have been made. There are local residual circulations: closed eddies, arising primarily as water flows past headlands, bays and islands; however, they contribute little to the overall mean circulation. As for the Celtic Sea there is flow across the mouth of the Channel at about 5° W.

3.4.4.5 Irish Sea

Surge- and density-driven currents both contribute significantly to the overall long-term mean circulation of the Irish Sea. Density-driven currents are particularly important in the eastern Irish Sea where the differences between the saline oceanic inflows and freshwater input from the Rivers Dee, Mersey, Ribble and Lune cause density changes in Liverpool Bay. The long-term effect in circulation offshore at the surface and onshore below is illustrated in Figures 3.100 and 3.101. These flows are strongest in winter and spring but can be overwhelmed during periods of strong winds.

The distribution of caesium-137 discharged from Sellafield has been used to infer the mean surface water circulation in the Irish Sea (Jefferies and Steele, 1989; Irish, 2003). The main input of water is from the Atlantic, flowing south to north through St. George's Channel. The general shape of the isopleths suggests that the main flow veers towards the Welsh coast as

Figure 3.100 Progressive vector diagrams from the full records of two ADCPs in Liverpool Bay, from 2.5 m above the seabed (blue) to 18.5 to 21.5 m above the seabed (black/grey). Site A shows the average for the period August 2002 to May 2008, while site B shows the average for the period April 2005 to June 2008. Courtesy of J. Howarth, National Oceanography Centre.

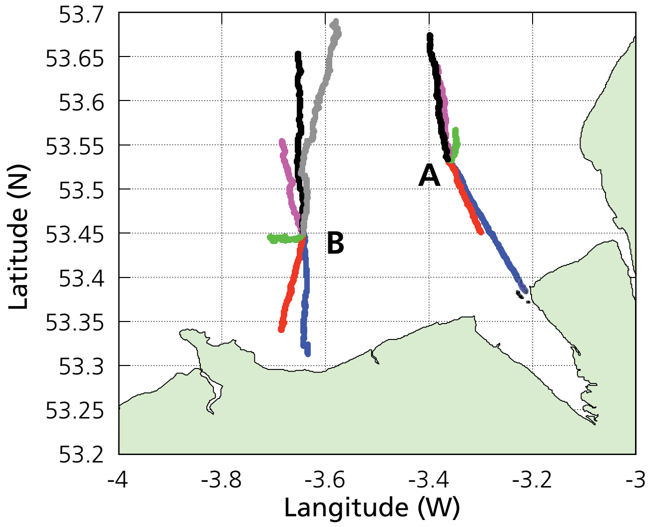
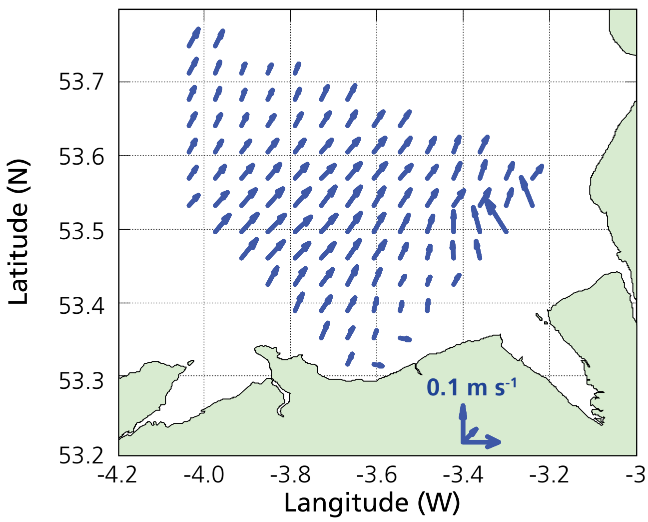


Figure 3.101 Mean near-surface currents from HF radar in Liverpool Bay for the period August 2005 to August 2008. Courtesy of J. Howarth, National Oceanography Centre.



it moves north, with a weaker flow, generally northward, to the west of the Isle of Man. A minor component of the flow enters the eastern Irish Sea to the north of Anglesey and moves anticlockwise around the Isle of Man before rejoining the main flow to exit through the North Channel. The overall flushing time for the Irish Sea as a whole is about one year (Knight and Howarth, 1999).

Most regions of the Irish Sea are continuously mixed because tidal currents are strong. However a deep basin region in the western Irish Sea (centred at 53°40' N, 5° W) and part of Cardigan Bay experience strong seasonal stratification in the summer and are separated from the well-mixed areas by tidal mixing fronts. In the western Irish Sea, a dome-shaped pool of cold water sits below the thermocline and is separated from surrounding waters by strong temperature fronts. These fronts drive strong narrow (~ 10 km) jets that dominate the circulation in the region during summer months, forming a closed circulation; the lack of through-flow enables material to remain in the region (Hill et al., 1997, 2008). Following the breakdown of stratification in autumn, the mean flow is then weakly northwards until the following spring.

Considerable changes in Irish Sea flow conditions are suggested by models. In order to obtain a reasonable model fit to observed caesium-137 concentrations, McKay and Baxter (1985) found that the coastal flow conditions from the NE Irish Sea to western Scottish coastal waters had changed considerably since 1977, with a further change in Irish Sea outflow during 1981. Jefferies and Steele (1989) had to infer a factor-of-two change in the Irish Sea circulation in the mid-1970s, doubling the flow rate out of the North Channel from the end of September 1976; they also inferred a change in flow during

1980/81, after which the flow pattern returned to that of 1977-1980. However, substantial transports can take place in one storm (more than 20% of the Irish Sea volume during two days in February 1994; Knight and Howarth, 1999) and affect the inference of longer-term flow from constituent distributions.

A direct link with the circulation of the Irish Sea and the NAO has not been established but it is reasonable to expect a degree of correlation. A positive NAO Index is associated with westerly (veering to north-westerly) winds over the Irish Sea, hence more frequent surges in the eastern Irish Sea and Liverpool Bay, enhancing the contribution of surge currents to the overall circulation. Changes in storm tracks may also modulate the circulation and flushing of the region.

3.4.4.6 Minches, west Scotland and Scottish continental shelf

Circulation on the shelf west of Scotland (the Scottish Coastal Current; SCC) is mainly northwards.

Tiree Passage currents have been measured since 1981 (see UK Directory of Marine Observing Systems; www.ukdmos.org). They are constrained by the Passage orientation (to the north-east) and narrowing (between Tiree and Mull) and are dominated by semi-diurnal tidal species (Figure 3.102 and Table 3.9). Hourly time series of northward and eastward velocity have been resolved into components *Ua* along the channel (057°T-237°T) and *Ux* across the channel. *Ua* exhibits much greater variance (standard deviation = 0.368 m/s) than *Ux* (standard deviation = 0.054 m/s), consistent with the alignment of the semi-major tidal ellipses along the channel (Table 3.9). *Ua* is offset from zero by a mean northward flow 0.108 m/s. This is a clear manifestation of the northward Scottish Coastal Current, and significantly larger than previous summer-only estimates; for example 0.108 m/s equates to 9.3 km/d, compared with previous values of 2 to 5 km/d (McKay et al., 1986; McCubbin et al., 2002). The corresponding mean volume flow through the Passage is calculated as 0.067 Sv, a similar value to that for the North Channel outflow, although this is not the same water. Caesium-137 studies (McKay et al., 1986) indicate that North Channel water is joined by Atlantic water; the average ratio in the Tiree Passage is approximately 3:1. The Atlantic water proportion in the Scottish Coastal Current increases steadily northwards to be a majority past Cape Wrath, where the Scottish Coastal Current total volume transport is correspondingly greater.

The tidal currents are almost rectilinear (semi-minor axis much smaller than the semi-major axis), aligned with the Tiree Passage (direction near 57°T) and strong (> 0.5 m/s at spring tides).

There is significant seasonality in *Ua* but not in *Ux*. After removing the tidal constituents listed in Table 3.9, the residual flow time series

Figure 3.102 Residual flow through Tiree Passage, resolved (positive) along 57°T. The tidal constituents listed in Table 3.9 have been removed, a low-pass filter applied (zero response for periods < 72 hours) and the time series sub-sampled at three days. Courtesy of M. Inall, Scottish Association for Marine Science.

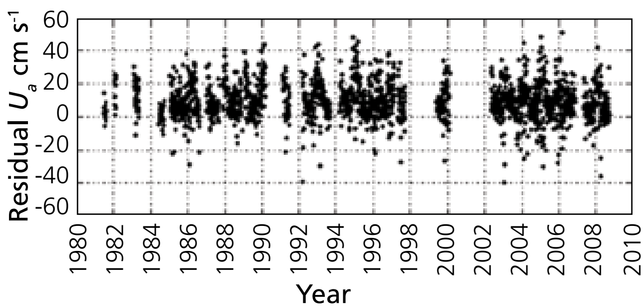


Table 3.9 11-constituent tidal analysis of the Tiree Passage current time series, 1981-2008.

Constituent		*Semi-major, cm/s*	*Semi-minor, cm/s*	*Orientation, degrees*	*Phase, degrees*
Fortnightly	MSF	0.619	0.167	56.96	284.61
Diurnal	O_1	3.722	0.367	62.43	137.46
	P_1	1.621	0.130	60.14	296.38
	K_1	5.614	0.303	59.92	301.59
Semi-diurnal	MU_2	0.420	0.050	54.50	328.60
	N_2	8.065	-0.075	56.98	80.15
	NU_2	1.672	-0.072	55.01	86.72
	M_2	41.855	0.194	57.03	104.14
	L_2	1.519	-0.085	54.75	123.53
	S_2	14.391	0.372	57.66	141.74
	K_2	5.341	0.106	58.97	155.80

clearly shows this seasonal variation in the along channel residual flow (Figure 3.102). Monthly mean residuals (not shown) display only one negative value throughout the entire time series, September 1984, when *Ua* = -2 mm/s. This flow reversal can be attributed to an anomalously strong and persistent northerly air flow during that month.

The direct and indirect influences of atmospheric pressure gradients on the residual flow through the Tiree Passage lead one to view the interannual flow variability in the context of the major mode of North Atlantic atmospheric interannual variability, the North Atlantic Oscillation (NAO). The NAO Index, after Hurrell (1995), and the residual transport through the Tiree Passage, similarly averaged over winter months December to March (DJFM), are presented in Figure 3.103. 35% of the variance in the along channel residual is explained by changes in the NAO (r = 0.59).

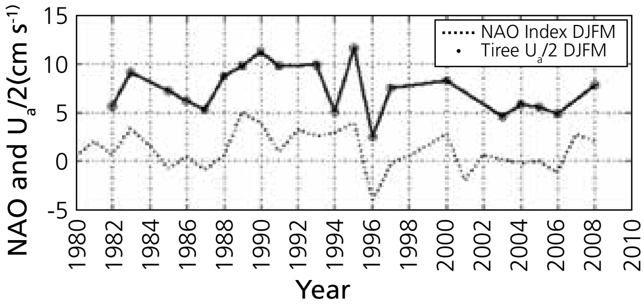
In summary, Tiree Passage currents are predominantly semi-diurnal, and constrained by the Passage. A strong northward residual varies significantly with season, correlated to winter storm activity. Interannual variation correlates significantly with the NAO index.

3.4.4.7 Continental shelf edge, including Rockall Trough and Faroe Shetland Channel

The steep bathymetry of the continental slope acts as a barrier between oceanic regions and the shelf sea systems, reducing the amount of water that can travel from the deeper waters of the North Atlantic into the shallower waters on the continental shelf. Nevertheless, wind forcing and tides enable some North Atlantic water to flow onto the Scottish shelf (and into the North Sea, between Orkney and Shetland and around Shetland) as well as along the slope into the Norwegian Trench.

Observations at the continental shelf edge indicate a poleward along-slope current, flowing along most sectors of the ocean-shelf boundary from Portugal to Norway (there is less evidence around Biscay). The flow is forced by the combined effect of steep topography and the

Figure 3.103 The December-to-March NAO Index and December-to-March-averaged along-channel residual flow from Tiree Passage. Positive flow is directed northwards through the Passage. Courtesy of M. Inall, Scottish Association for Marine Science.



mutual adjustment of shelf and oceanic regimes to meridional density gradients (Huthnance, 1984; Simpson, 1998), and is enhanced or modified by wind stress. The current is an important source of heat, nutrients and plankton to the waters around Scotland.

Currents and transports along the continental slope from the Celtic Sea to the Faroe Shetland Channel were summarised by Huthnance (1986). Estimated transports between the shelf break and the 2000 m depth contour (probably the great majority) were fairly consistently poleward in the range 1 to 2 Sv (1 Sv = 10^6 m^3/s) from the Celtic Sea to the Wyville-Thomson Ridge. Mean current speeds quoted are typically 0.05 to 0.2 m/s, but more variable than the transport as the flow may be locally 'squeezed' between depth contours. More recent information in the Celtic Sea region (Pingree and le Cann, 1989; Pingree et al., 1999; Huthnance et al., 2001) suggests some seasonality: weaker flow in spring and stronger flow in autumn.

West of Scotland, using detailed year-round measurements for 1995/96, Souza et al. (2001) found that the slope current at 56° to 57° N had a maximum mean flow of ~ 0.15 m/s, with greater flow variability in winter. In summer there was a maximum flow at about 200 m depth whereas in winter the flow was more nearly uniform in depth. The fastest mean flow was where water depth is 500 m or more, but in winter the mean flow was broader and extended onto the shelf. A mean transport of about 2 Sv is suggested by combining these measurements with tracked drogues (Burrows et al., 1999).

Holliday et al. (2000) and Holliday (2003a) calculated the mean transport though the Rockall Trough as 3.7 Sv, but the flow fluctuates on interannual timescales. There was unusually strong northward transport in the Trough during 1988/89 and 1998, peaking at 7.9 Sv in 1989 and 7.5 Sv in 1998. These values include the along-slope current and flow in the main width of Rockall Trough. The interannual fluctuations might be related to the position of boundaries between different North Atlantic water masses and hence the balance of inflows to Rockall Trough, but the ultimate cause is not known; there is no correlation with the NAO (Holliday et al., 2000, 2008).

At the Wyville-Thomson Ridge (near 60° N with typical depth 400 to 500 m) there is a complex exchange of flow. Some of the deeper slope current from the Hebrides slope is probably diverted to the north-west. However, the upper-slope current continues to the west Shetland slope (the Faroe-Shetland Channel). Here it is joined by a broader flow of warm, saline North Atlantic water across the Ridge from Rockall Trough. Further on, it is also joined by water that has circulated clockwise around the Faroe Islands to the Faroes side of the Faroe-Shetland Channel. These additions result in increased speeds (0.15 to 0.3 m/s or more) and increased transport along the west Shetland slope, on average about 4.5 Sv centred approximately over the 400 to 500 m isobath. Around Scotland, the slope current can be stronger in winter than in summer.

The concentrated flow at the shelf edge and the effective separation of the shelf and oceanic regimes by the topographically steered flow is illustrated by the behaviour of tracked drogues. Released into the narrow slope current, drogues have a strong tendency to remain in it and move rapidly along the slope, in contrast to those released on the shelf or in the oceanic regime, which show much more variable behaviour unless they are entrained into the slope current (Simpson, 1998; Burrows et al., 1999). *Charting Progress* includes a link to an animation of the along-slope current, as measured by tracked drogues.

3.4.5 What the evidence tells us about environmental status

The accumulation of observed data pertaining to the AMOC since the publication of *Charting Progress* (Defra et al., 2005) has led to a vociferous debate within the scientific community as to whether or not the AMOC is undergoing a significant slow-down. Considered in isolation, the series of ship-based estimates presented by Bryden et al. (2005) provides compelling evidence that there is a change underway and that the rate of this change is markedly greater than the gradual slow-down predicted for the 21st century by coupled climate models (Meehl et al., 2007). A number of considerations exist, however, which may lead to lower confidence in this assessment or, at the least, to highlight the need for further data and analysis.

First, high-frequency variability evident in the continuous mooring records now available raises the possibility that historical hydrographic sections of short duration may have sampled the background variability of the system, rather than a longer-term trend: the range of daily strengths in the first year's mooring data alone is 4 to 35 Sv, while the range of the five ship-based estimates spanning five decades is ~ 23 to ~ 15 Sv (however, the latter are sampled over six weeks, which may suppress some of the high-frequency variability).

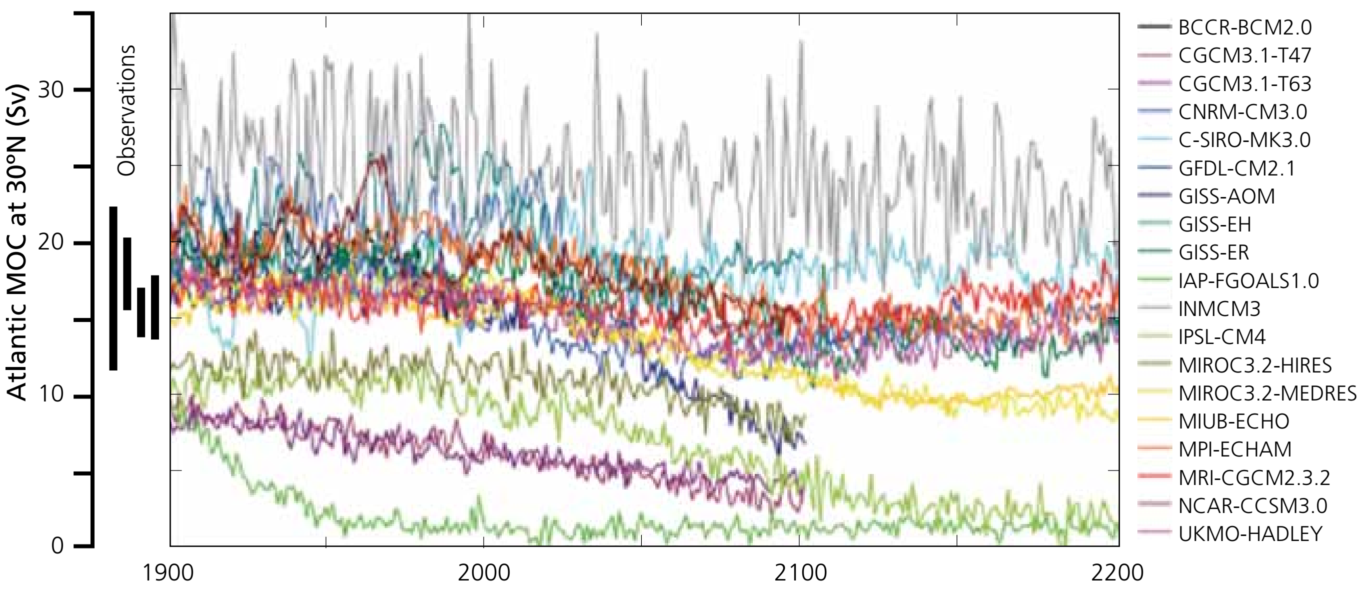
Second, a number of studies make use of an implied connection between the AMOC strength and patterns of Atlantic sea surface temperature (SST) anomalies to reconstruct past AMOC changes and to diagnose the present strength (e.g. Knight et al., 2005; Latif et al., 2006). These studies highlight the recent phase of warm North Atlantic SST anomalies as indicative of a relatively strong AMOC condition. However, these techniques and their associated conjectures depend critically on the anomaly pattern chosen to act as an AMOC proxy. For example, the anomaly index preferred by Latif et al. (2006) implies a sustained weakened AMOC phase from the 1920s to the 1970s which is entirely absent from the Knight et al. (2005) calculations.

Third, if the evidence presented at 26° N is representative of a full ocean-basin slow-down in the AMOC, then it is reasonable to ask why there is no lucid signal in Arctic-Subarctic transports. The evidence presented above shows variability but little by way of an overall trend, even in the longest records. This might be because the signal has yet to propagate internally within the overturning system, or because there is no bona-fide signal at all.

With respect to the future state of the AMOC, new co-ordinated climate-change modelling experiments were conducted for the Fourth IPCC (Intergovernmental Panel on Climate Change) Assessment Report (Meehl et al., 2007), indicating possible changes to the AMOC during the 21st century. In all plausible future greenhouse-gas emissions scenarios, the AMOC undergoes some weakening in most climate models. Figure 3.104 depicts the AMOC strength in 19 IPCC-class models under scenario A1B (medium greenhouse-gas emissions). The inter-model spread of strengths is large even during the observational period (i.e. the 20th century) although most models (apart from three or four) are able to reproduce strengths comparable with observed estimates of the AMOC strength (shown by black bars to the left of the vertical axis). Changes during the 21st century range from a 0% to a 50% decrease in simulated AMOC strength due to changes in the thermal properties and density structure of the Atlantic and Arctic Oceans.

These results lead the IPCC to conclude that a slow-down of the AMOC during the 21st century remains very likely (i.e. chance of occurrence > 90%). None of the models that maintain a realistic observational AMOC strength undergo a complete shutdown

Figure 3.104 Evolution of the Atlantic meridional overturning circulation (MOC) at 30°N in simulations with the suite of comprehensive coupled climate models (see HYPERLINK "ch8s8-2.html" \l "table-8-1"Table 8.1 for model details) from 1850 to 2100 using 20th Century Climate in Coupled Models (20C3M) simulations for 1850 to 1999 and the SRES A1B emissions scenario for 1999 to 2100. Some of the models continue the integration to year 2200 with the forcing held constant at the values of year 2100. Observationally based estimates of late-20th century MOC are shown as vertical bars on the left. Three simulations show a steady or rapid slow down of the MOC that is unrelated to the forcing; a few others have late-20th century simulated values that are inconsistent with observational estimates. Of the model simulations consistent with the late-20th century observational estimates, no simulation shows an increase in the MOC during the 21st century; reductions range from indistinguishable within the simulated natural variability to over 50% relative to the 1960 to 1990 mean; and none of the models projects an abrupt transition to an off state of the MOC. Adapted from Schmittner et al. (2005) with additions. From Meehl et al. (2007: figure 10.15, page 773).



before 2100. Hence the consensus is that a complete shutdown is very unlikely (i.e. chance of occurrence < 10%). However, there are uncertainties relating to these projections: in particular, if outflow from the Greenland Ice Sheet accelerates (not accounted for in most climate models), additional AMOC weakening may result.

It is important to remember that the cooling (and indeed reduced transport of salt) associated with any slow-down in the AMOC is accounted for in the IPCC climate change projections (e.g. Meehl et al., 2007). In other words, the reduction in heat transport related to any AMOC slowdown is 'competing' with the direct warming effects of anthropogenic climate change which continue to dominate. Thus UK waters are warming and this is projected to continue despite any counter-effect of AMOC slow-down.

In UK shelf seas, models and specific local measurements have confirmed current understanding of the variable forcing and space-time variability of currents and circulation. Factors include tides, winds and the density field (resulting from freshwater inputs and atmospheric exchanges) as elaborated in Section 3.4.2. In some locations (e.g. Tiree Passage) the relation to atmospheric forcing is manifested in a significant correlation with the NAO. In shallow areas, tidal and directly wind-driven currents on short time-scales tend to prevail; coastal currents from freshwater input give net transports. The large variability in space and time (on short and long scales in each case), together with knowledge of the variable factors, enables a confident statement that circulation is a derivative quantity and not showing a significant trend relative to shorter-term variations.

The summary table (Table 3.10) includes an assessment of trend but not status ('traffic-light') because (1) no accepted criteria apply for circulation giving significant risk of adverse effects; (2) the UK (government), or even the EU, cannot itself take measures to improve the status.

Circulation is subject to a wide range of natural variability on many time-scales. There is no reason to suppose that this variability or circulation intensity has changed significantly since *Charting Progress* for any present impact on the environment or human health. Local construction has the potential to introduce local changes and significant impacts on the spatial scale of the construction, such as in harbours and around wind turbine pylons. There is little basis to distinguish between CP2 Regions except in respect of such local activities.

Table 3.10 Summary assessment of trends.

Parameter	*CP2 Region*	*Key factors and impacts*	*What the evidence shows*	*Trend*	*Confidence in assessment*	*Forward look*
Circulation	1, 2, 3, 4, 5, 6, 7 (UK shelf-sea areas)	Climate change. Advects sea contents	Short-term variability, especially from tides and winds	Not determined	High (i.e. trend definitely not determined; shorter-term variability is greater)	Continued short-term variability
Circulation	8 (Deeper adjacent Atlantic)	Climate change. Advects sea contents	Short-term variability	Not determined	High (i.e. trend definitely not determined; shorter-term variability is greater)	Reduced AMOC

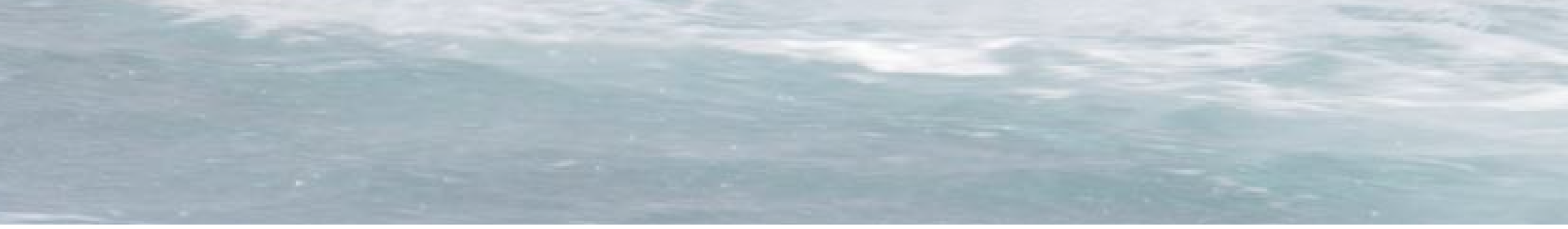
3.4.6 Forward look and need for further work

The influence of the Atlantic Meridional Overturning Circulation on NW European climate implies a pressing need to increase our understanding of the AMOC system, in particular its present status and sensitivity to change, as well as validating the coupled ocean-atmosphere climate models used to generate future predictions. Coverage and availability of observational data and monitoring capability are continually increasing, allowing limited assessment of the state of the AMOC. However, spatial and especially temporal coverage remains well short of that required to make any such assessment with high confidence. In particular, it is as yet impossible to ascertain with confidence whether or not the AMOC is undergoing change – or at what rate.

Some change, although not an abrupt collapse, can be expected this century, as indicated in climate model experiments, and such changes will be detectable, given sufficient time, by the array of monitoring equipment deployed in recent years. Any resulting effect on UK shelf-sea circulation is not yet predicted or resolvable in climate models, but is likely to be related most closely to any changes in the most adjacent along-slope flow and associated cross-slope fluxes.

The primary knowledge gap remains a lack of high-quality data sets of sufficient temporal length with which to elucidate climate-change signals from background variability. The RAPID-funded monitoring projects have recently acquired funding to extend observations until at least 2014, in order to assemble a continuous decade-long time series of AMOC strength. This extended record will enable clarification of interannual variability and will form the basis of a statistically significant time series with which to begin to comment on longer-term change. A research priority must be to ensure that supplemental measurements, especially at higher latitudes, are maintained simultaneously. Without the latter, it will not be possible to understand how changes in the AMOC are relayed from place to place – an understanding which, ultimately, will feed back into the monitoring strategy.

In UK shelf seas, current understanding of processes gives medium confidence in extrapolating from areas of specific process studies to comparable locations. There is also confidence in models to represent many processes. Challenges are still presented by (1) the large variability and random element in adjacent deeper-water flow impacting on the shelf and by (2) shorter-scale internal waves and their contribution to turbulence, hence stratification and associated depth-dependent flow. Measurements are still sparse relative to currents' large variability in space and time (on short and long scales in each case); reliance is placed on models for most distributional information. In view of the importance of currents to offshore operations and habitats, and of circulation to many species' lifecycles (for example), better understanding and prediction of short-term variability in circulation is needed. This entails further work on model validation and the development of observational networks. Circulation is strongly tied to the details of the atmospheric forcing. Predictions for future climate therefore depend on regional scenarios for which there is not yet confidence (e.g. regarding storm tracks and intensity). However, it seems unlikely that there will be large changes in rates of overall exchange and flushing in the coming decades.



3.5 Sea Level

3.5.1 Key points

i. Introduction

The coastal zone has changed considerably due to growing populations and increasing urbanization. In 1990, 23% of the world's population (1.2 billion people) were living within 100 km distance and 100 m elevation of the coast at densities three times the global average. Society is becoming increasingly vulnerable to sea level extremes as the storm surges of Hurricanes Katrina and Sidr have demonstrated. As UK populations rise, especially in the South-East in general and the Thames Estuary in particular, there are concerns that they are properly protected (www.environment-agency.gov.uk/te2100/). Sea level changes also have environmental consequences, with impacts on intertidal habitats and modifications to groundwater regimes. Rising sea levels imply more flooding and liability to erosion by waves, even if storm intensities do not increase.

ii. How has the assessment been undertaken?

The assessment is drawn from data, from the global and UK tide gauge networks and from international space missions, and from climate modelling. Most findings are available in the scientific literature and have been included in the periodic assessments by the Intergovernmental Panel on Climate Change (IPCC).

iii. Current and likely future status of sea level

Global mean sea level (MSL) is known to have risen by about 120 m between the peak of the last ice age around 20 000 years ago and approximately 6000 years ago. Global sea level rose by about 1.7 mm/y during the 20th century and the few long European records suggest slightly faster sea level rise in the 20th century than in the 19th century (Section 3.5.4.2.1). After adjusting for land movements, 'absolute' sea level around the UK coast has increased by about 1.4 mm/y during the 20th century; this is slightly lower than the 'global' estimate (Section 3.5.4.2.2). There were periods during the 20th century when rates were significantly greater or smaller than average. This includes the 1990s which experienced rates of sea level rise between 3 and 4 mm/y (Section 3.5.4.2.1).

UK sea level records indicate local short-term variations in the height and timing of the ocean tide, but no long-term trends which can be definitely attributed to oceanic rather than local causes. An exception appears to be data for Newlyn (a particularly long record and 'home' of Ordnance Survey Datum) which shows a long-term increase in mean tidal range. Most UK records do not present evidence for long-term changes in statistics of surges (non-tidal variations from mean sea level), including that from the UK's longest time series (from Liverpool since 1768). Similarly, long-term changes in extreme sea levels do not appear to exhibit significantly different long-term behaviour to that of mean levels (Section 3.5.4.2.3).

Global sea level is projected to rise in the 21st century by 0.18 to 0.59 m, plus an amount arising from the dynamic instability of ice sheets. Predictions for the UK itself are of comparable magnitude (Section 3.5.5.1).

iv. What has driven change?

Sea level has varied for the last few million years on timescales of the order of 100 000 years in response to the growth and retreat of the great polar ice sheets. Superimposed on these variations of sea level of the order of ± 100 m are changes of the order of 0.1 to 0.2 m associated with shorter timescale climatic events such as the Little Ice Age. More recently, there has been concern that anthropogenically induced climate change has resulted in enhanced sea level rise. These issues are addressed in detail in the IPCC Scientific Assessments (Church et al., 2001; Bindoff et al., 2007).

v. What are the uncertainties?

The main research uncertainties are concerned with accounting for observed sea level changes, including the present inability of climate models to simulate the magnitudes and timings of sea level changes. Monitoring and modelling need to be enhanced so as to provide greater confidence that sea level changes are understood and that models are capable of predicting future change, thereby contributing to more effective coastal planning and management (e.g. Church et al., 2007).

vi. Forward look

The scientific community is attempting to put in place a coherent monitoring system for sea level (altimetry, space gravity, tide gauges) and related parameters (mass balance of ice sheets and glaciers, temperature and salinity of the ocean, hydrological data sets) which, together with improved modelling, will increase understanding.

3.5.2 Introduction

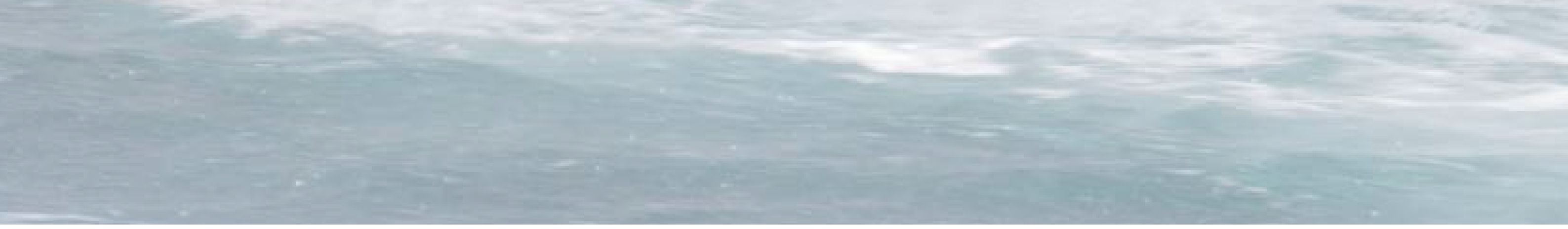
Sea level is the combination of tidal level, surge level, mean sea level, waves and their respective interactions. Any change in mean sea level affects sea level directly but also modifies tide, surge and wave propagation and dissipation by changing the water depth. Increased depth gives longer tidal wavelength and hence the tidal pattern is shifted, resulting in an increase in tidal levels at some locations and a decrease at others. The generation and dissipation of surges partly depends on water depth because the wind-stress effect increases in importance as the depth decreases. Increased depth in coastal waters leads to greater wave energy transmitted to the shoreline.

As the most serious coastal flooding events in the UK are caused by a combination of high tides, surges and waves, any overall long-term increases in tidal level, surge or waves will increase the frequency of coastal flooding, especially if a rise in mean sea level provides a higher ‘base-line’ for them. Rising sea level will tend (1) to reduce the width of beaches and intertidal rocky shores, particularly where high waters are contained by hard structures or rock, and (2) to increase nearshore wave energy and hence coastal erosion.

A rise in sea level can cause the loss of saltmarsh and mudflats, thus having an effect on intertidal ecosystems. Also, the impact of sea level rise on a changing wave climate, and hence on water turbidity, will have an impact in the nearshore environment. For example, stronger currents and less light will generally inhibit biological growth.

3.5.2.1 Tidal levels

Tidal levels are the regular motions of the sea generated by astronomical forcing due to the varying gravitational attraction of the Moon and the Sun. UK waters respond strongly to tidal forcing at the Atlantic Ocean boundary and the presence of the British Isles creates a series of more or less separate basins in which the tidal wave, incident from the deep ocean, is reflected and amplified to varying degrees. The general response in UK waters is to amplify semi-diurnal components of the tide; the largest are the M_2 (two tides per lunar day) and S_2 (two



tides per solar day) constituents. Irish Sea and Bristol Channel responses are particularly strong; their respective tidal ranges average 8 m and 11.5 m at spring tides (when M_2 and S_2 add constructively).

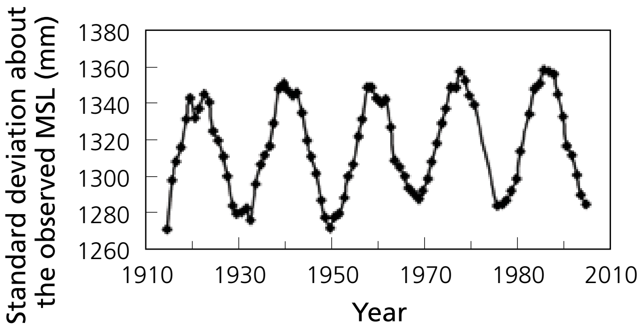
Animation of surface elevations through a tidal cycle in Liverpool Bay; available at: http://chartingprogress.defra.gov.uk/resources/.

Semi-diurnal lunar tides increase and decrease in range over an 18.6 year period (Figure 3.105) because of changes in the lunar declination cycle (i.e. the plane of the moon's orbit varies relative to the plane of the earth's orbit around the sun). When the declinations are small the semi-diurnal tides are bigger. The most recent minimum in the amplitude of semi-diurnal tides was in 2006, with the next maximum to be expected in 2015. The theoretical modulations in amplitude are 3.7% about the mean, but in practice because of shallow water effects, around the UK the modulations vary locally and tend to be smaller at around 2%.

3.5.2.2 Surge levels

Surge levels are caused by changes in atmospheric pressure and wind stress (the latter proportional to the square of the wind speed), and can result in water levels above ('positive surge') or below ('negative surge') those of the normal tide. Large positive surges are usually experienced in shallow water areas as the effect of wind-stress increases in importance as depth decreases. The pressure effect is independent of depth. 'Storm surges' are generated by major meteorological disturbances, and can result in sea level changes of up to several metres lasting for a few hours to days, depending upon the storm duration, water depth and the extent of the storm.

Figure 3.105 Standard deviation in the observed sea level variations at Newlyn, showing the 18.6 year modulations. Standard deviation is larger when the semidiurnal tides have a larger amplitude. Courtesy of David Pugh, from Pugh (2004).



Animation of surge levels around UK for 8-9 November 2007 storm (surge) event; available at: http://chartingprogress.defra.gov.uk/resources/.

3.5.2.3 Mean sea level

Mean sea level (MSL) is defined as the height of the sea averaged over a period of time, such as a month or year, long enough that short-term fluctuations caused by waves and tides are largely removed. Daily, monthly, seasonal and annual variations in MSL include contributions from tides and surges and are due to changes in atmospheric pressure, wind stress, density and/or water circulation. Around the UK, MSL changes seasonally by approximately 10 cm (range), and is at a maximum in late summer.

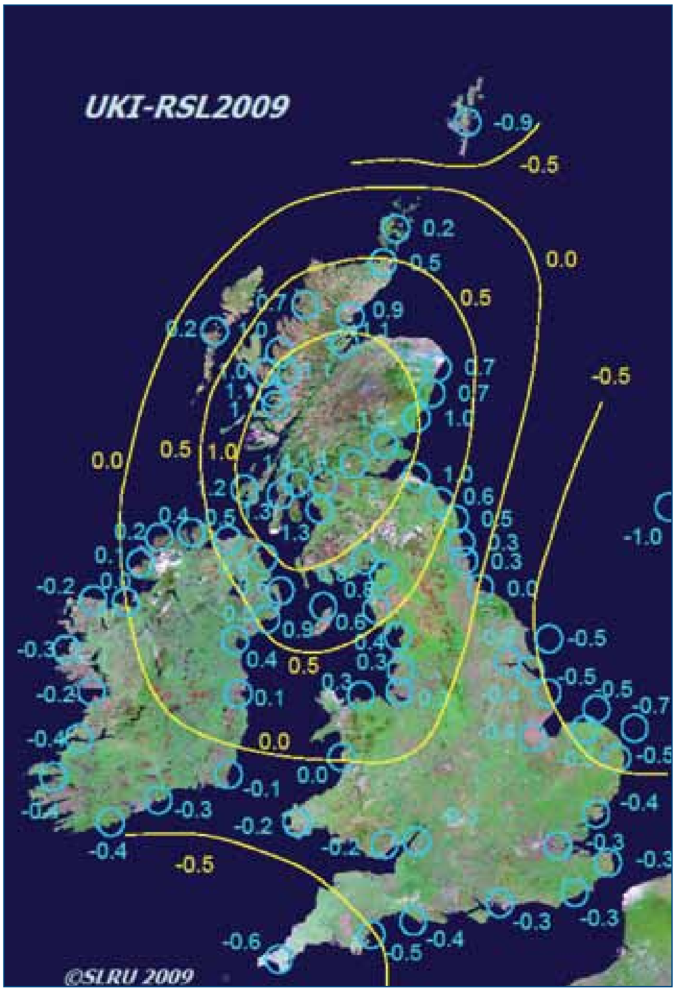
Changes in MSL measured by coastal tide gauges contain contributions both from real changes in ocean level and from vertical movements of the land upon which the gauges are situated. Therefore MSL 'relative' to the land also depends on local land movements, such as those resulting from local sediment compaction or groundwater extraction, or regional land movements, such as those resulting from 'glacial isostatic adjustment' (Figure 3.106). Thus a determination of 'absolute' sea level needs to have land movements removed from the measured 'relative' MSL signal. Long-term (or 'secular') changes in absolute MSL are mainly caused by changes in water volume, such as an increase caused by melting of grounded ice or the thermal expansion of seawater due to heating.

Although small compared to the Fennoscandian and Laurentian ice sheets that covered northern Europe and America respectively during the last ice age, the ice sheet that covered much of the British Isles was large enough for glacial isostatic adjustment processes to have produced contrasting relative MSL changes at different locations (Figure 3.106). Maximum relative land uplift, around 1.6 mm/y, occurs in central and western Scotland and maximum subsidence, around 1.2 mm/y, in southwest England (Shennan and Horton, 2002), although such large rates of subsidence in the south-west are disputed (Gehrels, 2006). Sediment consolidation, arising from compaction as the sediment accumulates and from land drainage, increases the subsidence in areas with thick sequences of Holocene sediments, with an average effect equivalent to an extra ~ 0.2 mm/y land subsidence (Shennan and Horton, 2002).

3.5.2.4 Measuring and monitoring sea level

Descriptions of global and national sea level networks can be found at the Permanent Service for Mean Sea Level (PSMSL) (www.pol.ac.uk/psmsl) and Global Sea Level Observing System (GLOSS) (www.gloss-sealevel.org) websites, while methods for monitoring sea level are explained on the PSMSL training web pages. Figure 3.107 shows a sub-set of the locations reporting to PSMSL, Figure 3.108 shows the GLOSS core network and Figure 3.109 shows the UK National (or 'A-class') network.

Figure 3.106 Current rate of relative land- and sea-level change in the British Isles in mm/y, showing relative land uplift as positive and relative subsidence as negative. Image is ~900 × 1300 km. Courtesy of the NASA Scientific Data Purchase Program and I. Shennan (Durham).



Links to the UK National Network and other monitoring networks and data sets follow here. Online search interfaces for catalogues and inventories are maintained by the Marine Environmental Data and Information Network (MEDIN) at: www.oceannet.org. This includes a UK tide gauge and sea level catalogue for tide

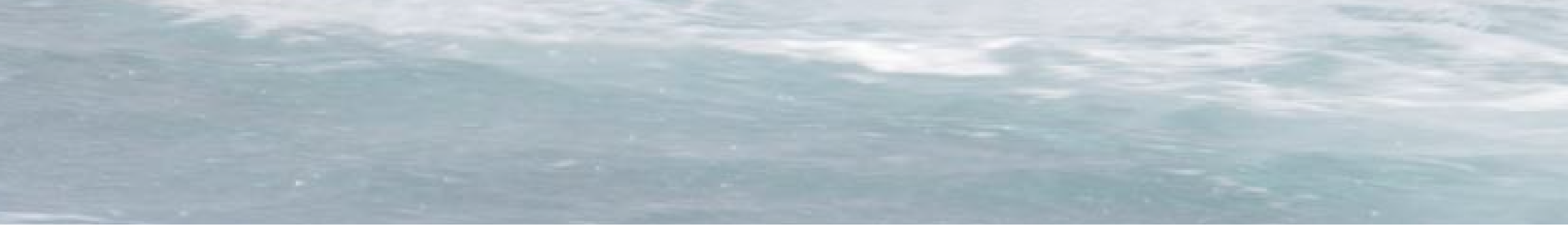


Figure 3.107 Stations with at least 40 years of consistently-levelled data in the Permanent Service for Mean Sea Level. Source: PSMSL website (www.psmsl.org).

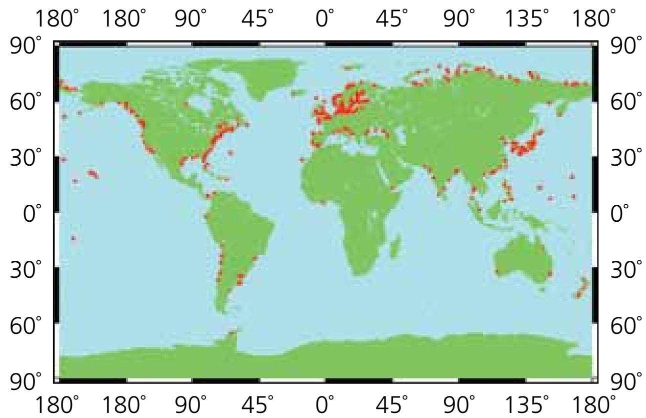


Figure 3.108 Priority sites which make up the core network of the Global Sea Level Observing System. Source: GLOSS website (www.gloss-sealevel.org).

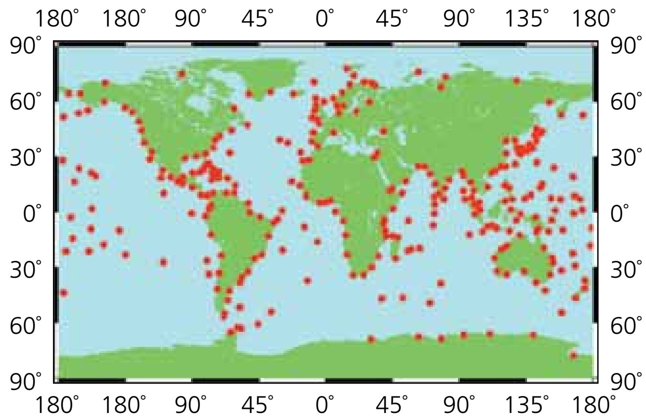


Figure 3.109 UK tide gauge network. Source: www.pol.ac.uk/ntslf/.

gauges currently operating in the UK: www.oceannet.org/online_data_by_theme/tide_and_sea_level/tide_tool/. Many UK monitoring networks are also included in the UK Directory of Marine Observing Systems (www.ukdmos.org). Other individual links include:

- UK National Tide Gauge Network – www.pol.ac.uk/ntslf/
- Channel Coastal Observatory: Regional Coastal Monitoring Programme www.channelcoast.org
- Irish Sea Observatory http://cobs.pol.ac.uk
- Environment Agency Anglian Region Strategic Coastal Monitoring Programme Shoreline Monitoring Data Catalogue available from EA Anglian Region, Kingfisher House, Goldhay Way, Orton Goldhay, Peterborough PE2 5ZR.

- Permanent Service for Mean Sea Level (PSMSL) www.pol.ac.uk/psmsl/
- Satellite missions www.aviso.oceanobs.com/, http://podaac.jpl.nasa.gov/

3.5.3 Progress since *Charting Progress*

Real-time data provision, in addition to the delayed-mode data needed for scientific research, is now becoming increasingly encouraged for several reasons: the data become available to a wide range of new users in 'operational oceanography' including coastal protection; faults can be identified faster, leading to more accurate delayed-mode data-sets in the long term. Some sea level stations are now 'multi-hazard' sites, with sensors specifically designed for the high rate recording needed for tsunami monitoring. Sensors for tsunami applications have been installed at Lerwick, Holyhead and Newlyn alongside the existing UK National Network gauges.

3.5.4 Presentation of the evidence

3.5.4.1 Trends in tides and surges

Woodworth et al. (1991) pointed to long-term changes in tidal range at many UK sites. However, it was not easy to identify the causes. One site at which there appeared to be a convincing change in mean tidal range of approximately 0.4 mm/y was Newlyn. Araújo at al. (2002) subsequently studied sea level records from Newlyn, Portsmouth and Dover and showed local short-term variations in amplitude and phase of tidal constituents but no convincing long-term trends. However, in a later analysis concentrating on Newlyn (Araújo and Pugh, 2008), the authors concluded that the main identifiable trends included a 0.17 mm/y change in M_2 amplitude (i.e. half the reported rate in mean tidal range of Woodworth et al., 1991).

Araújo et al. (2002) also showed that there is no evidence of a change in surge levels at Newlyn since the 1920s, Portsmouth since the 1960s or Dover since the 1960s; and that there was no correlation between the Newlyn surge levels and the NAO. Araújo and Pugh (2008) again found no evidence for trends in surge levels (non-tidal residuals) at Newlyn. Analysis of surge statistics from the Liverpool tide gauge data has shown that there were no major long-term changes in surges over the extended period 1768 to 1999 (Woodworth and Blackman, 2002).

3.5.4.2 Trends in Mean Sea Level

3.5.4.2.1 Global MSL trends

Since the last ice age around 20 000 years ago, MSL has risen worldwide by about 120 m. A consensus seems to have been achieved that the 20th century rise in global sea level was closer to 2 mm/y than 1 mm/y; values around 1.7 mm/y have been obtained recently for the past century (Church and White, 2006) or past half-century (Church et al., 2004; Holgate and Woodworth, 2004). However, the rate of change was far from constant, with an acceleration around 1920-1930, a deceleration after 1960, and a relatively recent acceleration in the 1990s (e.g. Douglas, 2008; Woodworth et al., 2009a). Since the early 1990s, the scientific community has had access to precise radar altimeter data from satellites, notably from the TOPEX/Poseidon and Jason missions. The fast rise in the latter period was observed not only by tide gauges but also by those satellite altimetry missions (Beckley et al., 2007). A longer-term acceleration appears to have taken place between the 18th and 19th centuries into the 20th century, based on the small number of available long European tide gauge records (Woodworth, 1999; Jevrejeva et al., 2008) and on complementary data from saltmarshes (e.g. Gehrels et al., 2006).

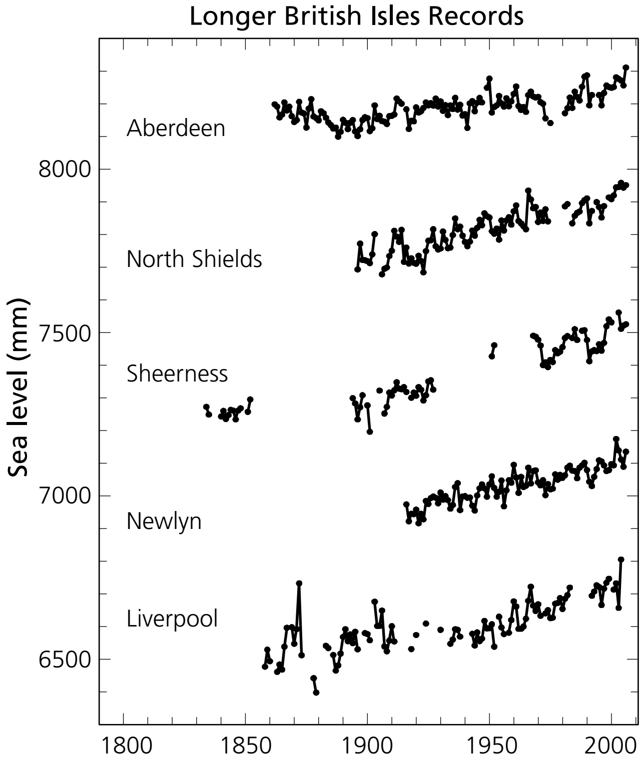
MSL is often described as an 'integrator parameter', providing an integration of many climate-change related processes, i.e. global warming leading to oceanic thermal expansion, glacier and ice-cap melt, modifications to hydrological exchanges between land and ocean etc. Consequently, if MSL is changing, it points to major changes in one or more of the drivers of that change. Ultimately, anthropogenic climate change appears to be the fundamental issue, although the attribution of the 'budget' of sea level rise remains a major research question (Bindoff et al., 2007).

3.5.4.2.2 UK MSL Trends

Woodworth et al. (2009b) have recently provided updated tabulations of UK sea level trends. They suggest a pattern of UK sea level change as measured at the coast, comprising effects of land movements and oceanic changes. Vertical land movements are spatially variable (primarily north-south but also locally); they can be inferred from geological (e.g. Shennan and Horton, 2002) or geodetic data (e.g. Teferle et al., 2006, 2009), together with geodynamic modelling (Milne et al., 2006). Sea level variations due to changes in the ocean are largely spatially-coherent. This overall picture is inevitably approximate, but consistency in interpretation of the different data sets (tide gauge, geological, geodetic) appears to have risen as their temporal and spatial coverage has increased.

Figure 3.110 shows the data from the five longest UK MSL records: at Aberdeen, North Shields, Sheerness, Newlyn and Liverpool. The records from Aberdeen and Liverpool are composites from more than one gauge at each site, whereas the others are from gauges where there is a full benchmark datum history, and therefore in the Revised Local Reference (RLR) subset of the PSMSL. All five stations show a positive trend (i.e. an increase) in MSL, relative to the land, as do the majority of the other shorter records (Woodworth et al., 2009b).

Figure 3.110 Mean sea level at Aberdeen, North Shields, Sheerness, Newlyn and Liverpool. Courtesy of Permanent Service for Mean Sea Level.



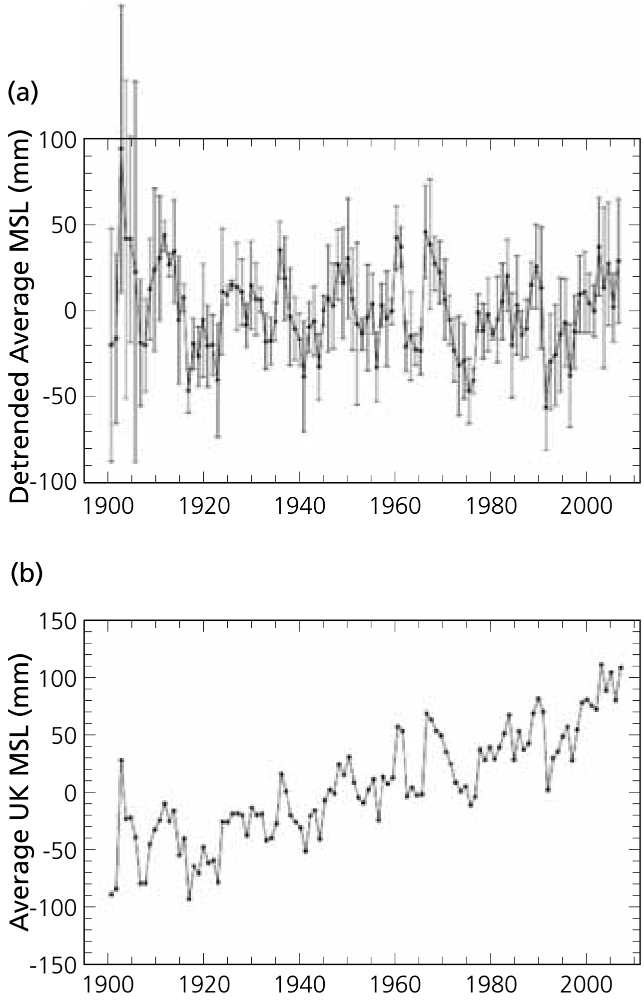
The five long time-series can be used to provide a representative sampling of sea level change around the coastline. First, the long-term rate of MSL change can be removed from each record, thereby removing contributions from vertical land movements and (linear) climate-change-associated sea level rise. Then, MSL values from the five records can be averaged to obtain an index of UK interannual and decadal MSL variability, with the index having zero trend by construction, as shown in Figure 3.111a. (The standard deviation of the five values about their mean in any one year is typically 25 mm except for the early years of the 20th century when it is several times larger.)

Finally, a UK-average value for the long-term climate-change component of MSL change, estimated from a comparison of tide gauge and geological rates at a number of UK sites, can be added to make the time series in Figure 3.111b. This average long-term trend is estimated as 1.4 ± 0.2 mm/y which is slightly lower than the 1.7 mm/y consensus value for global sea level change over a similar period.

The 14 cm rise during the 20th century has significantly increased (as much as doubled) the risk of flooding since 1901 at many locations around the UK coastline. In terms of risk, the most affected regions are those (1) where relative land movement due to glacio-isostatic rebound is adverse, such as the south (as opposed to Scotland), or (2) where extreme levels increase only slightly with return period. If sea level rises faster in the 21st century, as suggested by the IPCC Fourth Assessment Report (Meehl et al., 2007), there could be greater risk to the coastal environment and infrastructure.

The interannual changes in the UK sea level index (Figure 3.111a) must be related to changes in local meteorological forcing (storm surges) and to oceanographic changes in shelf and nearby deep-ocean circulation. The 1970s dip exceeds any direct steric effect of the North Atlantic 'Great Salinity Anomaly' that passed the UK in that period; it might reflect a change in North Atlantic gyral circulation (Woodworth, 1987) as is also suggested by the opposite (rising) trend of US east-coast sea levels in the early 1970s; such speculation needs to be tested by numerical modelling of the period.

Figure 3.111 British Isles sea level index. (a) Each record has been de-trended over the period 1921-1990 and the de-trended values averaged. The figure also shows standard deviations of de-trended values about the average. (b) UK-average time-series for long-term climate-change component of MSL change. Source: Woodworth et al. (2009b).



The index shows a dip in the early 1990s that is as deep as the 1970s dip and others before. Similar interannual and decadal variability of sea level is observed at stations along the adjacent European coastline (Woodworth et al., 2009b).

3.5.4.2.3 Changes in extreme high and low sea levels

Newlyn and Aberdeen are at opposite ends of the UK and have some of the longer data sets of hourly (or 15-minute) sea level data. The small red and blue dots in Figure 3.112 for Newlyn show the time series of annual 99 and 1 percentile levels respectively (i.e. the levels which sea level exceeds 1% and 99% of the time) with the long-term average for each series set to zero. The use of 99 and 1 percentiles is sometimes preferred over the choice of the annual maximum and minimum water levels (i.e. 100 and 0 percentiles respectively) as they provide a description of change in high and low water characteristics without the greater variability inherent in the true extremes.

The long-term rising trend in 99 and 1 percentile is 2.2 and 1.8 mm/y, compared to 2.1 mm/y for median sea level. Trends for the extremes are more difficult to calculate because of the greater variability in their records. Those for high and low extreme levels are 2.2 and 1.3 mm/y. The slightly greater increase in height of high waters compared to low waters is considered to be a consequence of increasing local tidal amplitudes (see Araújo and Pugh, 2008). However, otherwise it is not possible to assign convincingly different long-term behaviour to the extremes than to mean levels. Indeed, Woodworth and Blackman (2004) demonstrated that trends in high water extremes measured over several decades at most locations tend to follow the corresponding trends in mean sea level.

Figure 3.113 shows similar data for Aberdeen, indicating positive trends of 1.9 and 1.3 mm/y for the 99 and 1 percentiles for the period shown, compared to 1.3 mm/y for the median

Figure 3.112 The 99 and 1 percentiles of sea level each year at Newlyn, together with the measured extreme high and low waters. The large red and blue dots show the annual maximum and minimum water levels relative to the long-term means for the 99 and 1 percentiles. Courtesy of NOC

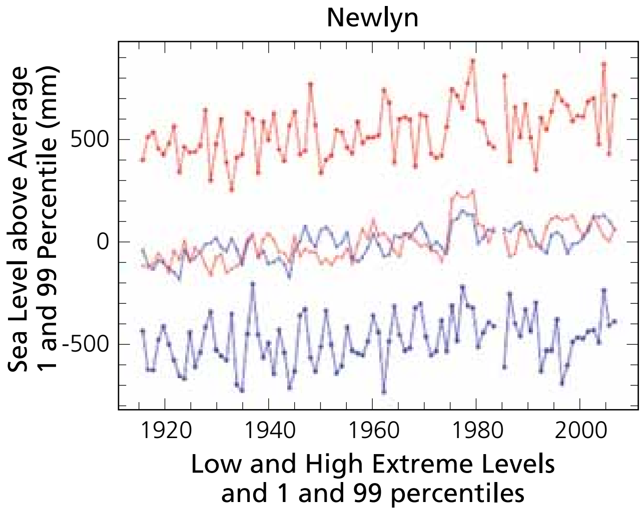
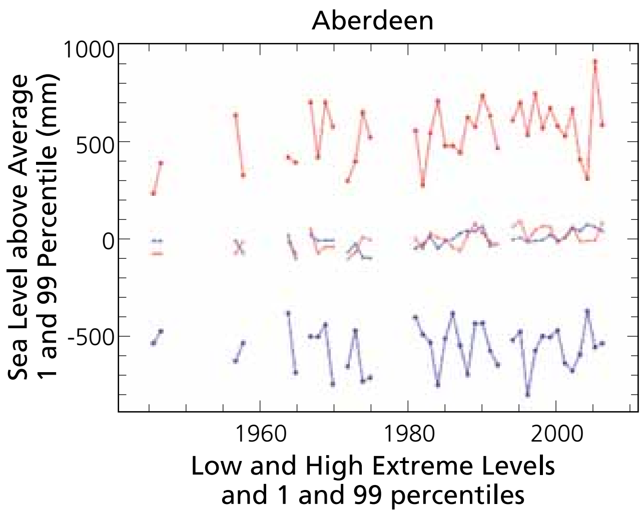


Figure 3.113 The 99 and 1 percentiles of sea level each year at Aberdeen, together with the measured extreme high and low waters. The large red and blue dots show the annual maximum and minimum water levels relative to the long-term means for the 99 and 1 percentiles. Courtesy of NOC



percentile. High and low extremes indicate trends of 3.8 and 0.0 mm/y but are based on very noisy time series.

3.5.4.3 Mean sea level and the North Atlantic Oscillation

Winter-mean (December to March) monthly MSL and the NAO Index (Jones et al., 1997) are significantly correlated over much of the NW European shelf (Wakelin et al., 2003). There is a clear spatial pattern in the correlation, with strongly positive (> 0.8) values in the northeast (e.g. German Bight) and strongly negative (< -0.7) in the south (e.g. Western Approaches). This is consistent with a positive NAO Index corresponding to anomalously low (high) atmospheric pressure in the north (south) leading to a hydrostatic increase (decrease) in the sea level due to direct pressure changes (the inverse barometer effect). The sensitivity of the sea level to the NAO is strongest in the southern North Sea, where most of the sensitivity is present also in the non-hydrostatic component of sea level, i.e. that due to changing wind stress. The rest of the North Sea has a correlation of > 0.3; around the north and east coasts of Scotland the correlation exceeds 0.6. For most of the rest of the shelf, the correlations are below the level of significance.

Wakelin et al. (2003) also showed that the relationship varies with time; sea level for the period 1909-1954 shows less correlation with the NAO than that for the period 1955-2000. There was an increase in correlation between the periods 1959-1979 and 1980-2000 for the North Sea. Sea level pressure anomalies related to the NAO were located further eastwards during the latter period (Hilmer and Jung, 2000), thus increasing the associated westerly winds and wind-induced sea level.

3.5.4.4 The North Atlantic Oscillation and extreme water levels

The role of the NAO in effecting changes in winter extreme high and low waters and storm surges in UK waters was investigated by Woodworth et al. (2007) with the use of a depth-averaged tide+surge numerical model. Spatial patterns of correlation of extreme high and low waters (extreme still water sea levels) with the NAO index are similar to those of median or mean sea level studied previously (Wakelin et al., 2003). Likewise, spatial patterns of correlations of extreme high and low and median surge with the NAO Index are similar to the corresponding extreme sea level patterns. Suggestions were made as to which properties of surges (frequency, duration, magnitude) are linked most closely to NAO variability. Several climate models suggest higher (more positive) average values of NAO Index during the next 100 years. However, the impact on the UK coastline in terms of increased flood risk should be low (aside from other consequences of climate change such as a global sea level rise) if the existing relationships between extreme high waters and NAO Index are maintained. The shallow waters of the eastern North Sea (i.e. the German Bight) will receive a much greater impact due to the NAO than will the UK.

3.5.5 What the evidence tells us about environmental status

Sea level is rising globally and around the UK. Differences in rate as seen at the coast may be caused by land movement and by altered circulation in the coastal or open ocean. Nevertheless, a rise at the coast is found all around the UK. There are periods when rates are significantly larger or smaller than average. The 1990s experienced fast sea level rise of 3 to 4 mm/y.

Tidal constituents (amplitude and phase) show no long-term trends which can be unambiguously assigned to oceanic causes. However, Newlyn appears to be an exception with a long-term increase in mean tidal range. Most UK records do not present evidence for long-term changes in statistics of surges (non-tidal variations from mean level). Thus long-term changes in extreme sea levels largely follow the long-term behaviour of mean levels.

3.5.5.1 Projected UK 21st century sea level rise

The following is based on a review of the IPCC Fourth Assessment Report (AR4) by Church et al. (2008) from which more details may be obtained.

The IPCC Third Assessment Report (TAR) of 2001 (Church et al., 2001) projected a global averaged sea level rise of between 0.2 and 0.7 m between 1990 and 2100 using the full range of IPCC greenhouse gas scenarios and a range of climate models. When an additional uncertainty for land-ice changes was included, the full range of projected sea level rise was 0.09 to 0.88 m.

In the subsequent UKCIP02 study, the climate modelling was based on a smaller set of models from the Hadley Centre and only four emissions scenarios (Hulme et al., 2002). Nevertheless, the range of likely global sea level rise (by 2080 in this case) was similar to that proposed by the IPCC TAR. The UKCIP study noted that large regional variations in sea level rise predictions exist in all models, and between models, such that predictions could not be provided reliably for the NE Atlantic alone. Consequently, global-average values of sea level rise were employed, modified by estimates of UK vertical land movement.

For the IPCC AR4 (Meehl et al., 2007), the range of sea level projections, using a larger range of models, was 0.18 to 0.59 m (90% confidence limits) over the period from 1980-1999 to 2090-2099. The largest contribution was from ocean thermal expansion with the next largest contribution from glaciers and ice caps. However, there is increasing concern about the stability of ice sheets (e.g. see Church et al., 2008, for details). Recognizing this deficiency, the IPCC AR4 increased the upper limit of the projected sea level rise by 0.1 to 0.2 m above that projected by the models, implying an overall range of projected sea level rise of 0.18 to 0.79 m. It is unclear what confidence intervals to ascribe to this range given the ice sheet uncertainties. Note that the IPCC AR4 also stated that ...*larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise*.

While the 2001 and 2007 IPCC projections are somewhat different in how they treat ice- sheet uncertainties and the confidence limits quoted, a comparison (Church et al., 2008: fig.6) shows that the ranges of projected rises are similar, except that the lower limit of the projections has been raised from 0.09 m in the IPCC TAR to 0.18 m in the IPCC AR4.

Despite the additional allowance for ice-sheet uncertainties, a number of scientists remain concerned that the ice-sheet contributions in particular in the IPCC AR4 may have been underestimated, and they adopt more of a phenomenological approach to estimating future sea level rise. For example, Rahmstorf (2007) developed a simple statistical model that related 20th century surface-temperature change to 20th century sea level change. Using this relationship and projected surface-temperature increases, he estimated that 21st century sea level rise might exceed the IPCC projections and be as much as 1.4 m. Holgate et al. (2007) raised concerns that Rahmstorf's model is too simplistic and may not adequately represent future change.

Similar conclusions, that the IPCC AR4 sea level rise projections may have been underestimated, have been based on analysis of longer-term temperature and sea level information (e.g. Grinsted et al., 2010). Concern remains as to the low physics content of some of these parameterisations. Nevertheless, the concern that the IPCC sea level projections may be biased too low has been reinforced by a comparison of observed and projected sea level rise from 1990 to the present. For this period, observed sea level has been rising more rapidly than the central range of the IPCC (TAR and AR4) model projections and is at the very upper end of the IPCC TAR projections (Holgate and Woodworth, 2004; Rahmstorf et al. 2007), again indicating that one or more of the model contributions to sea level rise may be underestimated.

In the recent UK Climate Projections (UKCP09) marine report (Lowe et al., 2009), sea level rise projections for the UK amounted to approximately 80 cm by 2095 for the London area and high emissions scenarios, and lower values for other areas and scenarios. These findings are not materially different from the earlier studies. However, a useful 'High++' high-end coastal flooding concept was also introduced, which indicated levels (93 to 190 cm) to engineers which lie above best estimates of uncertainty for 21st century sea level rise.

3.5.5.2 Status

The summary table (Table 3.11) includes an assessment of trend but not status ('traffic-light') because (1) no accepted criteria apply for sea levels giving significant risk of adverse effects; and (2) the UK (Government), or even the EU, cannot itself take measures to improve the status.

Sea level is rising. Changes since pre-industrial times are moderate, O(0.2 m), and have taken place relatively slowly, facilitating adaptation. However, the rate is forecast to increase (as a rise of 0.18 to 0.79 m or perhaps more in the 21st century), making adaptation more difficult (for marine species or as managed by humans). In particular, 'coastal squeeze' – reduction in the aggregate area of beaches and intertidal rocky

Table 3.11 Summary assessment of trends.

Parameter	*CP2 Region*	*Key factors and impacts*	*What the evidence shows*	*Trend*	*Confidence in assessment*	*Forward look*
Sea Level	1-5 (North Sea, Channel, Celtic Sea, Irish Sea)	Climate, geology. Affects local communities (flood risk)	Interannual/decadal MSL-variability superimposed on long-term trends. Changes in extreme sea levels largely follow MSL changes	Upward	High	Faster rise
Sea Level	6-7 (Scottish shelf seas)	Climate, geology. Affects local communities (flood risk)	Interannual/decadal MSL-variability superimposed on long-term trends. Changes in extreme sea levels largely follow MSL changes	Upward slowly	High	Faster rise
Sea Level	8 (adjacent N Atlantic)	Climate		Upward	High	Faster rise

shores – is likely unless compensatory measures are taken. There is some basis to distinguish between CP2 Regions in that rates are modulated by land movement which increases apparent sea level rise in the south and presently (but probably not in future) nearly negates it in the north-west.

3.5.6 Forward look and need for further work

Globally, the observed rate of sea level rise has not been well accounted for by the main contributing factors; thermal expansion of the ocean, melting of land-based ice, hydrological exchanges between land and water and land movements. However, now that the world has much better instrumented monitoring networks, both in space and *in situ*, the discrepancies between observations and understanding of the reasons for sea level change are beginning to decrease. These uncertainties translate to some extent into uncertain projections of future sea level rise. There is scope for looking at the distribution of sea level rise observed from space (altimetry and gravity) in addition to *in situ* methods (tide gauges and geological techniques). These studies are known as 'fingerprinting' and diagnose the origins of sea level change from its spatial variations. Such studies are necessarily complicated by any uneven distribution of measurements, especially by the *in situ* methods.

The distribution of UK tide gauges has been the subject of long consideration and is probably dense enough relative to the scale of sea level variations apart from local land movements. They need to be maintained along with accurate geodetic control (at present with GPS moderated by absolute gravity) to distinguish vertical land movements from geocentric (Earth centred) sea level changes within the tide gauge records.

3.6 Waves

3.6.1 Key points

i. Introduction

Waves affect marine operations (e.g. transport, fishing, offshore industry) and coastal communities; they can cause coastal erosion (contributing to flood risk) and structural damage. They influence stratification and enhance air-sea fluxes; in shallow waters they cause near-bed currents and suspend sediment, so affecting nearshore and benthic habitats, communities and demersal fish. Waves occur in all regions but decrease in shallower water (Section 3.6.2).

ii. How has the assessment been undertaken?

The assessment is in terms of characteristic forms of variability and some estimation of trends from regular wave measurements. No common baseline is possible. There are data from satellite altimetry, automatic weather stations on moored buoys and lightships, offshore and many nearshore sites. Modelling for wave prediction, forecasts and state estimation is well-developed (Section 3.6.2).

iii. Current and likely future status of waves

- Wave heights in winter (when largest) increased through the 1970s and 1980s, as shown by data: in the NE Atlantic (significant increase between the 1960s and early 1990s); in the North Sea (increase from 1973 to the mid-1990s); at Seven Stones off Land's End (increase of about 0.02 m/y over 25 years to 1988). However, recent trends are not clear and may depend on region; some series appear to show a decrease. Year-to-year variability is such that there is no clear longer-term trend and no clear change since *Charting Progress* (Defra et al., 2005) (Section 3.6.4.6).
- Winter wave heights correlate significantly with the North Atlantic Oscillation Index (a measure of the strength of westerly winds at UK latitudes), in the west and the Irish Sea; the correlation is particularly strong in the north west (Section 3.6.4.7).
- In very shallow waters (e.g. near coasts) trends are reduced; wave heights are limited by water depth (as waves break) (Section 3.6.4.5); however, if sea levels (raised by climate change) increase depths nearshore, then larger waves may approach the shore.
- Climate change may affect storminess, storm tracks and hence wave heights. Some climate models suggest more frequent very severe storms but there is little confidence in predicted changes of wave heights (Section 3.6.5).

iv. What has driven change?

Waves are directly driven by winds, modified by currents and shallow sea-floor topography, and can thus be affected locally by man-made structures (Section 3.6.2).

v. What are the uncertainties?

Interannual variability introduces uncertainty in estimating longer-term trends, especially in recent years with little clear trend. Locally, waves are strongly affected by local conditions and wider-area projections may not apply directly. Future projections in UK waters are very sensitive to climate model scenarios for storms, themselves uncertain (being sensitive to competing influences) (Section 3.6.5).

vi. Forward look

There will be a continuing need for the recently enhanced monitoring network. Models will (as now) be important for forecasting and state assessment. Management is limited to mitigating impacts and to affecting wave climate locally on the scale of any (possibly 'soft') engineering. Waves are a possible source of renewable energy (Section 3.6.6).

3.6.2 Introduction

The wave climate can be considered as comprising: (1) the long-term mean climate, (2) the annual or seasonal cycle, (3) non-seasonal variability (within-year and interannual). In UK waters, wave climate is strongly seasonal: mean wave heights peak around January, with a high risk of high monthly-mean wave heights and extreme wave heights from October to March. Interannual variability in monthly mean wave heights is large, particularly from December to March, the months primarily associated with the North Atlantic Oscillation (NAO). The NAO Index is a measure of a mean atmospheric pressure difference between the Azores (or Gibraltar) and Iceland (e.g. Jones et al., 1997).

The height of offshore waves depends on the strength of the wind, its duration and the 'fetch' (i.e. the distance) over which the wind has acted on the ocean surface. Waves approaching the UK coastline can be generated locally, in the NE Atlantic, in the NW Atlantic and even in the South Atlantic (with implications for forecasting; also extensive generation is associated with long waves which can affect the seabed down to 200 m). Waves at the coast are influenced by local water depth and by the nature of the seabed: waves can be reduced through dissipation by a broad gently-shoaling beach, a rough seabed nearshore or offshore shoals (banks). Conversely, raised sea level can decrease such dissipation of waves arriving at the coast and so increase coastal wave heights.

High waves are a risk to platforms and pipelines, and may disrupt routine marine operations (e.g. fishing, transport). Estimates of likely extreme waves are essential for the design of ships and offshore structures such as oil rigs. Waves are also a possible source of renewable energy. At the coastline, waves contribute to flood risk as a factor in total sea level through wave setup and overtopping; especially, they often exert the greatest forces and potentially cause structural damage and coastal erosion. Thus waves can affect coastal development and communities, especially on exposed coasts facing the Atlantic. Larger waves can damage seawalls and lead to increased rates of erosion of soft coastlines such as the glacial till cliffs in East Anglia and Yorkshire. The most serious coastal flooding events are often caused by a combination of high tides, storm surges and wave damage to coastal defences and other structures.

Waves are particularly effective (1) as agents of surface mixing, influencing stratification and enhancing air-sea fluxes of all quantities; and (2) at suspending sediment through their thin high-shear bottom boundary layer (if their currents extend to the seabed). Hence they affect nearshore and benthic communities and demersal fish.

Wave measurements before about 1955 were relatively crude. In the 1960s and 1970s, the National Institute of Oceanography equipped some lightships around the coast with wave-recorders that used acceleration and pressure fluctuations to provide information on wave heights and periods (but not directions). The recorders were typically only deployed at each site for 1 to 2 years, the main exception being

Seven Stones LV, which provides one of the longest wave records from UK waters. Wave-following buoys using accelerometers replaced pressure-type wave recorders; by the late 1970s most wave recording was being carried out using such wave buoys. More recently, several instruments for measuring waves have been developed, including directional wave buoys, downward-looking lasers and HF radar. The satellite altimeter is particularly good for climate studies, providing global coverage. Tucker and Pitt (2001) described wave-measuring instruments in detail.

Descriptions of the monitoring networks that regularly measure waves can be found on the UKDMOS website (www.ukdmos.org). There are data from satellite altimetry, Marine Automatic Weather Stations (MAWS) on moored buoys and lightships, WaveNet offshore locations, and many nearshore sites especially around the south of England. Modelling for wave prediction, forecasts and subsequent estimation is well-developed. The main limitations are (1) in areas of strong currents which can affect wave propagation; models are formulated but lack much good data for validation; and (2) nearshore where waves may vary greatly on short scales owing to topography which is often not known well enough.

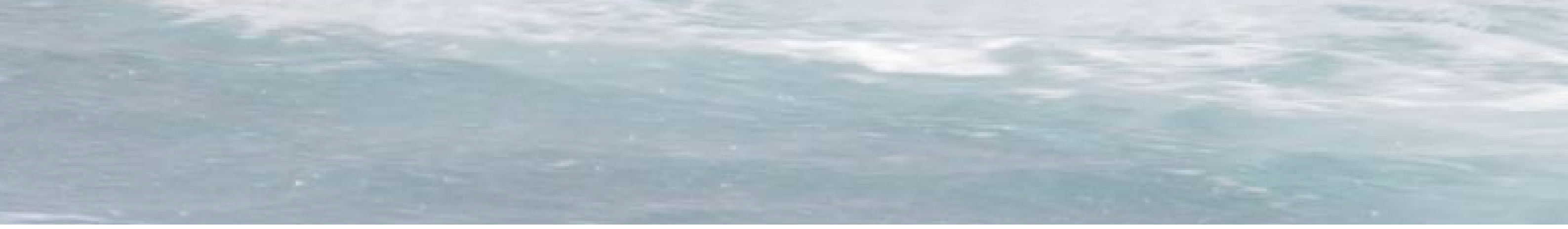
3.6.3 Progress since *Charting Progress*

The MAWS network now includes eleven moored buoys, nine of which are in open-ocean locations mostly 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). There are also Light Vessels equipped with automated marine sensors (Seven Stones, Channel, Greenwich, Sandettie and F3). Two North Sea moored buoys (K16 and K17) which contributed data to *Charting Progress* have been taken out of service. The longest (Seven Stones) spans 46 years, albeit with gaps.

The Strategic Regional Coastal Monitoring Programmes of England have developed a coastal wave network around the south of England with nearshore measurements at about 20 locations from Herne Bay (north Kent) to Minehead (Bristol Channel). Wave buoys deployed around Scotland in late 2008 and early 2009 (with funding from the Environment Agency and the Scottish Environment Protection Agency) form Scottish WaveNet and are planned to last up to five years. The buoys are south-west of Mull, west of South Uist, in the Moray Firth, just off Aberdeen (run by the University of Aberdeen) and in the Firth of Forth (Isle of May). A wave buoy just west of Orkney is operated by the European Marine Energy Centre. Buoys are planned in the North Channel/Clyde Sea and south of Galloway.

The longest periods of wave measurements, at consistent locations around the UK, are believed to be as follows (updating Law et al., 2003): coastal wave data – off North Kent (1979–1998 off Whitstable, 1996 to present off Herne Bay); Tees Bay (1988–present); Perranporth (1975–1986; resumed 2007); offshore wave data – Seven Stones Light Vessel (1962–1988 and 1995 to present); Forties Field (1974–present); Frigg QP (1979–present); Ekofisk Field (1980–present). Nevertheless, the density of wave measurements remains rather sparse relative to the short distances on which waves can vary, especially near complex coastlines.

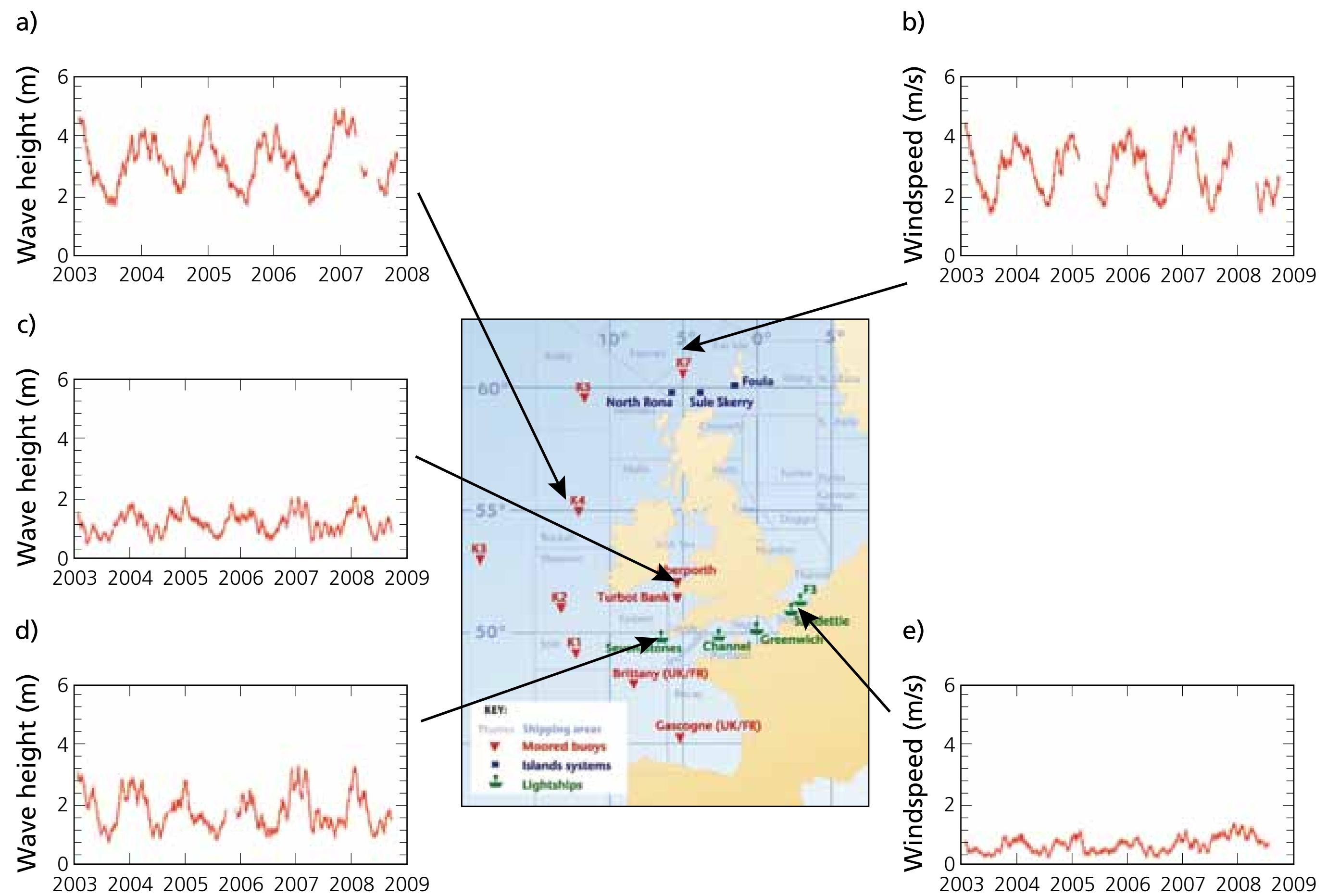
Wave predictions and forecasts continue to be made routinely by the Met Office, and several research groups have continued to develop shallow-water wave modelling to improve the representation of (two-way) wave-current



interaction, dissipation and effects of nearshore topography. In some nearshore locations, lidar has been used to update local bathymetry. X-band radar has also been developed as a potential means to monitor bathymetry quasi-continuously over coastal areas within range (a few kilometres; Bell, 1999).

Figure 3.114 shows significant wave height as measured from a selection of the Met Office MAWS network of buoys and Light Vessels. (Significant wave height, H_S, is approximately the average peak-trough height of the highest third of the waves.) The data are quality controlled and filtered using a running-boxcar 30-day mean. The figure shows largest wave heights in the north and west (exceeding those at Seven Stones), a decrease to the somewhat less exposed southern Irish Sea (off Aberporth) and a big reduction in the southern-most North Sea. Here (Sandettie) long waves from the open ocean have largely dissipated in shallow water; moreover, the fetch is limited for the directions of frequent wind occurrence. The wave heights are strongly seasonal with mid-winter maxima, but there is significant month-to-month and interannual variability. There is no clear trend for the limited period 2003 to 2008 (Section 3.6.4.6 discusses longer-term trends).

Figure 3.114 Significant wave height (m) at (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) Sandettie at 51° 06'N, 1° 48'E. Data from Moored Automatic Weather Stations, courtesy of the Met Office.



3.6.4 Presentation of the evidence

3.6.4.1 Mean wave climate and seasonal variability

Estimates of significant wave height (H_S) obtained from May 1992 to September 2007 from satellite altimeters on ERS-1, ERS-2, Envisat, Geosat Follow-On, Jason-1 and Topex (from the SOS 'Wavsat' database) have been used to obtain the description given below of the wave climate in the areas around the UK shown in Figure 3.115. The H_S values were calibrated by comparing altimeter values with those from US National Data Buoy Center buoys when the altimeters passed within 100 km of them.

3.6.4.2 Annual cycle

The dominant cycle in H_S is the annual cycle, although in UK waters this explains only 25% to 35% of the variance in H_S in open Atlantic waters and less than 15% in more sheltered locations. A simple sine curve describes most of this annual cycle. Higher frequency components of 2 and 3 cycles per year – although accounting for less than 1% of the variance – are generally statistically significant, and incorporating these higher cycles in the analysis does appear to give a better representation of average conditions than the annual sine curve. For example, the annual sine curve fitted to the data from 59°–60° N, 6°–8° W peaks in January whereas the three-cycle fit peaks in February – as do the monthly means from the data. Figure 3.115 shows the average H_S throughout the year obtained by fitting these three cycles to the data.

3.6.4.3 Variation about the annual cycle

There is considerable variation in H_S about this mean curve. Indications of this variability are shown in Figure 3.115 which also shows the 25 percentile and 75 percentile curves – wave heights can be expected to be below the 25 percentile a quarter of the time and above the 75 percentile a quarter of the time.

The figures differ from *Charting Progress*: primarily due to fitting 1, 2 and 3 cycles per year instead of just the annual cycle; also due to using more recent data and to fitting individual H_S values rather than mean values but these make relatively small differences. The quartiles are from fitting $\log(H_S)$ so that residuals are more nearly normally-distributed, assuming that the statistical distribution of H_S is lognormal.

3.6.4.4 Between-year variability

There are considerable interannual variations in wave climate, especially between winter months; some winters are much stormier than others. Some of this variability in the winter months can be linked to the NAO Index (see Section 3.6.4.7). MAWS locations K4, K7 and Aberporth possibly show a small increase for the period 2003–2007 relative to the previous period illustrated in *Charting Progress*, but interannual variability is greater.

3.6.4.5 Distribution

Wave-heights are greatest in the most exposed waters of the north and west, and decrease markedly into the North Sea and southward therein, into the Irish Sea and into the English Channel. These trends may be attributed to shallow water dissipation of long waves from the open ocean and limited fetch for the directions of frequent wind occurrence. In the Irish Sea, Channel and southern North Sea, the relative magnitude of the seasonal cycle also decreases. Timing of the maximum in the seasonal cycle ranges from mid-January in the south to the end of January or early February in the north. These trends show in data from buoys off eastern and especially southern England. Figures 3.116

Figure 3.115 Means and quartiles (25% and 75%) of significant wave height throughout the year determined from altimeter data for the period 1992 to 2007. The location boxes indicate the areas from which the data were taken. Courtesy of D.J.T. Carter and SOS Ltd.

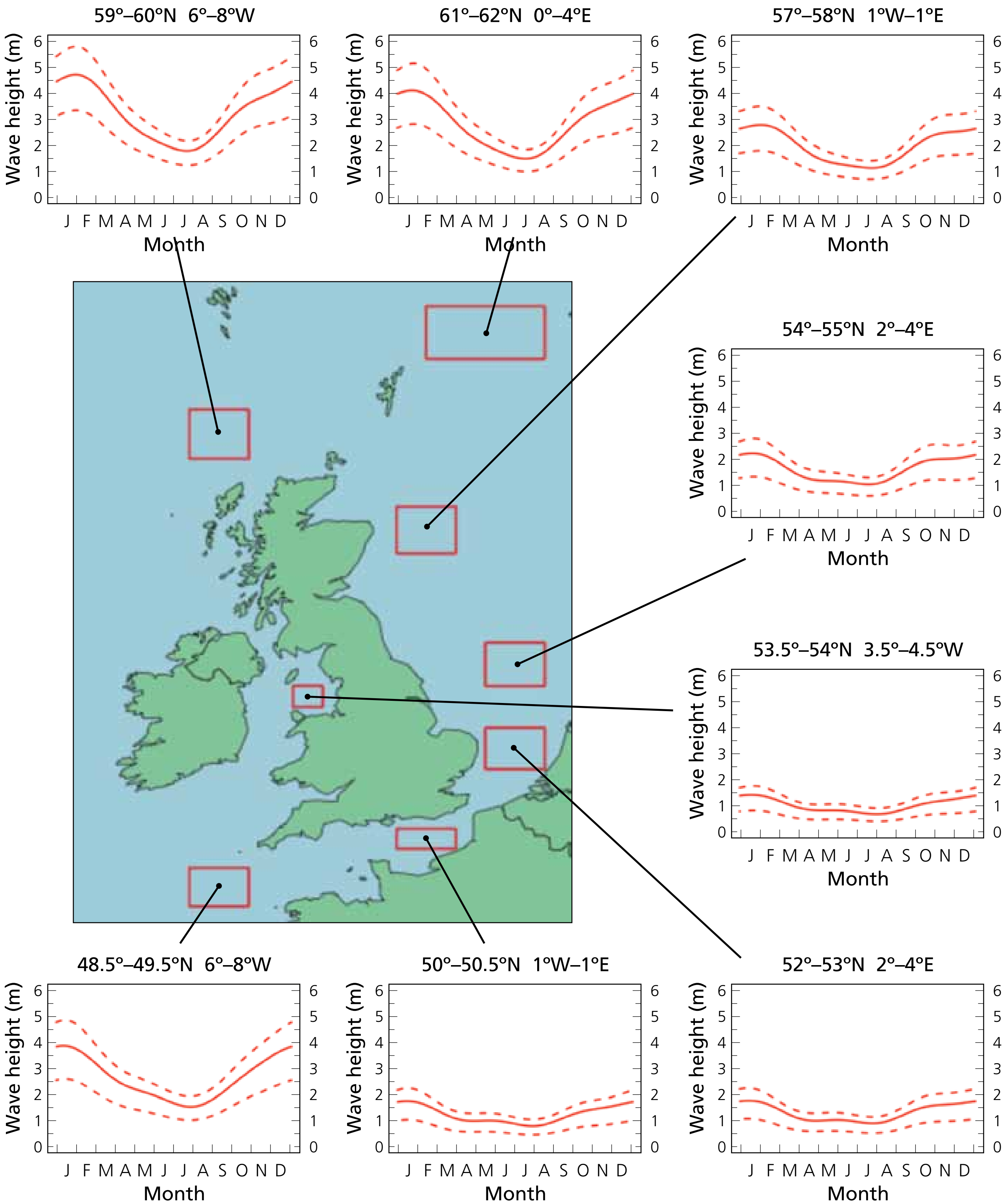


Figure 3.116 Tyne/Tees. Wave height by month for 2007-2008: means are shown in colour, maxima by bars. Courtesy of J. Rees, Cefas.

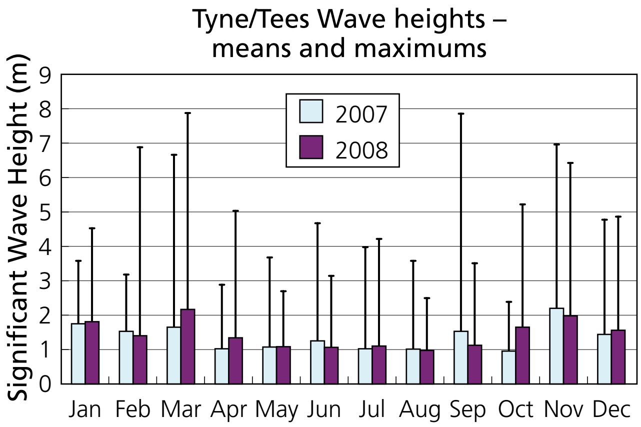
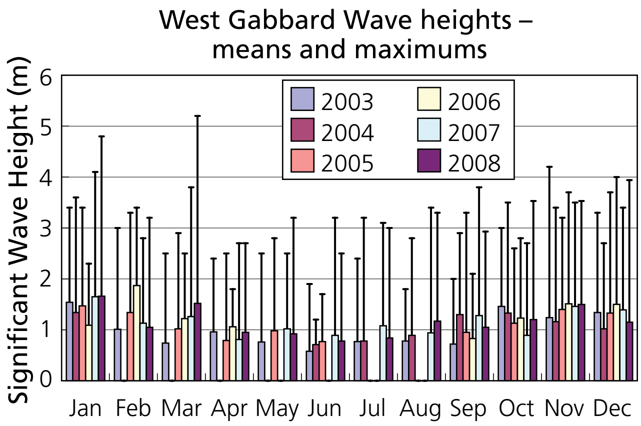


Figure 3.117 West Gabbard (Harwich). Wave height by month for 2003-2008: means are shown in colour, maxima by bars. Courtesy of J. Rees, Cefas.



and 3.117 show wave heights in the North Sea offshore from Tyne/Tees and Harwich.

Around southern England the Coastal Wave Network records waves at a recently-increasing number of locations (now 20 wave-riders) from Herne Bay (Kent) to Minehead (Bristol Channel). Typically these are 1 to 2 km offshore in about 10 m water depth. Example plots show histograms of values for: significant wave height H_s, wave direction, wave period (peak of the spectrum Tp, average of the zero-upcross wave periods Tz). The plots are for Folkestone (Figure 3.118), Pevensey Bay (Figure 3.119), Hayling Island (Figure 3.120), Milford-on-Sea (Figure 3.121), Weymouth (Figure 3.122), Perranporth (Figure 3.123) and Minehead (Figure 3.124) – i.e. in sequence along the coast. Also shown are year-by-year extreme wave height statistics (values exceeded by particular small percentages; note the varying duration of the time axis). For Milford, times of occurrences of the highest waves are shown in Figure 3.125. Data from Poole Bay are also shown in sequence (Figure 3.126) and data for Liverpool Bay in Figure 3.127.

These examples show:

- The influence of extensive shallow water limiting wave heights and wave periods; this is a general effect, albeit refraction and consequent focusing or wave-spreading can introduce much local variation in wave heights. The most exposed site illustrated, Perranporth, has much greater wave heights and longer periods than the other locations.
- Strong directionality reflecting exposure (fetch) and probably some refraction of incident waves towards normal-to-shore in shoaling waters; these are general effects but the resulting direction varies strongly with location. Eastern Channel locations (Folkestone, Pevensey Bay) and Minehead show bi-directional distributions; Milford-on-Sea and Weymouth are adjacent but show markedly different directionality as they face SW and SE respectively.
- Strong variability within any month so that the maximum is typically three or more times the mean in that month; seasonally and interannually. However, there is no discernible trend in the series, even for the 11 years at Milford-on-Sea.

Figure 3.118 Folkestone. Histograms of wave parameters and wave height exceedance over time. Courtesy of T. Mason, Channel Coastal Observatory.

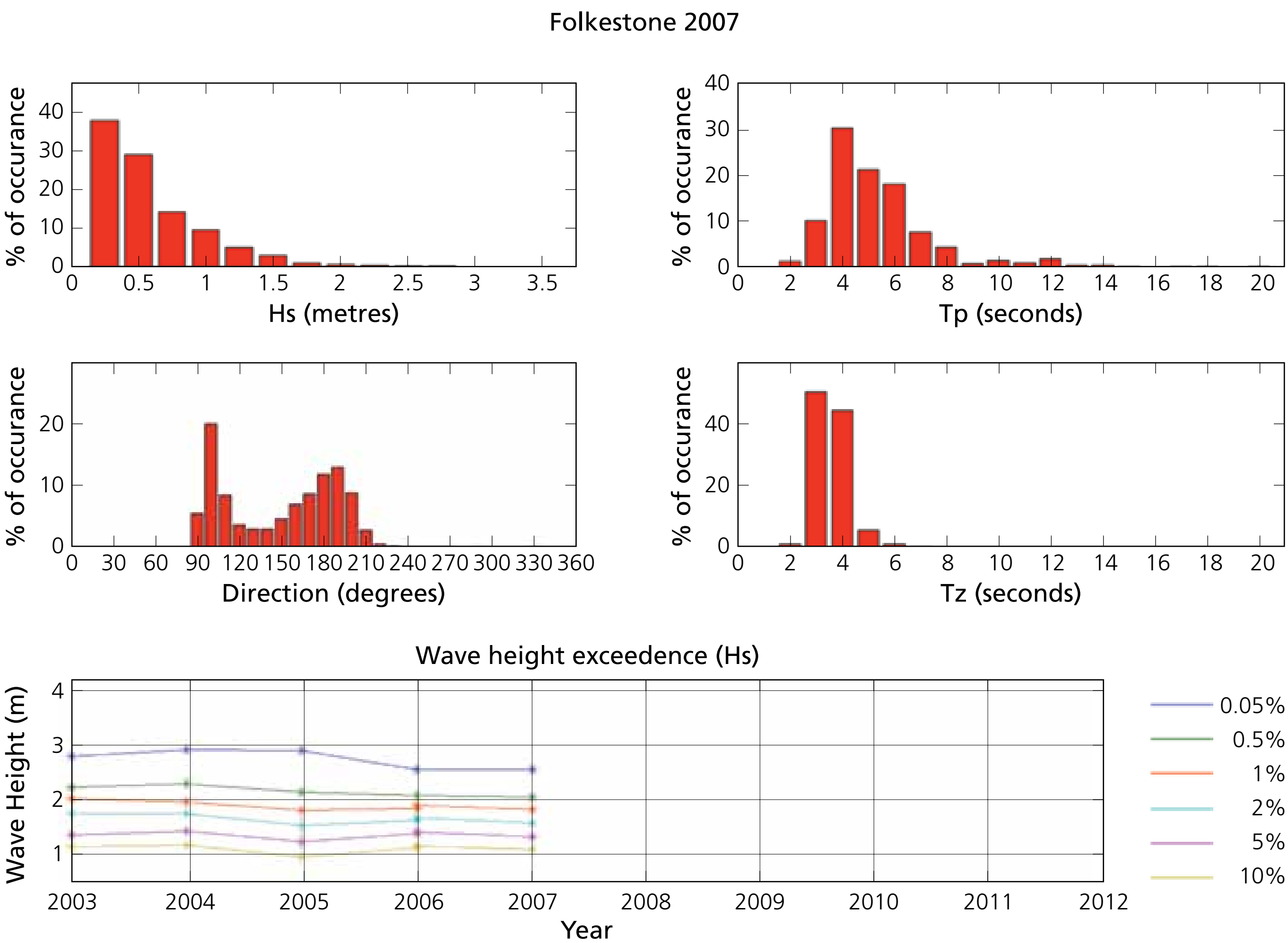
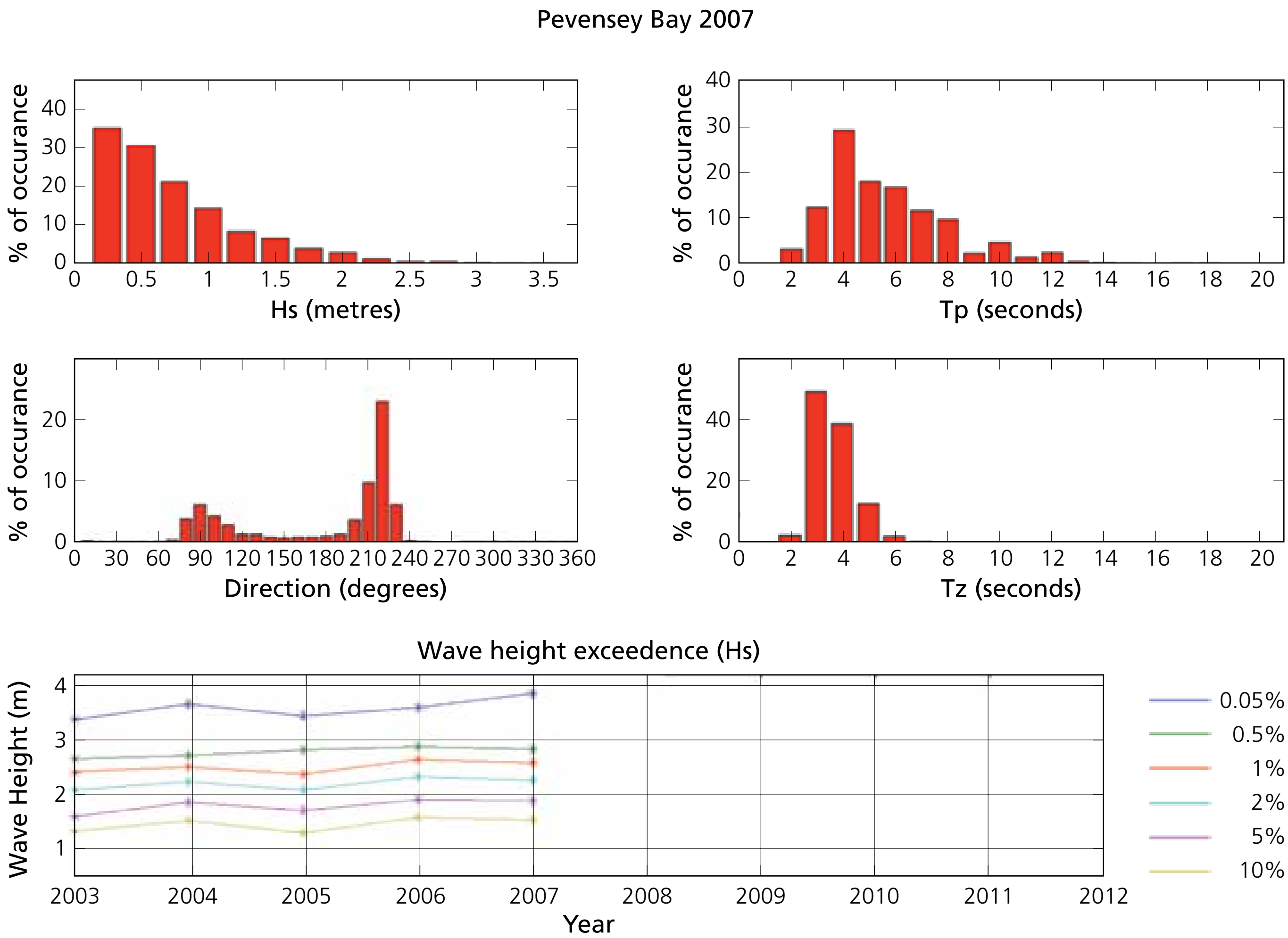


Figure 3.119 Pevensey Bay. Histograms of wave parameters and wave height exceedance over time. Courtesy of T. Mason, Channel Coastal Observatory.



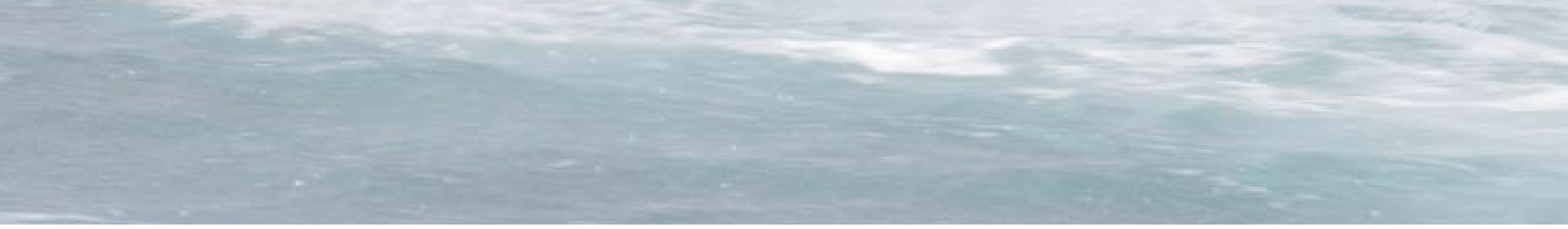


Figure 3.120 Hayling Island. Histograms of wave parameters and wave height exceedance over time. Courtesy of T. Mason, Channel Coastal Observatory.

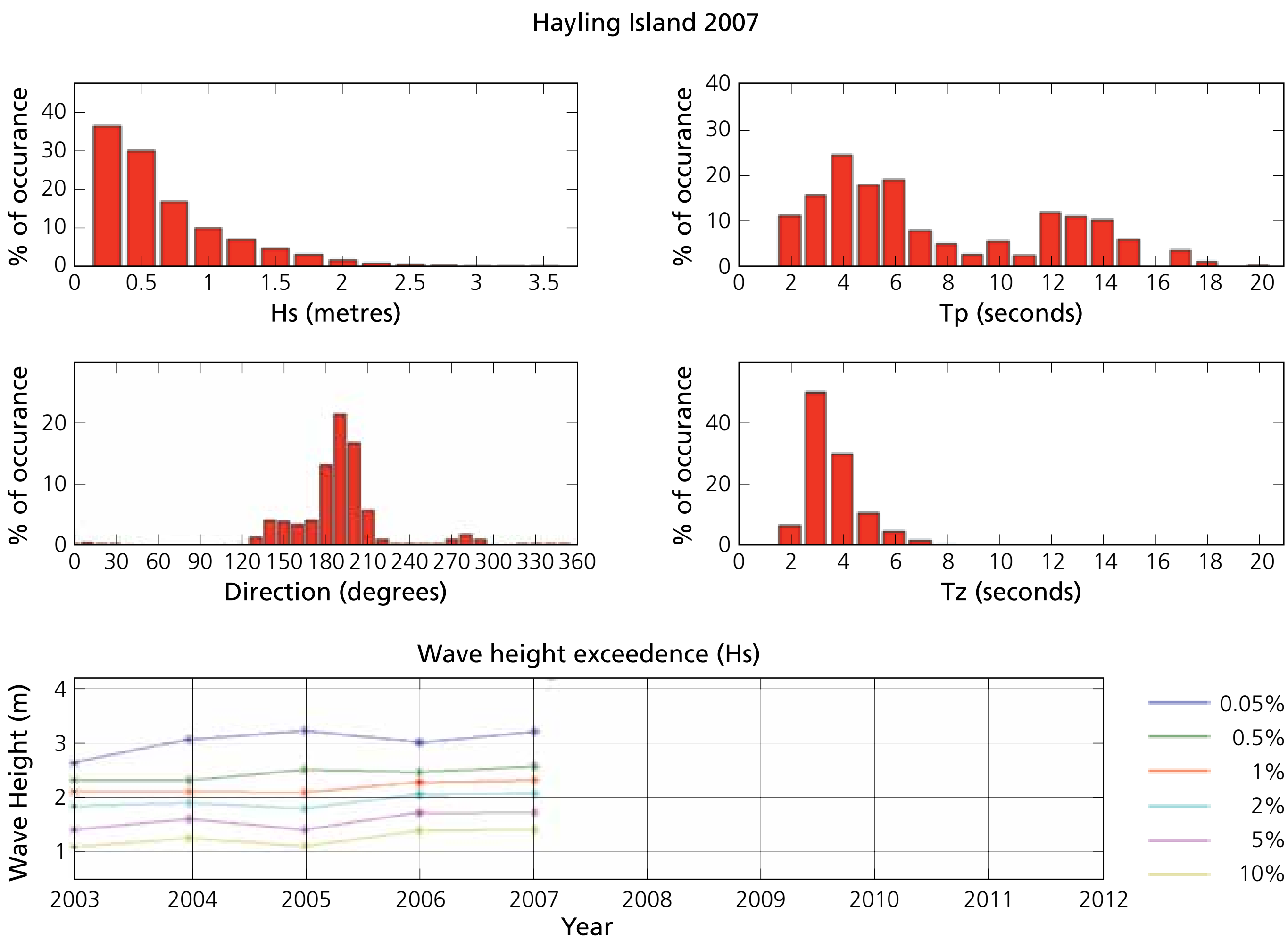


Figure 3.121 Milford-on-Sea. Histograms of wave parameters and wave height exceedance over time. Courtesy of T. Mason, Channel Coastal Observatory.

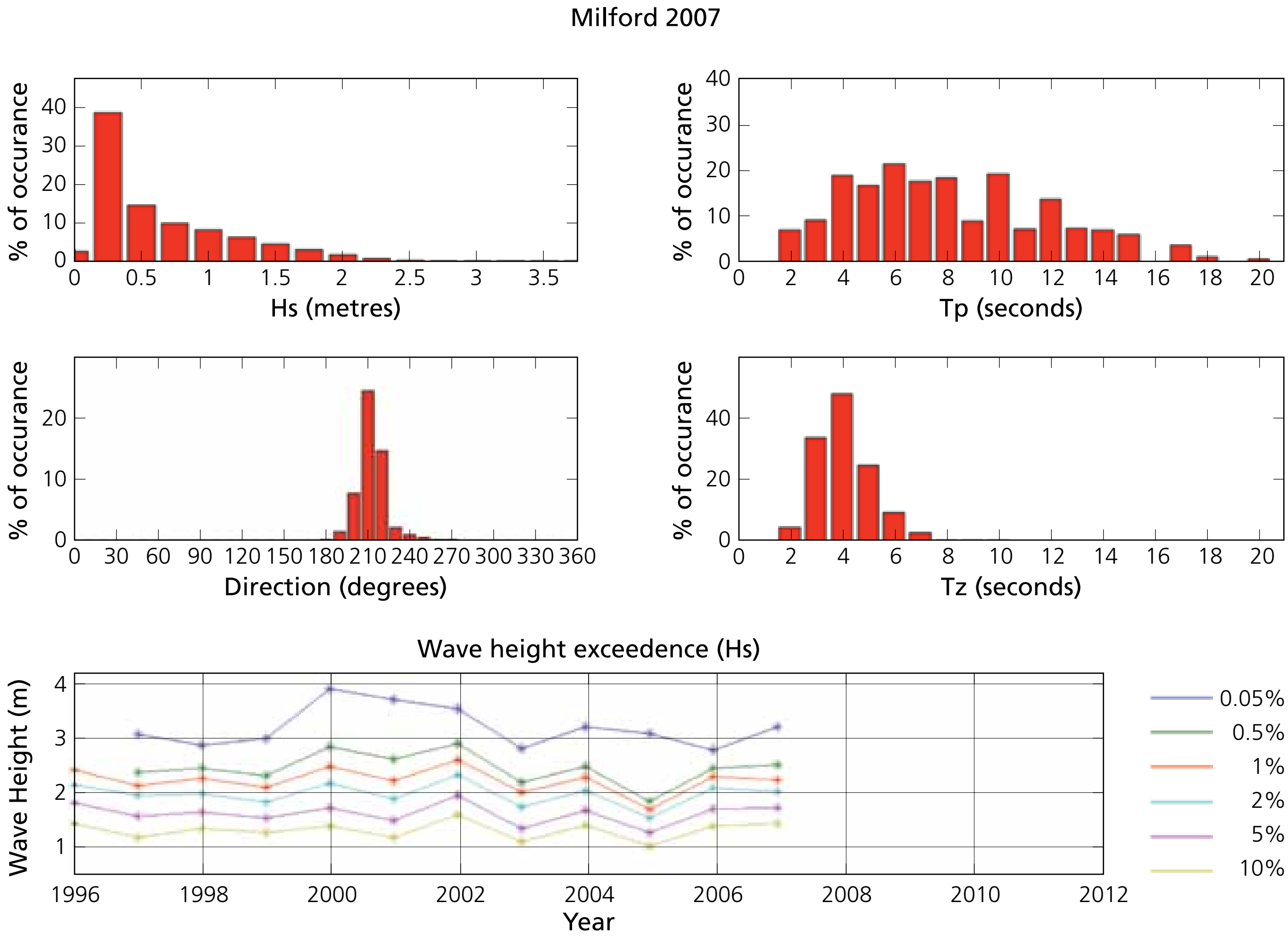


Figure 3.122 Weymouth. Histograms of wave parameters and wave height exceedance over time. Courtesy of T. Mason, Channel Coastal Observatory.

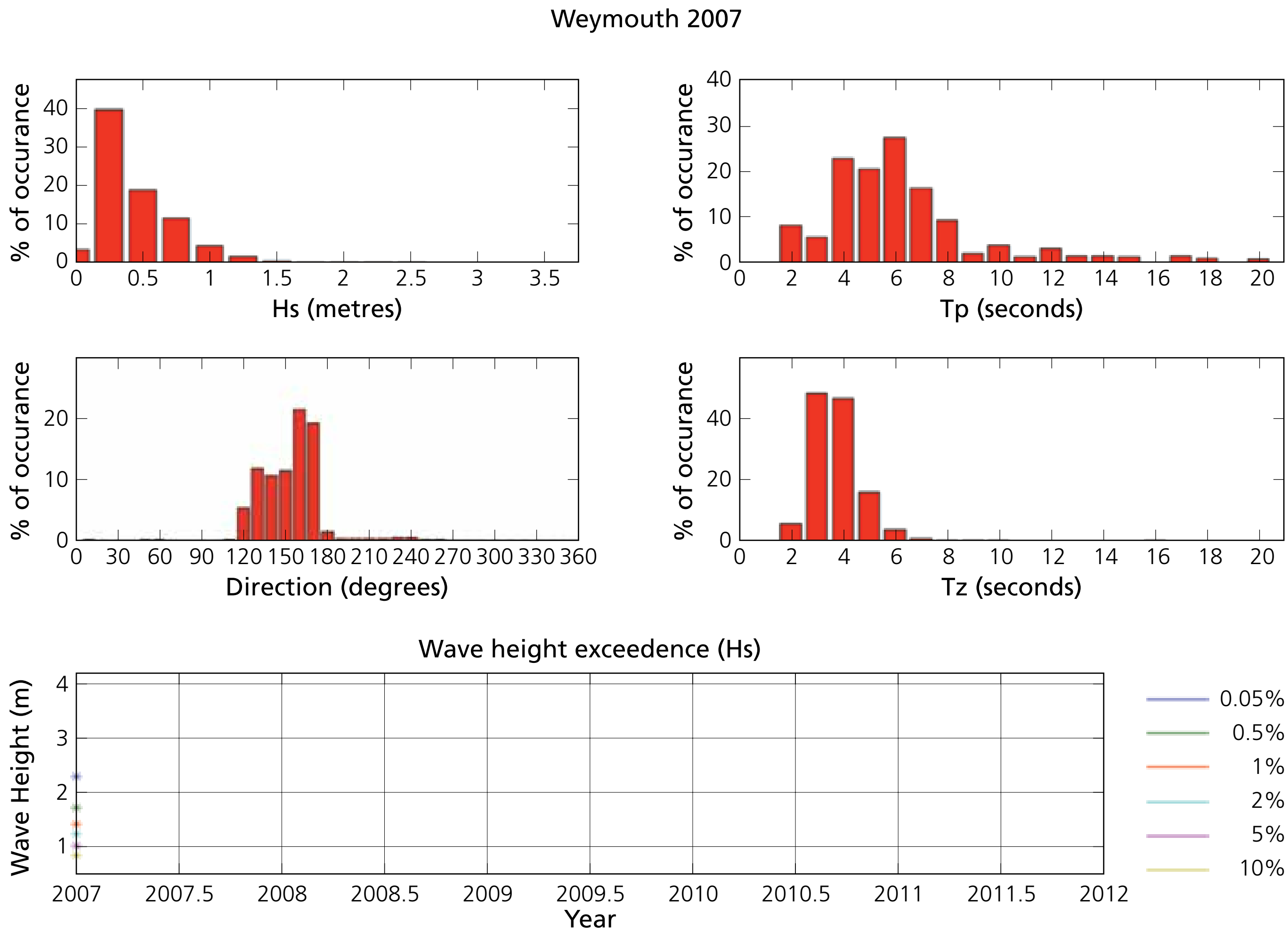


Figure 3.123 Perranporth. Histograms of wave parameters and wave height exceedance over time. Courtesy of T. Mason, Channel Coastal Observatory.

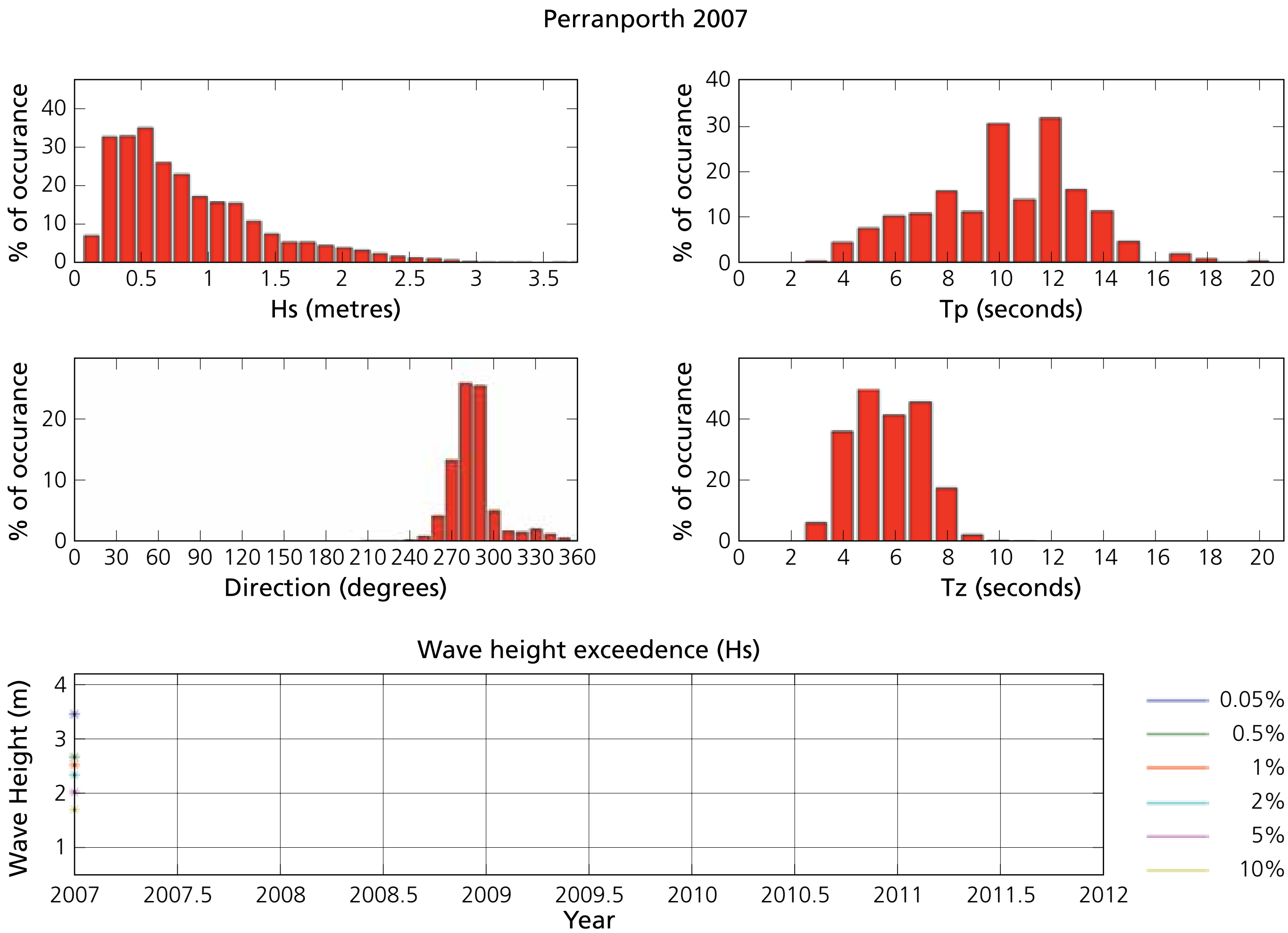


Figure 3.124 Minehead. Histograms of wave parameters and wave height exceedance over time. Courtesy of T. Mason, Channel Coastal Observatory.

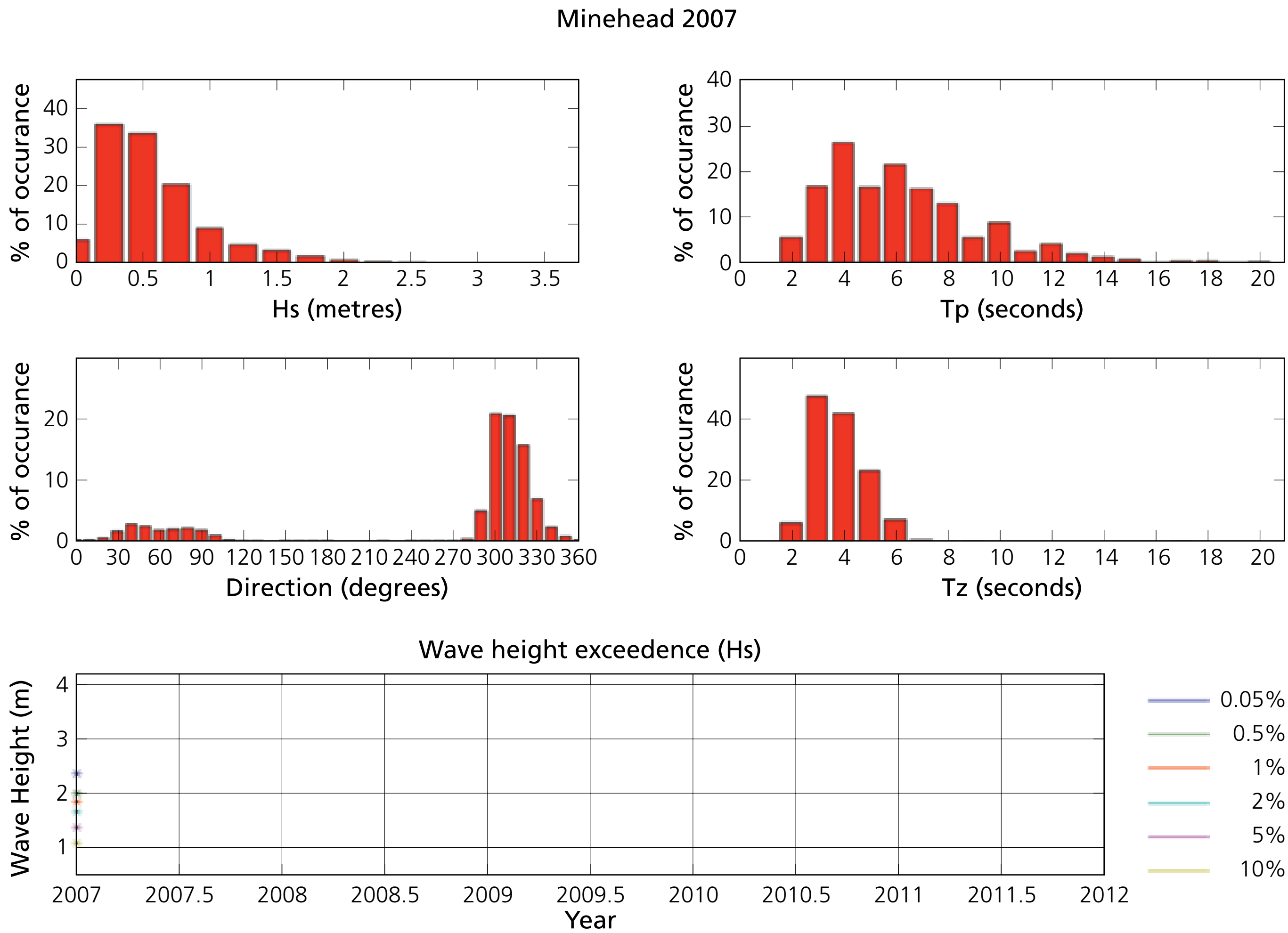


Figure 3.125 Time-series of storms (highest waves) at Milford. Courtesy of T. Mason, Channel Coastal Observatory.

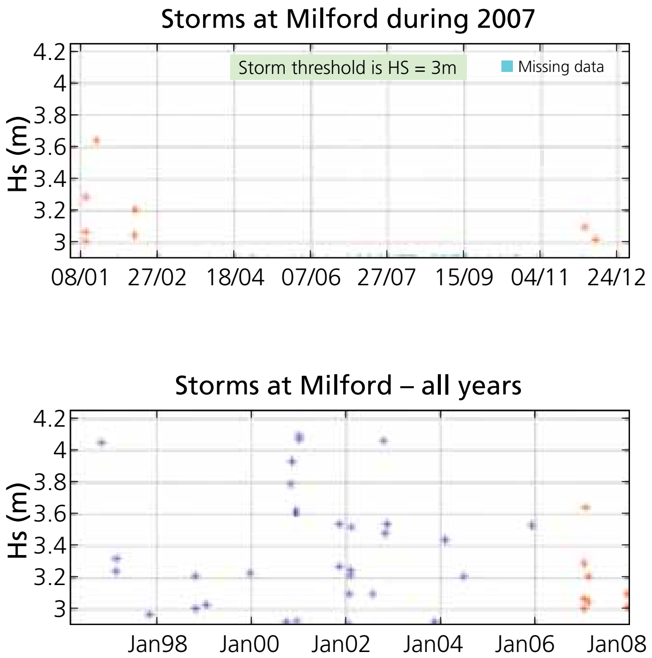


Figure 3.126 Poole Bay. Wave height by month, 2005-2008: means are shown in colour, maxima by bars. Courtesy of J. Rees, Cefas.

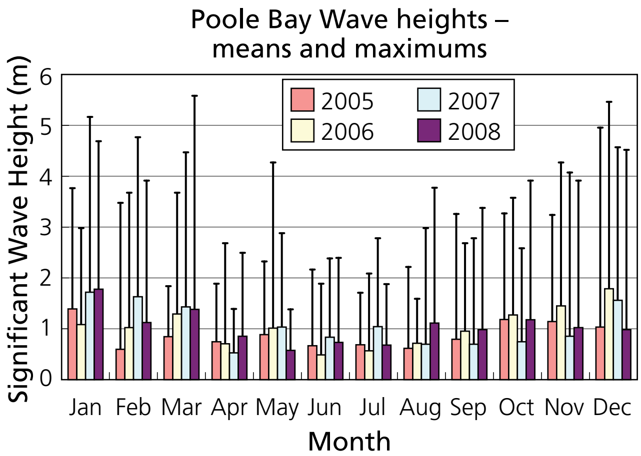
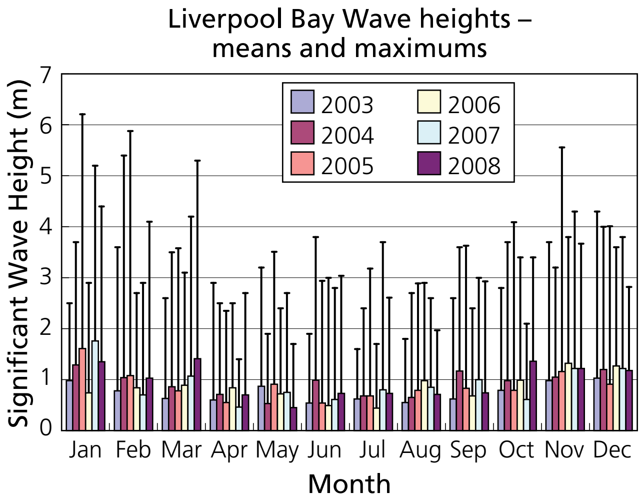
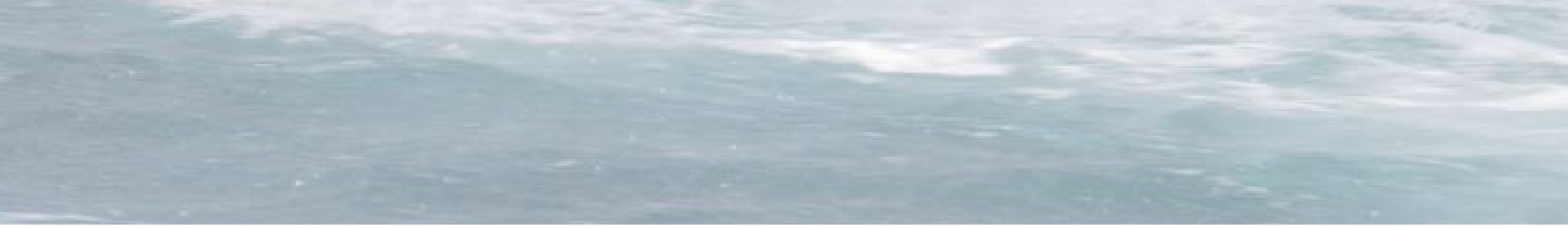


Figure 3.127 Liverpool Bay. Wave height by month, 2003-2008: means are shown in colour, maxima by bars. Courtesy of J. Rees, Cefas.



As stated in *Charting Progress*, coasts exposed to the west experience the largest wave heights; especially, the Outer Hebrides have a long-term mean wave height of 3 m. The annual range has a pattern similar to the long-term mean: greatest in the north-west; decreasing eastwards into the English Channel and southwards into the North Sea.



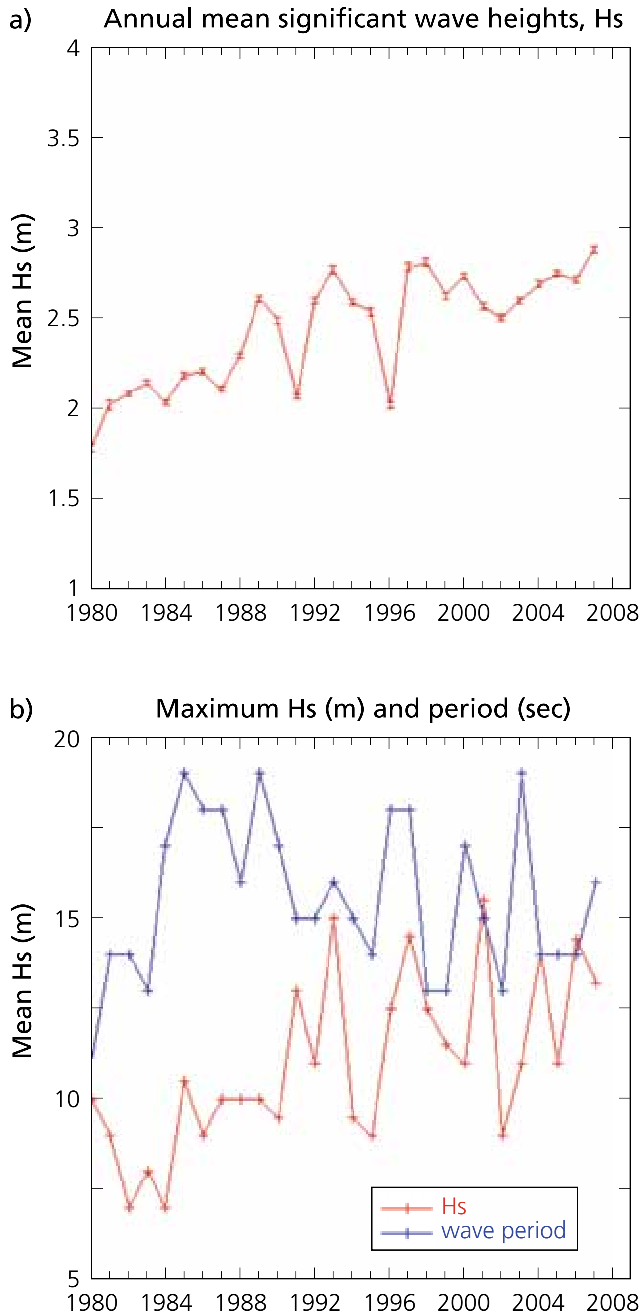
3.6.4.6 Short- and long-term non-seasonal variability

As stated in *Charting Progress*, much of the observed variability is seasonal, but the average annual cycle explains less than half the variance of wave height in the North Sea and English Channel; interannual variability is relatively important.

At Station Mike (66° N, 2° E; operated by the Norwegian Meteorological Institute DNMI), there is a trend of increasing significant wave height from 1980 to 2007. *Charting Progress* noted that in the NE Atlantic, the annual mean H_s had increased during the 1960s through to the early 1990s. Data from OWS (Ocean Weather Ship) *Polarfront* at Mike showed a similar trend for the 1980s and early 1990s, but from then to 2002 the trend was less clear (Iden, 2003). However, more recent data from OWS *Polarfront* confirm that the increase in H_s has continued from the early 1990s to date; annual mean H_s rose from nearly 2 m in 1980 to nearly 3 m in 2007 (Figure 3.128a). There was no corresponding increase in mean wind speed over this period. Annual maxima in H_s show a similar trend with more noise (Figure 3.128b). The large maximum values of around 15 m are due to strong winds persisting in the same direction for days at a time, allowing the waves to develop over a long period of time (Holliday et al., 2006).

Trends at other Ocean Weather stations (no longer operating) were given in *Charting Progress* (Defra et al., 2005). It was also reported there that (1) mean winter wave height in the NE Atlantic increased between the 1960s and early 1990s; (2) winter wave heights increased in the North Sea from 1973 to the mid-1990s with a decrease thereafter. Overall, however, year-to-year variability is such that there is no clear longer-term trend.

Figures 3.128 (a) Annual mean significant wave height H_s and (b) maximum H_s and wave period each year, from the Ocean Weather Ship ***Polarfront*** *at Station Mike (66° N, 2° E). Error bars in the annual means show ± 1 standard error. Note: the wave period is not correlated with wave height H_s. Courtesy of Norwegian Meteorological Institute.*



Monthly-mean wave heights at Seven Stones are shown in Figure 3.129 spanning 1962 to the present (with gaps). The widely reported increase to 1988 appears to have been followed by a decrease from 1995 to a minimum in 2006, with increased values again in the winters 2006/07 and 2007/08.

3.6.4.7 Wave climate and the North Atlantic Oscillation

Waves are strongly related to wind conditions, particularly strength and persistence, so a link to the north-south atmospheric pressure gradient over the North Atlantic could be expected. The increase in wave heights from 1962 to 1985 off Land's End (Carter and Draper, 1988) has been correlated with air pressure gradients (Bacon and Carter, 1993). Kushnir et al. (1997) have tied the increase in wave heights to the increase in wintertime storminess and mean wind speeds in the North Atlantic from the 1960s to the 1990s (see Section 3.1: Weather and Climate; the increase in storminess is only to levels comparable with those at the start of the 20th century). However, there was also a marked rise in the winter NAO Index between the 1960s and the early 1990s (e.g. Hurrell and Deser, 2009), giving strengthened westerly winds. The WASA Group (1998) considered that any noticeable increase in H_S since the 1960s could be positively correlated with the NAO, rather than with storm intensification; a positive NAO Index is associated with greater wave height than is a negative Index. The ability of the NAO to act as a predictor for the incidence of severe storms – as distinct from waves – appears to vary with location and historically (Allan et al., 2009). This one index does not represent all relevant atmospheric variability.

Mean winter NAO values are plotted in Figure 3.130. The smoothed curve shows the 1960s to 1990s rise from low to high values,

Figures 3.129 Monthly-mean wave heights at Seven Stones from 1962 to present, using data held by BODC (1962-1988) and data from the Met Office (1995 to present). Courtesy of G. Evans, BODC and Met Office.

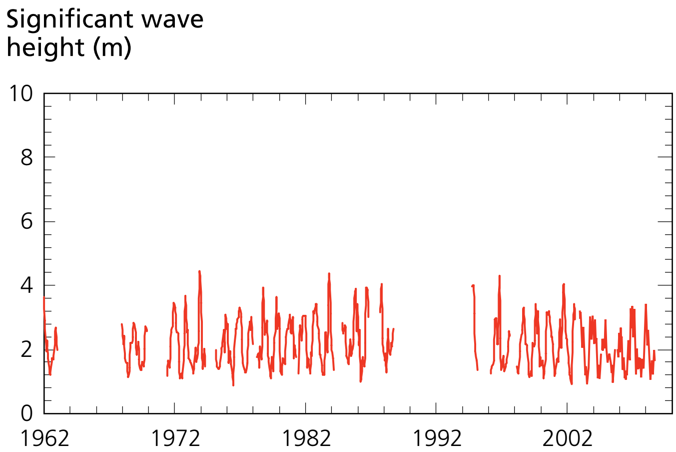
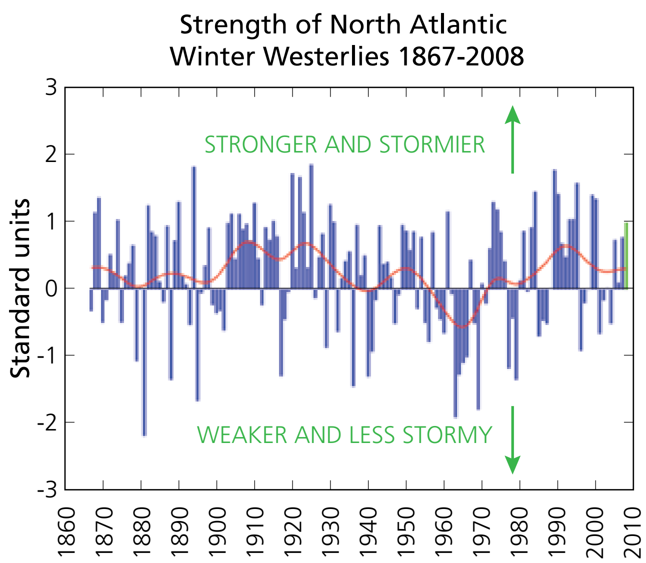
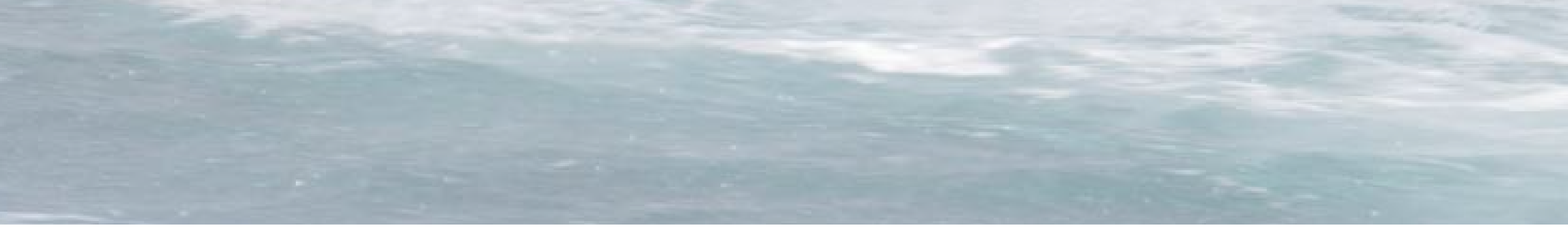


Figure 3.130 NAO index, 1867-2009, based on the normalized pressure difference between Ponta Delgada (Azores) and Stykkisholmur (Iceland). Courtesy of Met Office.





as associated with the increase in winter wave heights. Since then the NAO Index has been at about the long-term average, but the considerable variation from year to year makes it impossible to determine any trend. (Note that the NAO has an annual cycle; the winter average is about 0.5 above the overall mean.)

The influence of the NAO on the winter wave climate in the NE Atlantic and UK waters has since been studied in more detail, primarily using satellite altimeter measurements of significant wave height (Cotton et al., 1999; Woolf et al., 2002, 2003). As an example, Figure 3.131 shows a relationship between monthly mean wave heights (from altimeter data) at two UK sites and the NAO Index.

For this report, data from the locations shown in Figure 3.115 were analysed. The NAO Index has the biggest impact on wave heights in the area 59°–60° N, 6°–8° W. Here the mean significant wave height in the 15 Januaries from 1993 to 2007 was 4.5 m. The January NAO indices for 1980 to 2008 (based on pressure differences between Gibraltar and Iceland) had 25% and 75% quartiles of –1.12 and 1.24. Only two Januaries from 1993 to 2007 had indices below –1.12 and their mean significant wave height was 3.7 m; six Januaries had indices above 1.24 – their mean significant wave height was 5.2 m. Average conditions were not a good indicator of conditions in any one January. (Variations in wave power, proportional to (wave height)^2, are yet more marked.)

Figure 3.132 shows a relationship between the mean wave heights for the four months December to March and the NAO indices for those months from December 1992 to March 2007. The linear fit explains 57% of the variance. (There were no significant differences between the lines fitted to the individual

Figure 3.131 NAO Index versus wave height at Malin Head (MH) and Sea of Hebrides (SoH). The NAO index here (from Gibraltar and Iceland) follows Jones et al. (1997) updated by P.D. Jones (UEA, pers. comm., 2000). Courtesy of D. Woolf, NOC (now at UHI Thurso).

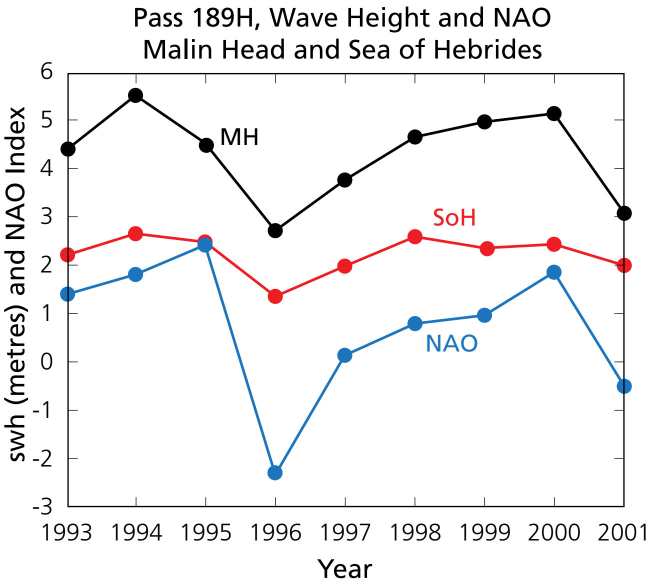
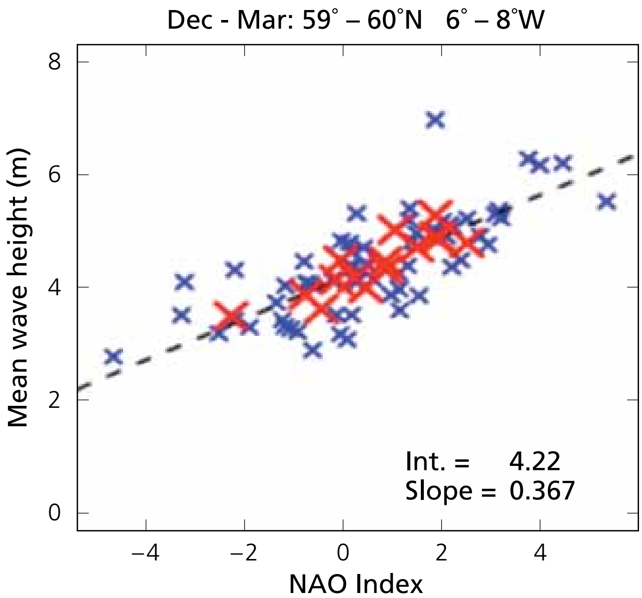


Figure 3.132 Mean winter (December-March) wave heights against mean winter NAO values, December 1992 to March 2007 (large red 'X') and individual monthly values (small blue 'x'). The dashed line is the fit to the 15 mean winter values. Courtesy of D.J.T. Carter.



calendar months.) An analysis of the average winter conditions (the mean of the four monthly means, December to March, and the mean of the four monthly NAO indices) – also shown in Figure 3.132 – gives an even closer fit, explaining 76% of the variance of the mean winter wave heights.

The goodness of fit of the mean winter values can be illustrated by plotting the mean winter wave heights against the year and adding values calculated from the fitted line; the result is shown in Figure 3.133. The fit is particularly good for the relatively calm winter of 1995/96 (altimeter data 3.51 m, regression fit 3.37 m) and the rough winter of 2006/07 (4.93 m and 4.89 m). There was no significant trend in the mean winter wave heights over this period (1992/93 to 2006/07); nor in the mean winter NAO Index values.

The regression line shown in Figure 3.132 (which also gives the intercept and slope of this line) is statistically significant at P < 0.1% – i.e. the probability that the slope would have arisen if there were no correlation is less than one in a thousand. The only other location with such significance is in the Irish Sea (53.5°–54° N, 3.5°–4.5° W) – see Figure 3.134. However, here the regression slope (sensitivity of the mean winter wave height to the NAO Index) is only 0.15 metres per NAO index, compared with 0.37 NW of Scotland; hence the range in wave heights explained by the NAO is less in the Irish Sea.

Figure 3.135 shows the variance explained by the NAO and the sensitivity of the mean winter wave height to the NAO Index at the eight locations shown in Figure 3.115. The regression was significant (P < 10%) at seven of the eight

Figure 3.133 Mean winter (December-March) wave heights and values estimated from regression with the NAO index. (Actuals from altimeter data: solid blue line; estimated: red dashed line.) Courtesy of D.J.T. Carter.

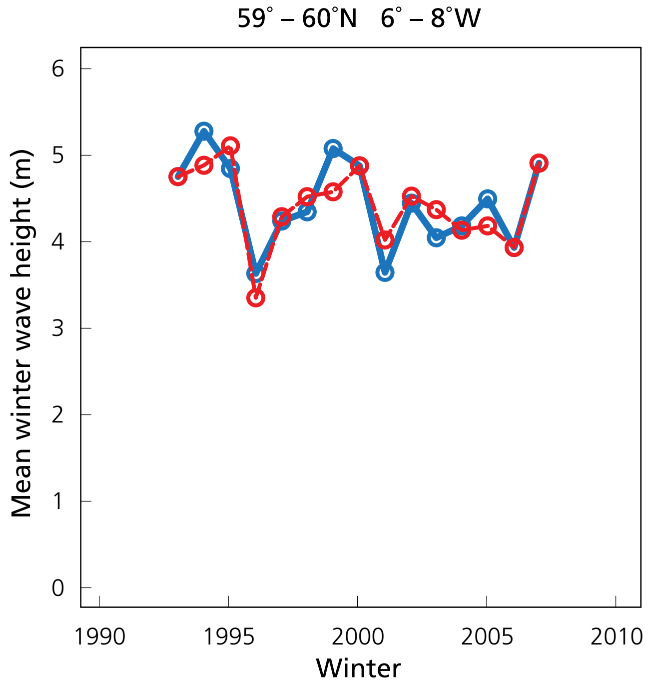
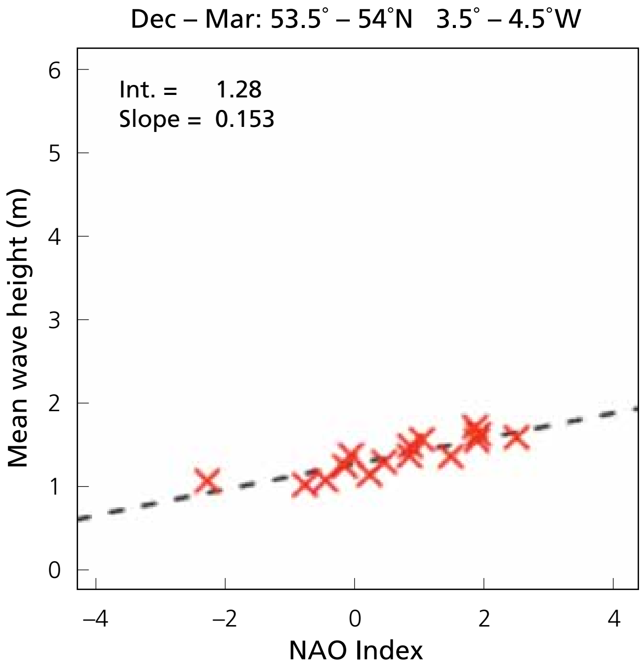


Figure 3.134 Mean winter (December-March) wave heights against mean winter NAO values, December 1992 to March 2007 and regression lines at the Irish Sea location. Courtesy of D.J.T. Carter.



locations; only at that site east of Scotland (57°–58°N, 1°W–1°E) was it not significant. But at only two locations did the NAO account for the bulk of the variation in the mean winter wave height.

Figure 3.136 from *Charting Progress* (Defra et al., 2005, and consistent with Figure 3.135) shows sensitivity to the NAO Index of mean monthly wave height offshore of northern Europe – estimated by linear regression analysis of an altimeter-based climatology.

To the west of Scotland, the relationship is particularly strong – describing about 70% of the variance and implying monthly mean wave heights varying from 3 to 7 m for extreme negative winter NAO Index and positive winter NAO Index respectively. The relationship is weaker elsewhere – vanishing on the East Coast of Britain – but is a major feature of the NE Atlantic. In terms of the sensitivity of the winter mean H_s to changes in the NAO, the wave climate off the north-west of Scotland (the Outer Hebrides) is highly sensitive, such that a unit change in the NAO will induce a 0.42 m increase in the mean winter H_s, and a 1.28 m change in the 100-year return value (Cotton et al., 1999; Woolf et al., 2002, 2003).

The wave climate in the Celtic Sea/Irish Sea and Lyme Bay is also sensitive to the NAO (for example: 54% of the variance in Carmarthen Bay, i.e. 0.2 m change in mean H_s and 0.69 m change in 100-year H_s per unit NAO change; 13% of the variance in Lyme Bay). The relationship in the northern North Sea is strong during December to March, but the correlation between the NAO Index and the waves for a region offshore of Holderness (NE England) is insignificant (Cotton et al., 1999; Woolf et al., 2002, 2003).

Figure 3.135 Variances of mean winter wave height explained (%) by linear regression with the NAO index, and sensitivity of the wave height to the NAO index (metre/index); the latter shown outside the area of analysis. Courtesy of D.J.T. Carter.

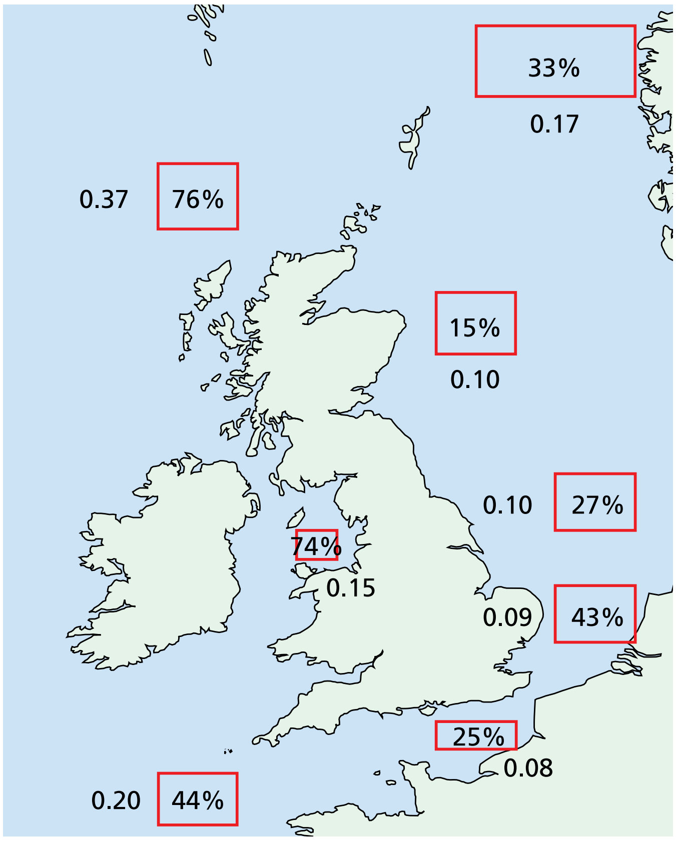
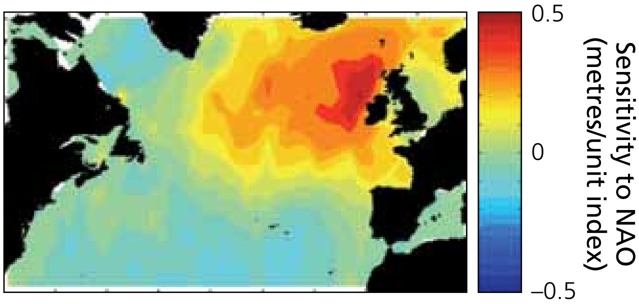


Figure 3.136 Sensitivity of winter monthly mean significant wave height to NAO. Courtesy of D. Woolf, NOC (now at UHI Thurso).



3.6.5 What the evidence tells us about environmental status

Wave heights are related to winds, with their seasonal dependence, and to interannual variability, some of which is related to the NAO Index. The various factors contributing to variance within the system make any long-term trend hard to estimate. Thus the future surge and wave climate is more difficult to predict than sea-level rise, for example. However, it will clearly depend on the future atmospheric climate, and specifically winds. An ancillary factor nearshore is altered water depth as a consequence of sea-level rise; this may enhance the ability of higher waves to approach the coast, increasing their impact.

It is generally accepted that in a warming climate the intensity of tropical cyclones will increase as their generation is closely linked to sea-surface temperature (Emanuel, 2005). On the other hand, the number of mid-latitude depressions may not necessarily increase as there is evidence of two opposing mechanisms: the equator-to-pole temperature difference decreases with global warming; and the number of winter storms may increase at the downwind end of northern hemisphere storm tracks (Wolf and Woolf, 2006). A significant increase in cyclonic activity over the North Atlantic has been observed during the second half of the 20th century and storminess increased in the NE Atlantic and NW Europe (Alexandersson et al., 1998, 2000). Trends toward higher storm surge levels have recently been reported for various locations in northern Europe (Lowe et al., 2001; Lowe and Gregory, 2005; Woth et al., 2006). However, the trend of increasing storminess and wave heights in the North Atlantic, from the 1960s to the 1990s, has ended with a return to calmer conditions (Matulla et al., 2008). The trend in storminess and wave heights coincided with increasingly positive NAO Index over the 1960s to 1990s (Figure 3.130); however, the ability of the NAO Index to act as a predictor for storminess appears to vary with location and in time: winter NAO is a significant but historically-varying factor in the incidence of severe storms (Allan et al., 2009). Nearshore wave parameters can be modelled given the offshore wave climate for future scenarios (Leake et al., 2007, 2008; Wolf, 2008). UKCP09 model projections for future wave climate in UK waters indicate (with large uncertainties) a slight increase south-west of the UK, a reduction north of the UK and little change in the North Sea (Lowe et al., 2009); these changes reflect a shift of storm tracks to the south (likewise uncertain).

The summary table (Table 3.12) includes an assessment of trend but not status ('traffic-light') because (1) no accepted criteria apply for waves giving significant risk of adverse effects; and (2) the UK (government), or even the EU, cannot itself take measures to improve the status.

Waves are subject to a wide range of natural variability on many time scales from storm duration to interannual, reflecting the multiple factors affecting the wind that drives them (e.g. season, NAO). This variability and (annual-average) wave heights have shown changes perhaps related to the character of storms on interannual to decadal time scales. However, given the greater range of seasonal variability (e.g. in monthly-averaged wave heights) it is hard to argue that these changes have had a significant impact on the environment or human health. (A distinction is made from the ongoing occasional high risk posed by high waves.) Longer-term or future climate-related trends might have an impact, but further research is needed to clarify these. For example, knowledge of the likely future trend in the NAO Index would be useful – but at present there is no agreement

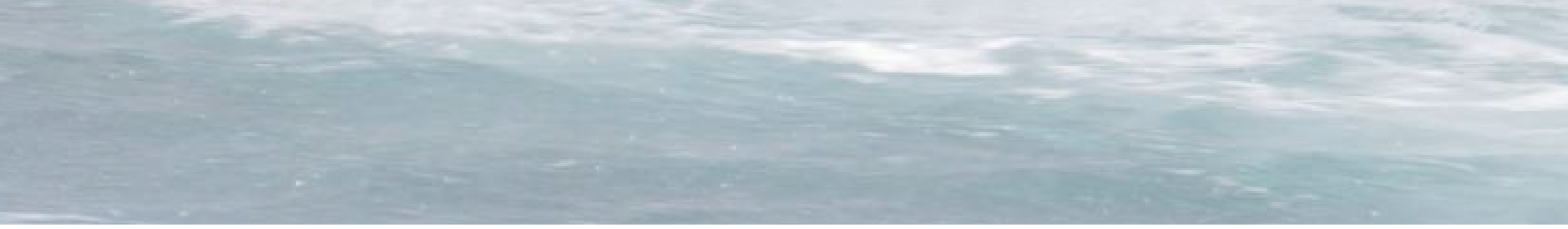


Table 3.12 Summary assessment of trends

Parameter	*CP2 Region*	*Key factors and impacts*	*What the evidence shows*	*Trend*	*Confidence in assessment*	*Forward look*
Waves (significant wave height H_s)	1, 2, 3, 4, 5, 6, 7 (all UK shelf-seas)	Winds, site. Affects coast, benthos, demersal fish	Interannual variability; bigger waves in winter; strongly directional near coasts; in shallows, heights are limited, seasonality and trends are reduced	Upward to mid-1990s; no clear trend or possibly slight decline since	Medium	Unclear trend
Waves (significant wave height H_s)	8 (adjacent North Atlantic)	Winds, site. Affects benthos, demersal fish	Interannual variability; bigger waves in winter	Upward to mid-1990s; no clear trend or possibly slight decline since	Medium (mean H_s at 66° N, 2° E (just to the north-east) continued to rise to 2007	Unclear trend

on what this might be (Woolf and Coll, 2006). Local construction, for example in harbours and around wind turbine pylons, has the potential to introduce local changes and significant impacts on the spatial scale of the construction. There is little basis to distinguish between CP2 Regions except in respect of such local activities and overall wave heights. There are large differences in average wave heights between locations within any one CP2 Region, as values (but not necessarily impacts) decrease nearer to shore.

3.6.6 Forward look and need for further work

There will be a continuing need to monitor waves for their impact on offshore operations and the coast. Thus the reasons for recent enhancement of the monitoring network remain valid. The advanced state and continuing development of models gives them an important role in prediction, forecasting and state assessment, supported by data for model validation and assimilation. Little management can be done except to mitigate impacts and the immediate inshore wave climate locally (by nearshore structures of various types). There is continuing interest in waves as a possible source of renewable energy (total wave energy arriving in UK waters is of magnitude comparable with UK electricity consumption).

3.7 Suspended Particulate Matter and Turbidity

3.7.1 Key points

i. Introduction

Suspended Particulate Matter (SPM) carries pollutants, shades light and so inhibits primary production, and embodies particulate organic matter forming part of the marine ecosystem (Section 3.7.2). It is highly variable according to depth and physical processes in the area (i.e. tide and current regimes and wind; Sections 3.7.2.1 and 3.7.3).

ii. How has the assessment been undertaken?

Traditional assessment methodologies are still used successfully, but various optical techniques are increasingly being used, for particle size as well as weight of SPM. This has increased understanding of the dynamics and processes associated with SPM in shelf seas, especially tidal stirring of sediments (Sections 3.7.2.2, 3.7.3.1, 3.7.4). Remote sensing measurements of ocean colour provide time series for studying variability of suspended material, phytoplankton pigments and coloured dissolved material.

iii. Current and likely future status of suspended particulate matter and turbidity

Trends in SPM concentrations and therefore turbidity for UK waters show no significant change between *Charting Progress* (Defra et al., 2005) and the present assessment, *Charting Progress 2*.

iv. What has driven change?

Not applicable.

v. What are the uncertainties?

Remote sensing measurements are still hampered by weather (especially cloud) and by a lack of understanding of optics in (turbid) coastal and shelf waters (Section 3.7.4).

vi. Forward look

For improved shoreline management plans there is a need for more quantitative information, especially on shoreline processes, wave interactions (inshore wave climate) and water flow along coasts (Section 3.7.5). There is much interest and activity in SPM within coastal regions of the UK and Europe with EU Integrated Coastal Zone Management recommendations and a number of large EU-funded projects studying turbidity in coastal regions (Section 3.7.6). The improved methods of assessment provide added data on suspended sediments, to allow better mapping of UK waters for environmental quality through turbidity measurements (Section 3.7.5).

3.7.2 Introduction

Suspended particulate matter (SPM) in shelf seas is important because its properties determine turbidity in the water column (which constrains primary production and influences heat transfer), material transfers to the seabed (which determines sedimentation rates, biogeochemical transfers from water to seabed, and productivity of the benthos), and the flux and fate of associated pollutants and contaminants. Shifts in the fate of SPM between export to the pelagic food web or deposition to the benthos are critical in the assessment of eutrophication. Very close to a sandy seabed, suspended matter consists of resuspended mineral matter, but elsewhere in the water column SPM is typically in the form of flocs – loosely bound aggregates composed of mineral matter (e.g. clay minerals), organic matter (living and dead components of phytoplankton, heterotrophic organisms, bacteria, faecal matter), and water. While the primary components of flocs may be of the order of 1 to 5 µm in size, fully developed flocs grow to 600 µm or more. Because of their structure, flocs have a high surface-area to volume ratio, high water content and low density. Flocs are formed by collisions of smaller particles in low-turbulence regimes, and are ruptured by shear in high-turbulence regimes. Consequently, they vary in size and properties on short-time scales (significantly during a tidal cycle). Their fragility makes them difficult to sample conventionally so interrogation of floc properties relies on *in situ* techniques.

This section of the OPEG Feeder Report deals with SPM and turbidity but not specifically with the biological components of SPM: living plankton and phyto-detritus (plankton are considered in Section 3.3: Carbon Dioxide and Acidification). However, given the composition of flocs, it is impossible to ignore the profound biological influence on floc properties, dynamics, and fate. 'Turbidity' is a measure of the concentration of SPM in the water, which includes both biological and mineral material; SPM causes scattering and absorption of light rays and hence affects water 'clarity'. Light is scattered mainly by mineral suspended solids, whereas light is absorbed by mineral suspended solids, phytoplankton pigments, dissolved organic matter and the water itself (Bowers et al., 2002). Hence any consideration of suspended matter in shelf seas necessarily encompasses the biological components and phyto-detritus that at times in the seasonal cycle comprise the bulk of SPM.

Much of the information about suspended material in UK waters, as presented in *Charting Progress* (Defra et al., 2005), is still current. This section will show examples of new (more recent) data and highlight how this improves current knowledge. Key additions include recent instrumental developments that provide new measurements and fresh insights on SPM properties and dynamics.

Although there are a number of recent papers looking at SPM in the North Sea (e.g. Gayer et al., 2006; Eleveld et al., 2007; Fettweis et al., 2007), these largely focus on the Dutch and German areas of the North Sea, especially in regions of sand extraction and are based on pre-2004 data. Modelling SPM is a major contributor to new work, especially linked to the higher resolution satellite imagery from MODIS and MERIS, but also based on older data and imagery.

3.7.2.1 Processes controlling suspended particulate matter and turbidity

The concentration of SPM in UK shelf seas depends on a range of physical forcings, biological mediation, and the characteristics of the seabed. Suspended sediment concentration (SSC) is the net result of the competition between resuspension and deposition on which is superimposed the effect of advecting horizontal gradients.

Resuspension is due to the bed shear stress caused by horizontal momentum changes experienced by fluid parcels as they move up or down in turbulent eddies into faster or slower moving levels in the boundary layer. In large areas of UK shelf seas, tidal currents are the primary forcing of resuspension, while waves become the dominant agent in shallow water. Waves and tidal currents combine to generate bed shear stress over much of the shelf; waves enhance the bed stress so that sediment is mobilised and currents determine the magnitude and direction of transport. For non-cohesive beds, the threshold shear stress for initiation of grain movement and for suspension can be predicted, the important sediment property being grain size. For cohesive beds (i.e. a bed containing at least 10% clay), prediction becomes increasingly difficult as the proportion of cohesive clay increases. At present there is no reliable empirical or theoretical criterion for estimation of the threshold condition for cohesive beds. Furthermore, some or much of the resuspended material is benthic fluff (Jago et al., 1993), a low density surficial layer on the seabed derived in large part from phyto-detritus and other organic matter. Benthic fluff is resuspended by much smaller shear stresses than the bed sediment itself, and is the source of a significant part of the resuspension signal in the water column. The fluff layer generates anoxia at the sediment-water interface changing the biogeochemical regime at the seabed.

Deposition depends on settling of SPM which is governed by the size and density of the particles. Settling can be considered as ‘sinking rate’, i.e. the net downward flux as might be captured in a sediment trap, but is better conceptualised as ‘settling velocity’, the velocity with which particles settle in still, non-turbulent water since this absolute parameter can be used in numerical models of vertical exchange. The settling velocity of flocs is very variable (and difficult to measure) with values in the range 10^{-4} to 2×10^{-2} m/s (Jago et al., 2007); the upper part of this range exceeds that of fine quartz sand grains. Since flocs are prone to aggregation and rupture in a fluctuating turbulence regime, the settling velocity may vary over orders of magnitude on tidal time scales. The response of flocs to turbulence depends on floc strength – also very variable depending on how the flocs were formed in the first place. Consequently it is difficult to assign settling velocities to flocs in real shelf conditions. There is evidence that floc size and settling velocity have upper limits due to floc rupture by sinking stresses (Hill, 1998), but field observations show that, at least in the short term, flocs significantly exceed such limits.

Biological mediation of floc size and floc strength is well documented but not easy to quantify. A range of microbiota exude extracellular polysaccharides which, when associated with flocs, increase their propensity to aggregate. This process is variable: for example, the nutrient status of plankton cells probably affects their stickiness, and different types of biota undoubtedly give rise to flocs of different structure and strength. Biological mediation is seasonally variable and is probably most significant towards the end of the spring phytoplankton bloom. Its impact may also be spatially variable: limited data suggest that stratified waters are characterised by small, weak, slow-settling flocs while mixed waters are characterised by larger, stronger, fast-settling flocs, but how much of this is due to biological mediation is not clear (Jago et al., 2007).

3.7.2.2 Measurement of suspended particulate matter and turbidity

Measuring SPM *in situ* is difficult and can be subject to large sampling (including methodological) errors (Ellis et al., 2005); satellite-derived and modelled SPM data are more compatible (Binding et al., 2005). It is particularly difficult to make discrete *in situ* SPM measurements in tidal waters largely due to water movements and small-scale mixing processes which lead to significant variability in samples. *In situ* measurements are important for validation of optical measurements and for modelling, especially issues of size distribution which are key inputs to any SPM model.

Studies in CASIX (the NERC Centre for observation of Air-Sea Interactions and fluxes) showed that models of the UK shelf seas need to consider the effects of turbulence and how the SPM and coloured dissolved organic matter (CDOM) impact the light in the sea. The largest errors in shelf sea models are in the coastal and shelf-sea waters, due to their complexity in terms of light and physical processes. Turbulence is a key issue for the physics of models due to the interactions of coastal processes. Seabed type and particle size also need to be included when considering shallow waters.

High-resolution measurement of SPM concentration is achieved using optical and acoustic techniques. Optical sensors employ light transmission or backscatter (transmissometers, optical backscatter sensors OBS, respectively) as proxies for SSC. Since transmittance and backscatter are influenced by the size of particles as well as by their concentration, these optical instruments must be calibrated *in situ* for every deployment. Acoustic methods (e.g. Acoustic Doppler Current Profiler ADCP) can also be used but these too need calibration for specific applications. There are inherent problems in interpreting optical and acoustic data when SPM properties are changing on short time scales and/or when plankton cells augment SPM in the water column (Bunt et al., 1999) as calibration becomes increasingly uncertain. Nevertheless, such instruments have greatly increased understanding of the processes that determine SSC in shelf seas.

3.7.3 Progress since *Charting Progress*

A more recent innovation is *in situ* particle sizing using lasers (e.g. LISST; Agrawal and Pottsmith, 2000). These instruments provide, for the first time, the ability to monitor particle-size spectra of SPM with high temporal and spatial resolutions. LISST also provides volume concentration of SPM which in association with determination of SSC allows for calculation of floc effective density (Mikkelsen and Pejrup, 2000). However, LISST data need to be interpreted with caution in stratified regions of the shelf since water density differences can cause light scattering – schlieren – even though only few particulate scatterers may be present (Mikkelsen et al., 2008). Moreover, the veracity of optical and acoustic techniques for sensing SPM properties is uncertain when the particles are mostly flocs.

Remotely-sensed data using Earth Observation techniques potentially overcome some of the difficulties in measuring SPM properties on a regional scale, but the ability to use remotely-sensed ocean colour depends on the atmospheric correction, and the inherent optical properties (IOPs) of the water – the absorption and scattering properties which are highly variable in the so-called Case 2 waters of turbid coastal seas. (Case 2 waters are those waters whose optical properties are dominated by suspended particulate matter, dissolved organic matter and phytoplankton pigments; Case 1 waters are optically clear and the optical properties are determined only by phytoplankton.) Attenuation, being the sum of scattering and absorption, a measure of turbidity, encompasses all particles in the water, both the suspended sediment and the biological particles (e.g. phytoplankton), and all the dissolved material in the water. Disentangling the various contributors is problematic (e.g. Bowers et al., 2002). The diffuse attenuation coefficient, 'k_d', is one of the most accurate remotely-sensed measurements available. The NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) is able to produce time series of imagery from a number of ocean colour sensors to cover the whole UK shelf region or specific seas. Imagery can be presented as normalised water-leaving radiance at 551 nm, $nL_w(551)$, or any other similar wavelength which is considered to represent the concentrations of suspended sediment in the top optical depth of the water column. This depth is retrievable from the attenuation coefficient and for recent satellite sensors, k_d at 490 nm provides plots of this. This attenuation coefficient relates to the 'turbidity' of the water, and so includes all suspended material (of both inorganic and organic origin). Time series of $nL_w(551)$ and $k_d(490)$ from NEODAAS, for the whole UK shelf for January, April, July and October 2003 to 2007, derived from MODIS AQUA data, are shown in Appendix 1. For $nL_w(551)$ these plots highlight the higher turbidity closer inshore that is associated with certain large river outputs (e.g. the Thames), with shallow bank areas (e.g. Arklow Bank in the Irish Sea) and areas of strong tidal mixing (e.g. off Holyhead in the Irish Sea). The $k_d(490)$ plots show a more usual seasonal signal associated with phytoplankton blooms.

3.7.3.1 New evidence for suspended particulate matter in UK waters

The spatial distribution of suspended sediments is a consequence of hydrodynamic forcings acting on the unconsolidated sediments of the shelf and the coastline. In general, waves are more important for resuspension in shallow water (< 10 m) and currents become more important in deeper water (> 10 m). However, waves can be important at greater depths; for example, at the Liverpool Bay SmartBuoy which is a mooring at about 20 m depth, the variability in SPM is dominated by storms/waves, and the effect of these on turbidity is much longer than the storm events themselves. The sedimentary nature of the seabed is the result of an inherited relict distribution of glacial and fluvio-glacial deposits, much modified by waves and currents during and since the post-glacial transgression.

The complex interactions of process and response result in marked temporal variations of SSC superimposed on strong spatial gradients. The simplest model of SSC variation is the 'twin peaks' model (Weeks et al., 1992) whereby a time series of SSC at any location is composed of tidal signals – an M_4 signal (four tides per lunar day) due to resuspension superimposed on the semi-diurnal M_2 signal (two tides per lunar day) due to advection of a horizontal concentration gradient. The combination gives rise to a twin peaks signature with varying concentration minima at successive slack waters. This signature is best developed during spring tides; it may disappear on neap tides and during storms. Much of the signal is due to resuspension of benthic fluff and, in areas where there is a finite supply of fluff, peak SSC in the lower part of the water column occurs in advance of the peak current velocity (Jago and Jones, 1998). Subsequent observations using LISST have shown that disaggregation of flocs, with M_4 frequency, is an additional major contributor to SPM properties over tidal cycles (see below).

On a regional scale, SSC is greatest in coastal zones due to enhanced supply from resuspension of bed material, fluvial inputs, and direct erosion of the shoreline (most important in areas where the shore is composed of poorly consolidated glacial deposits). The seasonal variation of wave conditions gives rise to a comparable variation of SSC and turbidity in those areas dominated by waves. There are also biological factors controlling turbidity which increases during phyoplankton blooms. There is a marked reduction in turbidity after the spring bloom; a possible explanation is that enhanced biological mediation of aggregation creates rapidly settling flocs which are sedimented to the seabed.

3.7.4 Presentation of the evidence

3.7.4.1 Irish Sea

The Irish Sea continues to be a test-bed for UK shelf sea processes, with easy access for the R.V. *Prince Madog*. There have been several Irish Sea initiatives concerned with SPM in the Irish Sea since *Charting Progress* (Defra et al., 2005). These include INTERREG projects such as MATSIS and The Use of Ferries to Monitor Water Quality in the Irish Sea, and the NERC-funded CASIX and TURBSED. There are ongoing studies as part of the NOC-led Irish Sea Observatory with regular cruises, and linked modelling and remote sensing studies.

Using satellite reflectance imagery, White et al. (2003) have shown that there was no overall trend in near-surface turbidity between 1987 and 1997 in the Irish Sea, but that year-to-year variability was positively correlated with changes in the mean annual regional wind strength, controlled by the north-south atmospheric pressure gradients and related to the North Atlantic Oscillation (NAO) Index. However, there is evidence that water clarity in the Irish Sea deteriorated between the mid-1960s and the late 1980s – the mean annual Secchi depth in the Menai Straits decreased from around 2.3 m to less than 1.5 m during that period (Lumb, 1990). More recent measurements (Kratzer, 2000; Kratzer et al., 2000) indicate that this decrease has reversed and unpublished measurements made as part of MSc practical work support this.

An overview of SPM seasonal variability can be seen at: http://www.oceannet.org/library/publications/documents/marine_processes_and_climate.pdf

The images are composites at a resolution of 1.1 km, from a 1998 time series of NASA SeaWiFS satellite images for reflectance at 555 nm (closely related to SPM concentrations). More recent data are available through the MATSIS project, provided by NEODAAS, for $nL_w(551)$ bimonthly for 2005 (Figure 3.137) and 2006 (Figure 3.138), and for $k_d(490)$ bimonthly for 2005 (Figure 3.139) and 2006 (Figure 3.140).

Seasonal SeaWiFS data from the CASIX archive shows a very clear cycle of SPM for a site off Anglesey (Figure 3.141), but models are currently unable to reproduce this with a fixed settling velocity. The water is more turbid in the winter months, becoming clearer in the spring, reaching a low over the summer months and increasing again in autumn as autumnal winds induce more mixing. A seasonally-varying settling velocity resulting from aggregation/disaggregation linked to turbulence and biological mediation is required. This SeaWiFS output is an average value for a box around the Anglesey *in situ* sampling station (52.9°N, 5.525°W to 53.82°N, 4.15°W)) derived from the Moore-Aiken algorithm (Moore et al., 1999). The error bars represent one standard deviation, i.e. the spatial variability. This algorithm, however, produces SPM values which are less than the *in situ* data measurements.

Analysis of Irish Sea satellite imagery by Bowers et al. (1998, 2002) shows that isolated, persistent turbid patches of SPM occur in regions of enhanced tidal currents, for example, the presence of two separate turbidity maxima, one off Wicklow Bay, the other off Anglesey. These areas correspond to the areas of strongest

Figure 3.137 Bimonthly MODIS Aqua images for 2005 showing $nL_w(551)$ for the Irish Sea. Data supplied by NEODAAS to the MATSIS project. Land and cloud and edge of scene are masked in black. Higher suspended loads are indicated by the green to red colourations. Courtesy of P. Miller, Plymouth Marine Laboratory.

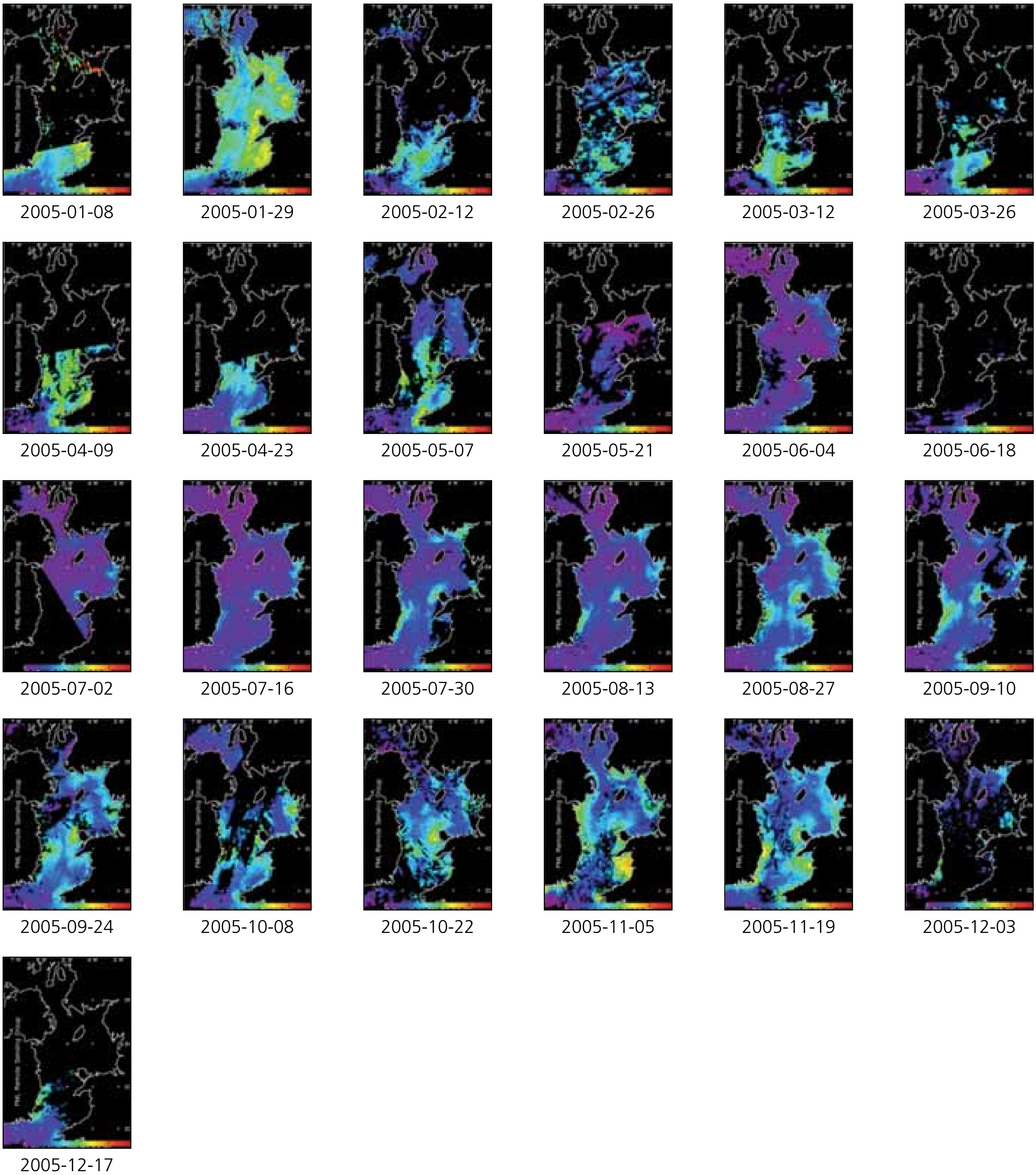


Figure 3.138 Bimonthly MODIS Aqua images for 2006 showing $nL_w(551)$ for the Irish Sea. Data supplied by NEODAAS to the MATSIS project. Land and cloud and edge of scene are masked in black. Higher suspended loads are indicated by the green to red colourations. Courtesy of P. Miller, Plymouth Marine Laboratory.

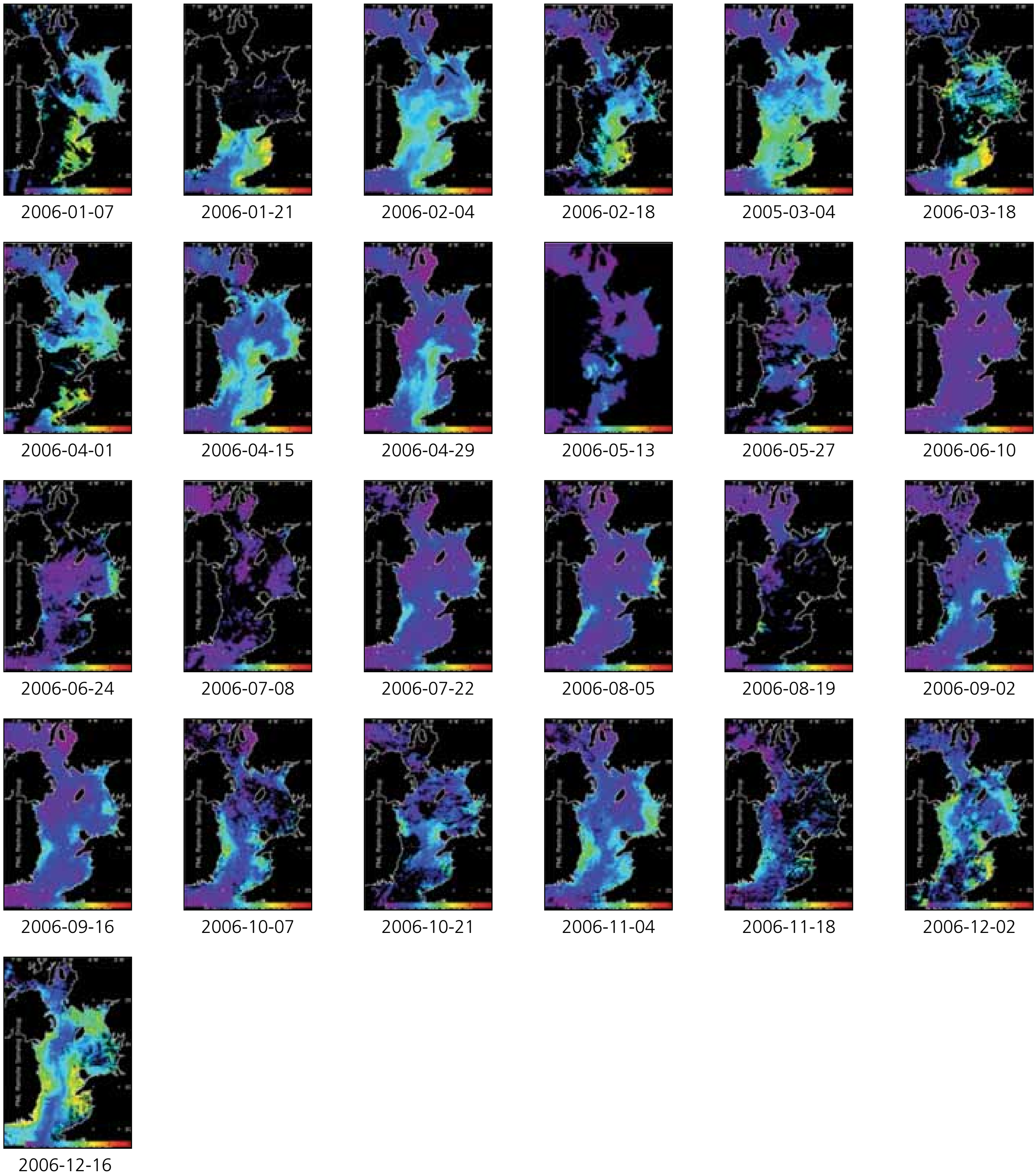
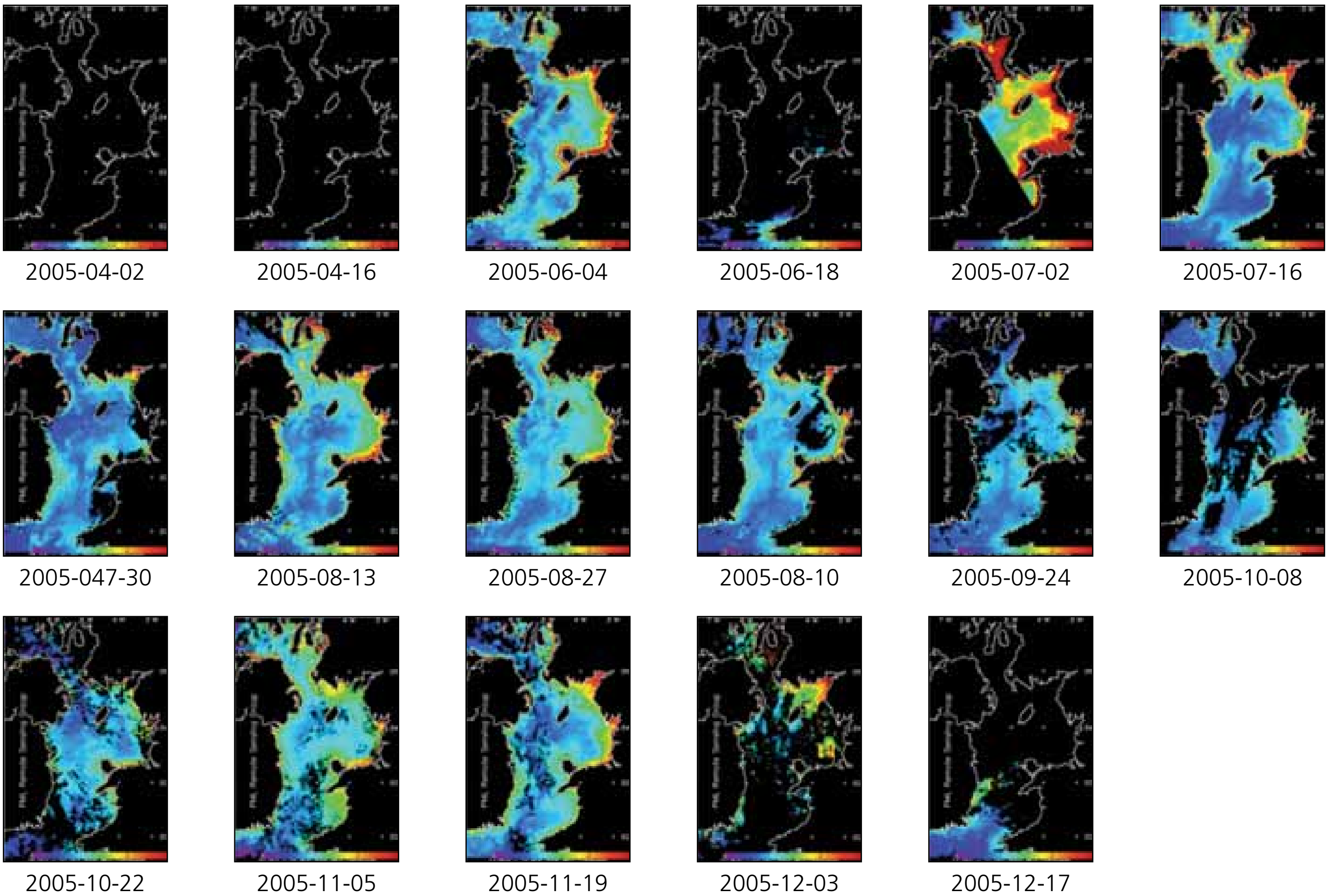


Figure 3.139 Bimonthly MODIS Aqua images for 2005 showing k_d(490) for the Irish Sea. Data supplied by NEODAAS to the MATSIS project. Land and cloud and edge of scene are masked in black. Higher turbidity is indicated by the green to red colourations. The July image illustrates the high turbidity associated with phytoplankton blooms in Liverpool Bay. Courtesy of P. Miller, Plymouth Marine Laboratory.



tidal currents, and it is considered that the high reflectance is produced by fine sediments maintained in suspension throughout the water column by tidal stirring. However, the seabed sediment at these localities is predominantly coarse grained. Ellis et al. (2008) ascribed the persistence of these patches to a conservative balance of diffusion of small particles out of the turbid patch and diffusion of aggregated material towards it. An alternative explanation is that the patches result from throughput of SPM by advection plus settling, resuspension and disaggregation by turbulence within the patch.

Novel interpretation of satellite data by Bowers et al. (2007) provides a synoptic overview of particle size of surface SPM (Figure 3.142). The particle size appears to be limited by the Kolmogorov turbulence scale.

A major advance since *Charting Progress* has been the extensive deployments of LISST instruments providing both spatial gradients and temporal variations in particle size. New methods for measurement of turbulence properties (Rippeth et al., 2003) have provided insights into the physical controls of SPM properties in response to tidal forcing. These

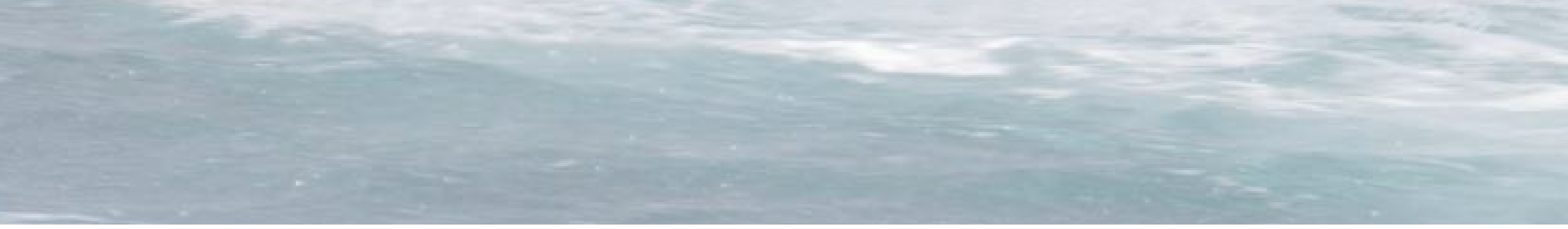


Figure 3.140 Bimonthly MODIS Aqua images for 2006 showing $k_d(490)$ for the Irish Sea. Data supplied by NEODAAS to the MATSIS project. Land and cloud and edge of scene are masked in black. Higher suspended loads are indicated by the green to red colourations, with periods of phytoplankton activity having the highest values. Courtesy of P. Miller, Plymouth Marine Laboratory.

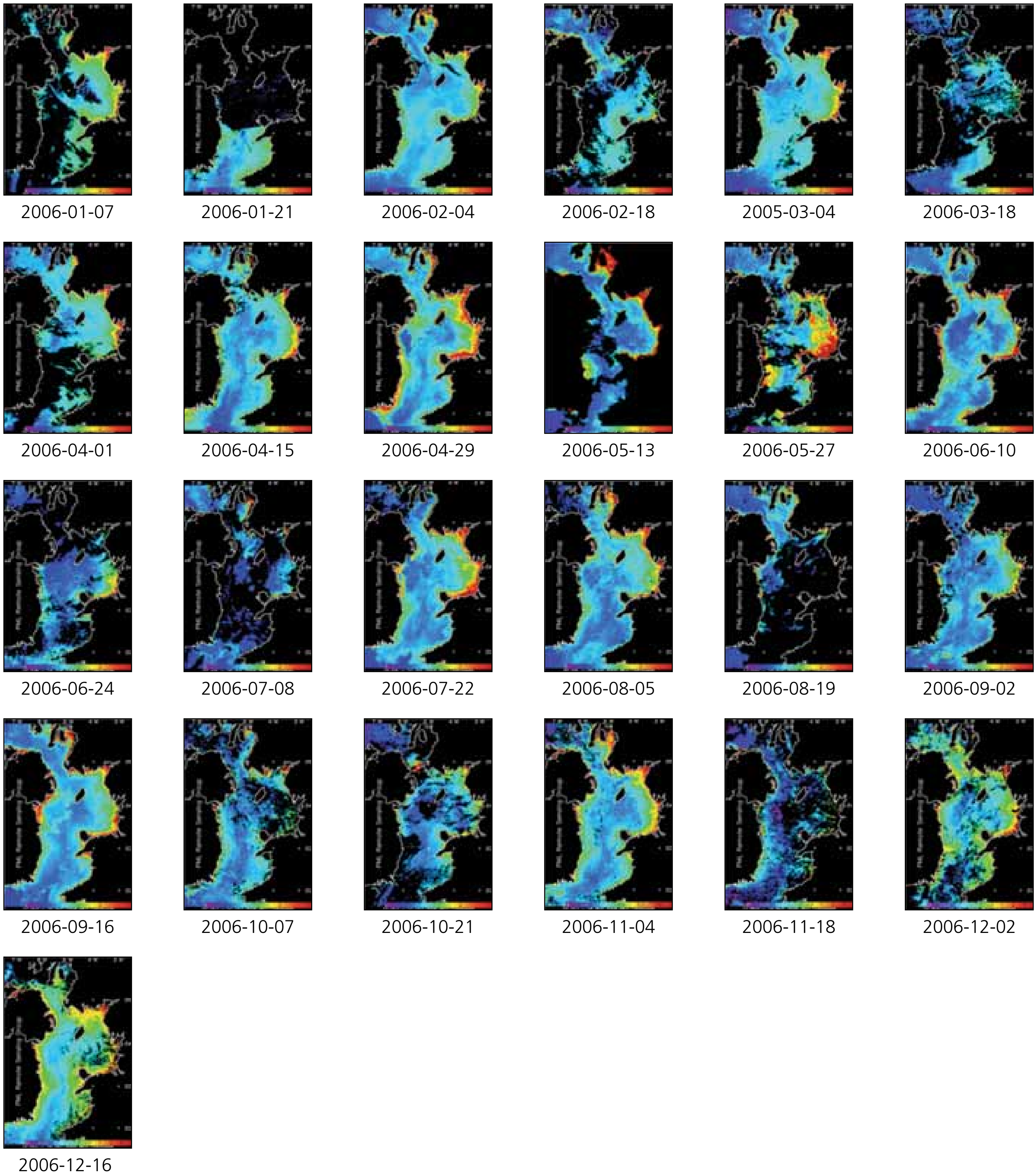


Figure 3.141 SPM concentrations derived from SeaWiFS data from 2001, for Holyhead, Anglesey. The error bars represent one standard deviation. From Mitchelson-Jacob et al. (2006).

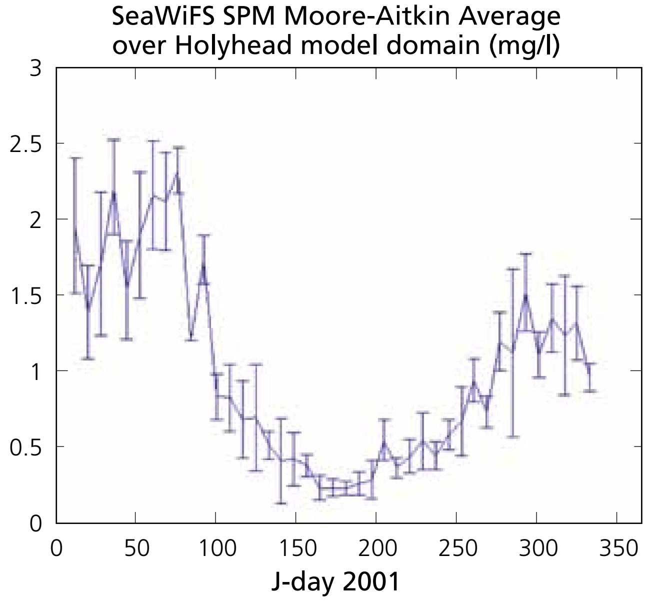
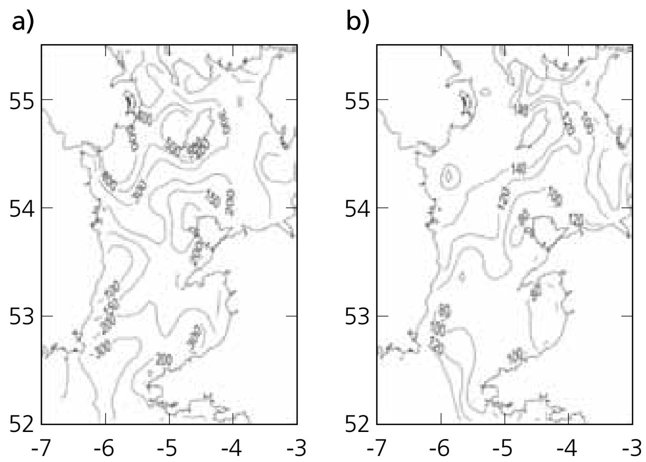


Figure 3.142 Near-surface median particle size by volume estimated from satellite images for (a) summer (contour interval 50 μm), and (b) winter (contour interval 20 μm). From Bowers et al. (2007).



measurements provide previously unavailable information on how SPM responds to physical processes (especially water movements) and therefore provide new data on the reasons for the variations in turbidity in UK shelf waters. The influence of tides on turbidity is better defined, with information relating to resuspension of bottom sediments, as well to potential aggregation of material in suspension.

Extensive measurements in fast tidal streams off Anglesey have demonstrated that the particle size of SPM is due to a combination of time-varying turbulence at any point superimposed on space-varying turbulence advecting through the site (Jago et al., 2006). Time asymmetry in the turbulence field gives rise to an asymmetric M_4 signal in SPM volume concentration (Figure 3.143) due to asymmetric resuspension and disaggregation of flocs at times of peak turbulent energy.

Harmonic analysis of LISST time series (Figure 3.144) shows that aggregation of flocs occurs at high and low slack waters but the largest flocs occur at low slack water. This is due to space-varying ambient turbulence which produces a horizontal gradient in floc size with small and large flocs at opposite ends of the gradient (Figure 3.145); hence there is an M_2 signal in floc size.

Superimposed on this is the effect of time-varying turbulence at the observational site: resuspension and disaggregation occur at peak turbulence generation with M_4 frequency. At this particular site, the disaggregation contribution was ~ 40% as much as the resuspension component near the bed and ~ 20% integrated through the water column. Thus the time series shows a more complex interaction of processes than proposed by the simple twin-peaks model.

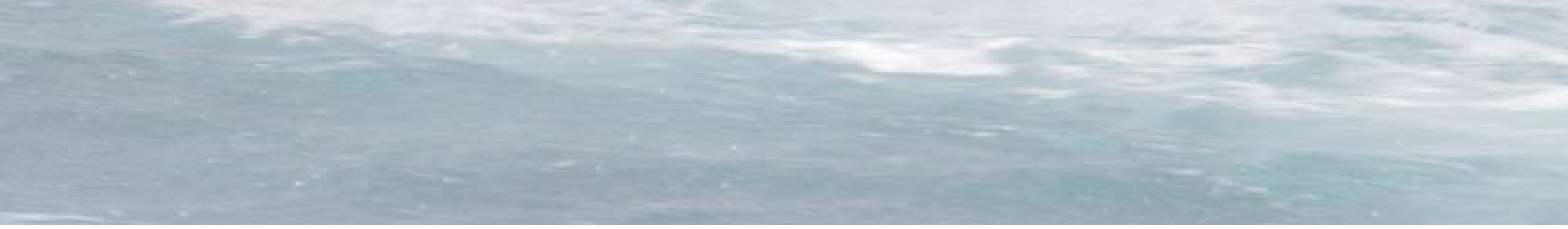


Figure 3.143 Turbulence and SPM properties at a site off Anglesey, Irish Sea. (a) Turbulence production from seabed ADCP; (b) turbulence dissipation from profiling FLY; (c) SPM volume concentration from profiling LISST. Measurements at 1 h intervals. Turbulence in $\log_{10}$ W/m^3 and volume concentration in µl/l (= ppm). From Jago et al. (2006).

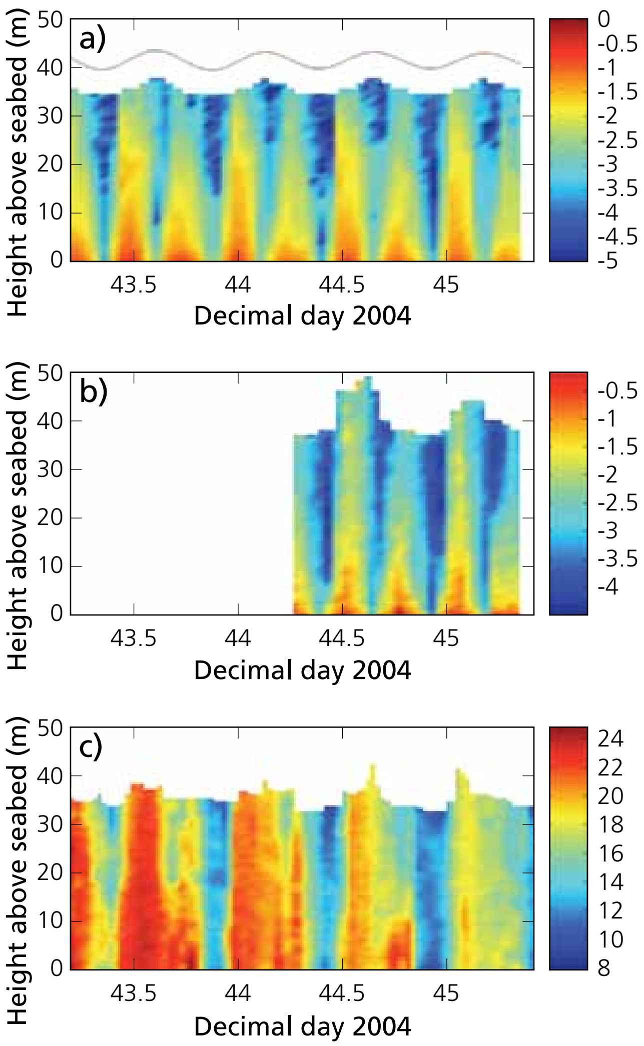


Figure 3.144 Variation in SPM properties over a 50 h period. (a) Median particle diameter (µm); (b) volume concentration (µl/l) of particles < 100 µm (arrows indicate peak values corresponding to times of peak turbulence; the signal diminishes over time as neap tides are approached); (c) volume concentration (µl/l) of particles > 100 µm (arrows indicate peak values corresponding to times of minimum turbulence (slack waters): red arrows at low water slack, yellow arrows at high water slack; high water signal disappears towards neap tides). Time scale is in hours after the first low water slack. Width of arrows approximates to magnitude of signal. From Jago et al. (2006).

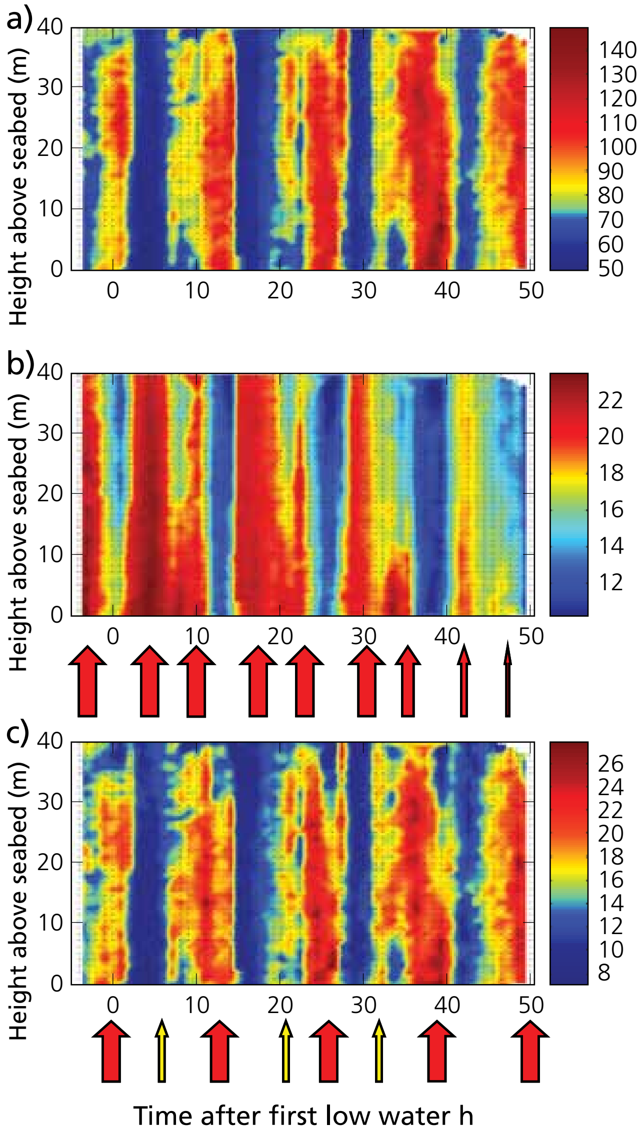


Figure 3.145 Spatial variation in median particle diameter (μm) along a transect off Anglesey. From Mitchelson-Jacob et al. (2006).

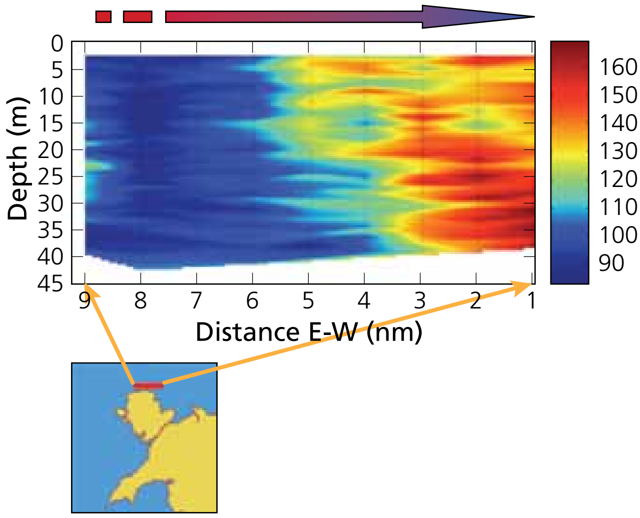
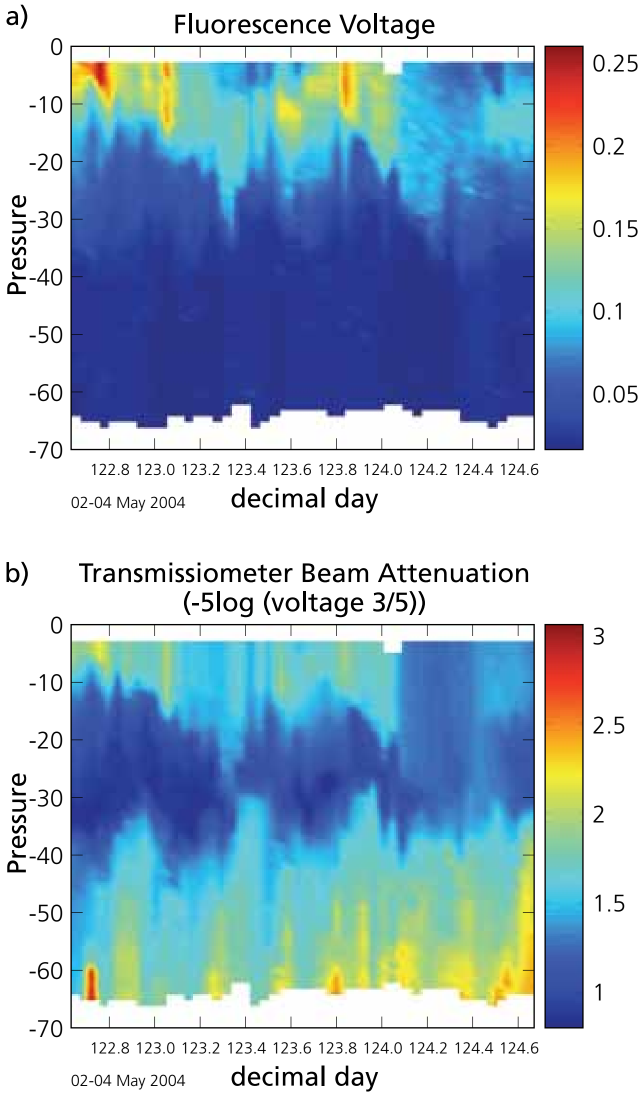


Figure 3.146 (a) Fluorescence and (b) beam attenuation during spring tides in the gyre of the Irish Sea. From unpublished CASIX data; courtesy of G. Mitchelson-Jacob, Bangor University.



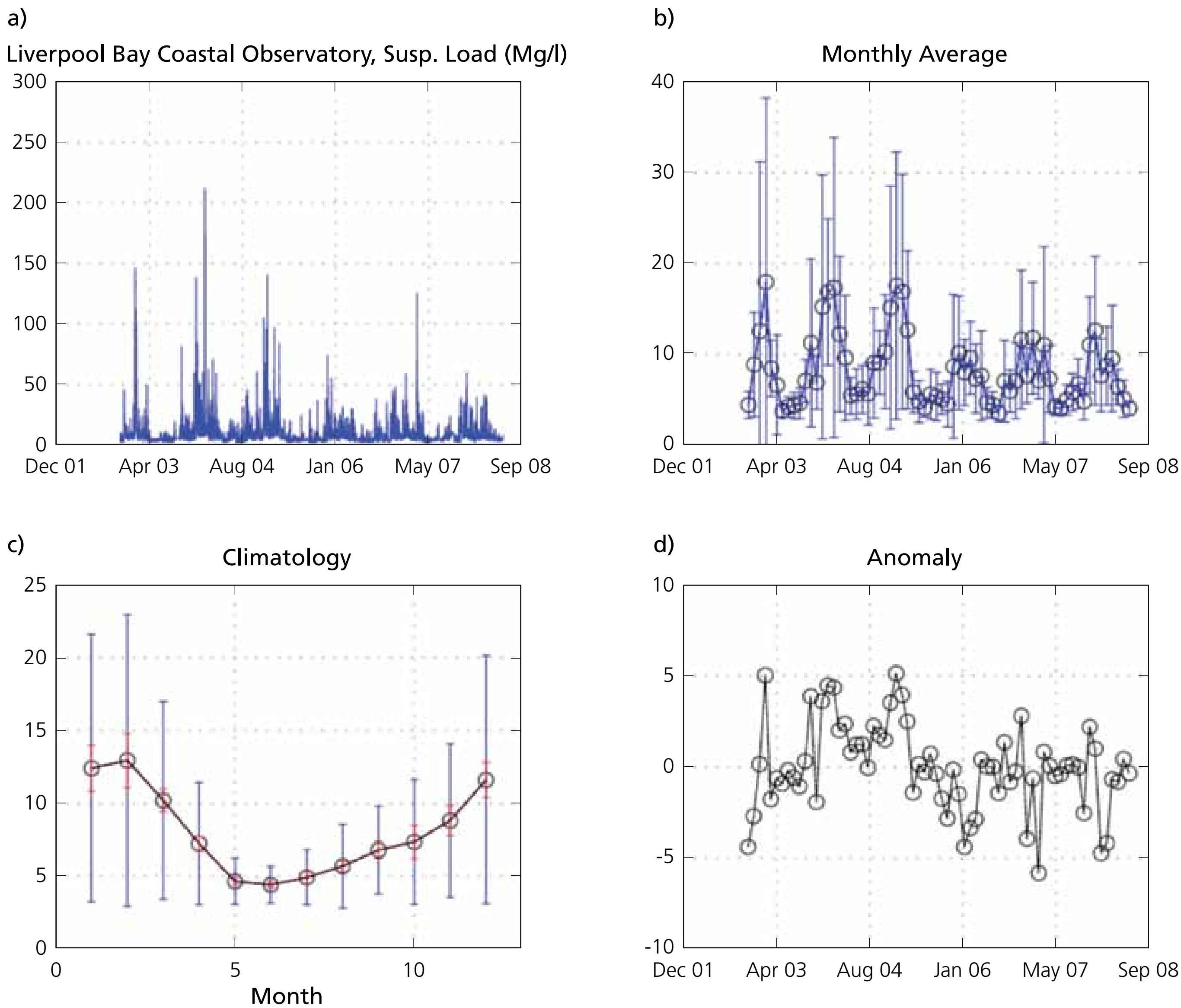
Resuspension occurs in deeper, stratified waters during spring tides. Thus in the gyre of the western Irish Sea, in water depth ~ 65 m, there is a clear M_4 resuspension signal on spring tides (Figure 3.146) but this is not seen on neap tides.

CASIX data (unpublished) shows the strong link between turbidity and phytoplankton (see Figure 3.146). The transmissometer data show turbidity maxima in the surface layer of the Irish Sea gyre and in the bottom mixed layer. Comparison with the fluorescence signal (representative of phytoplankton concentrations) shows the turbidity in the upper layer to relate to the higher abundance of phytoplankton in the stratified surface waters in May 2004. Turbidity in the surface layer is clearly linked to phytoplankton activity, while in the bottom layer it is due to resuspension of benthic fluff.

The National Oceanography Centre (NOC) runs the Irish Sea Observatory with regular sampling cruises and fixed moorings. For up to date data and full details of the instrumentation used, go to the website http://cobs.pol.ac.uk.

With Cefas, NOC maintains a SmartBuoy in Liverpool Bay from which time series of data measurements can be made. Figure 3.147 shows the Liverpool Bay time series of suspended load, with the monthly average, the climatology and the anomaly for the seven-year period from December 2001 to September 2008. The station in Liverpool Bay has high variability, as shown by the error bars for the monthly average and climatology.

Figure 3.147 Liverpool Bay time series for suspended load from the Cefas SmartBuoy for December 2001 to September 2008. The upper panels show the time-series of (a) half-hourly data and (b) monthly mean and standard deviation (blue error bars) of the half-hourly data. Panel (c) shows the seasonal cycle by mean and standard deviation (red error bars) of the monthly means, and also (blue error bars) the mean monthly standard deviation of the half-hourly data. Panel (d) shows the anomaly time-series of the monthly mean to the climatology. Courtesy of J. van der Molen and N. Greenwood, Cefas.



A recently developed 1D model of the resuspension of a mixture of non-cohesive SPM size fractions has been used to simulate successfully several years of the observed SPM in Liverpool Bay on supra-annual timescales, as shown in Figure 3.148 (van der Molen et al., 2009).

Studies in 2004-2006 piloted a scheme for using above-water radiometers mounted on ships of opportunity to monitor water quality in the Irish Sea (Mitchelson-Jacob et al., in prep). Figure 3.149 shows the variation in remote sensing reflectance across the Irish Sea over the range of wavelengths of the above-water radiometers mounted on the Irish Ferries' ship Ulysses crossing between Dublin and Holyhead twice daily. The plot from 23 September 2004 shows high reflectance in the east, off Holyhead, generally lower in the central Irish Sea and slightly elevated reflectance towards Dublin, indicating that suspended loads are higher closer inshore and lowest in the central region.

Figure 3.148 SPM concentrations at 1 m below the surface in Liverpool Bay. (a) Total concentration (grey: observations, black: model); (b) 10 µm fraction (model); (c) 31 µm fraction (model); (d) 60 µm fraction (model). The total concentration in the model is the sum of the three size fractions. All fractions were assumed to be non-cohesive quartz. The gaps in the model results represent times for which wave data were not available to force the model. The finest fraction rarely settles and provides a background concentration. The 31 µm fraction provides a seasonally varying background. The 60 µm fraction primarily responds to wave events because of its larger settling velocity. Reproduced from van der Molen et al. (2009).

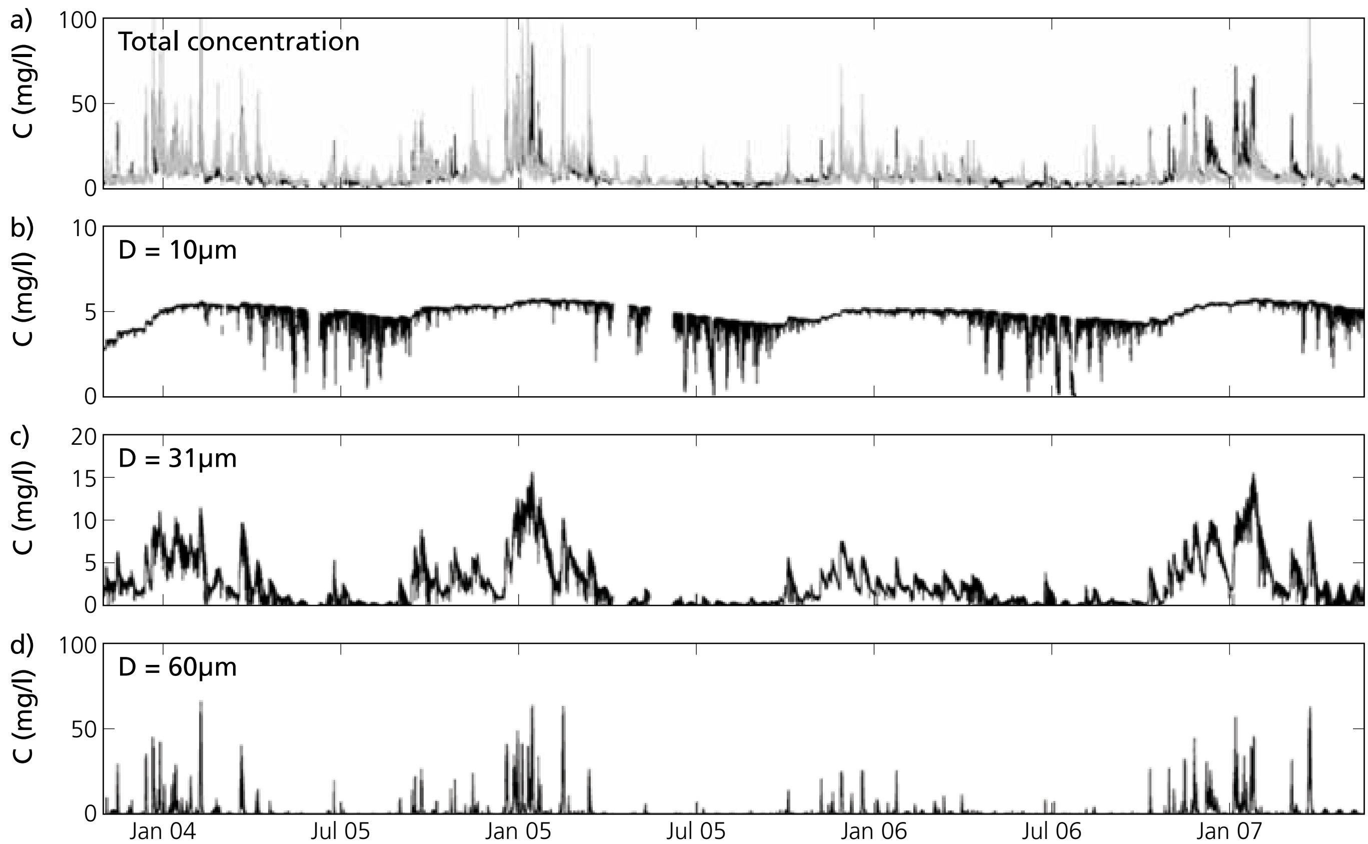


Figure 3.149 Variation across a spectrum (350 to 950 nm) of remote sensing reflectance measurements along a transect across the Irish Sea from Dublin to Holyhead. From Mitchelson-Jacob et al. (in prep).

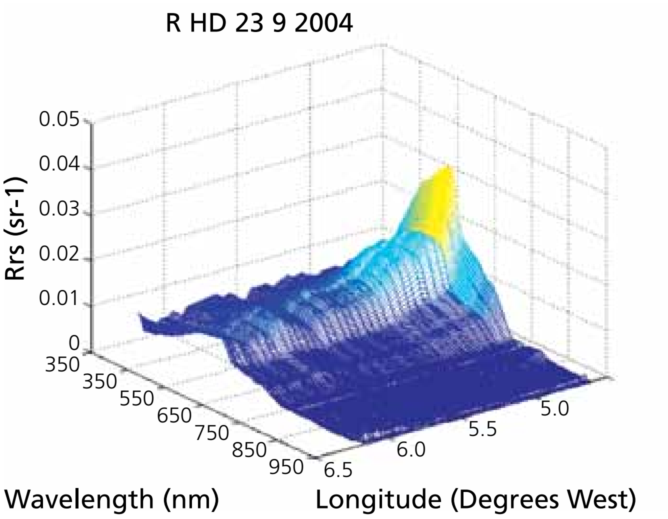
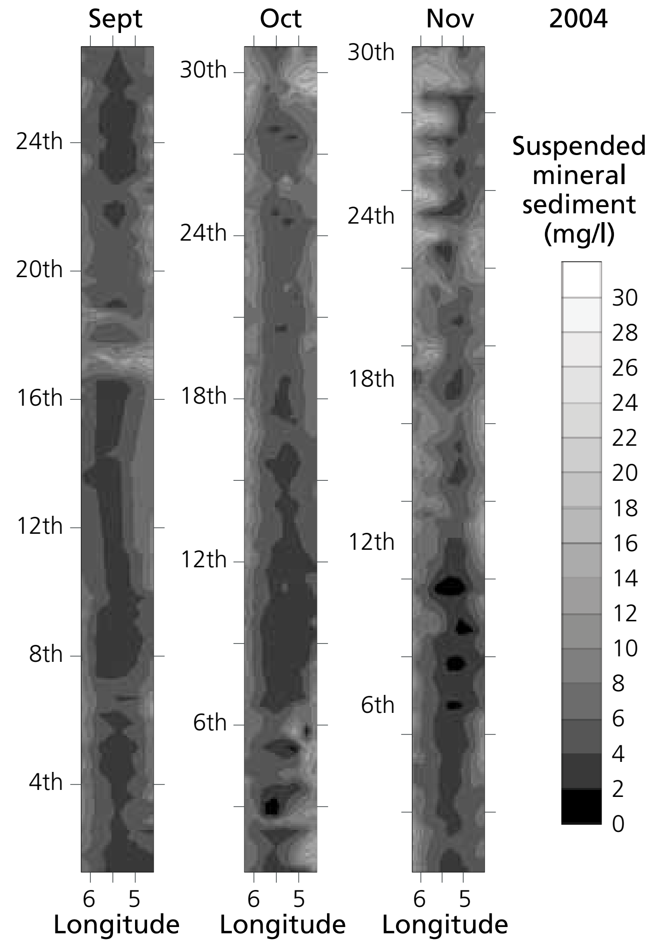


Figure 3.150 Monthly variations of turbidity (represented as mineral suspended sediment, mg/l) with a daily resolution for September to November 2004. From Mitchelson-Jacob et al. (in prep.).



From long-term *in situ* measurements carried out in the Irish Sea, a robust relationship has been observed between the reflectance ratio (665 nm / 555 nm) and the concentration of mineral suspended matter (MSS) (Binding et al. 2003, 2005). A relationship similar to this has been derived from the *in situ* data collected here – using the in-water samples collected to validate the optical measurements made. This relationship is used to retrieve MSS concentrations from the ferry radiometer data.

Monthly variations of turbidity with a daily resolution can be created using a kriging method for gridding the data in the Surfer Software. The results for September to November 2004 (Figure 3.150) show a number of features relating largely to the dynamical processes involved in the Irish Sea. There was minimum turbidity in the middle of the Irish Sea (~ 2 to 6 mg/l), with maximum values and variations close to the coasts (~ 6 to 30 mg/l). Distinct pulses, likely to be due to tidal resuspension or river inputs, can be seen off Dublin and Holyhead at times. Turbidity increased towards the winter.

3.7.4.2 North Sea

The southern North Sea, with stronger tidal currents and shallower water, has higher SPM concentrations than the northern North Sea. There is a strong seasonal signal in the southern part related to seasonality in the wave climate. A series of satellite images of reflectance at 555 nm during 1998, closely related to SPM concentrations, is at: http://www.oceannet.org/library/publications/documents/marine_processes_and_climate.pdf.

The images are NASA SeaWiFS composites for the North Sea 1998 at a resolution of 1.1 km. The scale is mg/l. The residual transport of SPM follows the anticlockwise gyre of the North Sea which, as a result, transports suspended matter eroded from the east coast of the UK (especially East Anglia). For comparison, more recent time series of $nL_w(551)$ and $k_d(490)$ for the UK shelf seas, as supplied by NEODAAS, are shown in Appendix 1.

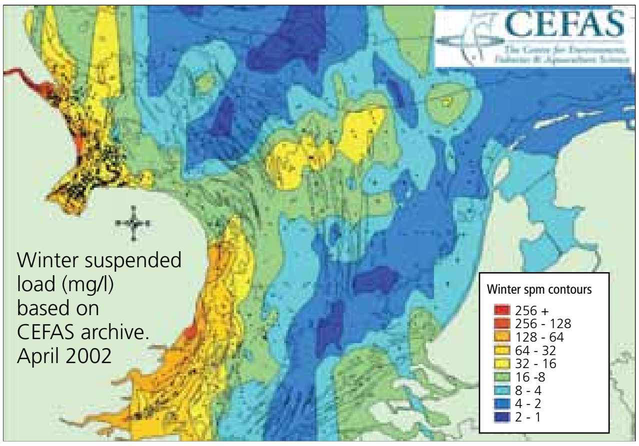
As part of the Southern North Sea Sediment Transport Study Phase 2 (SNS2), from 2000 to 2002, historic measurements of SPM were compiled (including the measurements made under Phase 1 completed in 1996), new measurements were made (April-December 2001) and compared with sediment transport models. The SNS2 was designed to provide a broad appreciation and detailed understanding of sediment transport along the eastern coastline of England between Flamborough Head in Yorkshire and North Foreland in Kent, on the south side of the Thames Estuary.

SPM values held by Cefas (as at April 2002 including the data collected in the SNS2 project) were grouped into measurements taken in summer and winter. The summer and winter distributions of suspended fine sediments obtained by sampling the surface waters of the southern North Sea are shown in Figure 3.151.

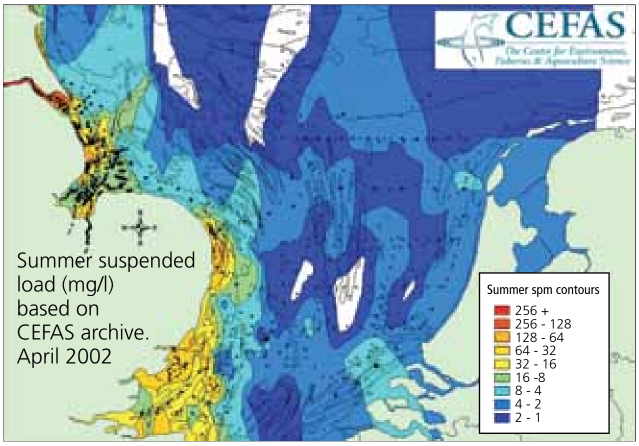
Concentrations of suspended sediment in the southern North Sea in summer (Figure 3.151) are generally low in offshore areas (0 to 4 mg/l), with higher SPM concentrations found in estuaries, especially the Thames and Humber with values over 300 mg/l. Some higher concentrations close to the coast were attributed to the Humber plume and the effect of high spring tidal currents off Great Yarmouth/ Lowestoft.

Figure 3.151 Suspended load based on SPM data in the CEFAS archive for April 2002 for (a) winter and (b) summer months. The data are from discrete water samples. From SNS2 (2002).

a)



b)

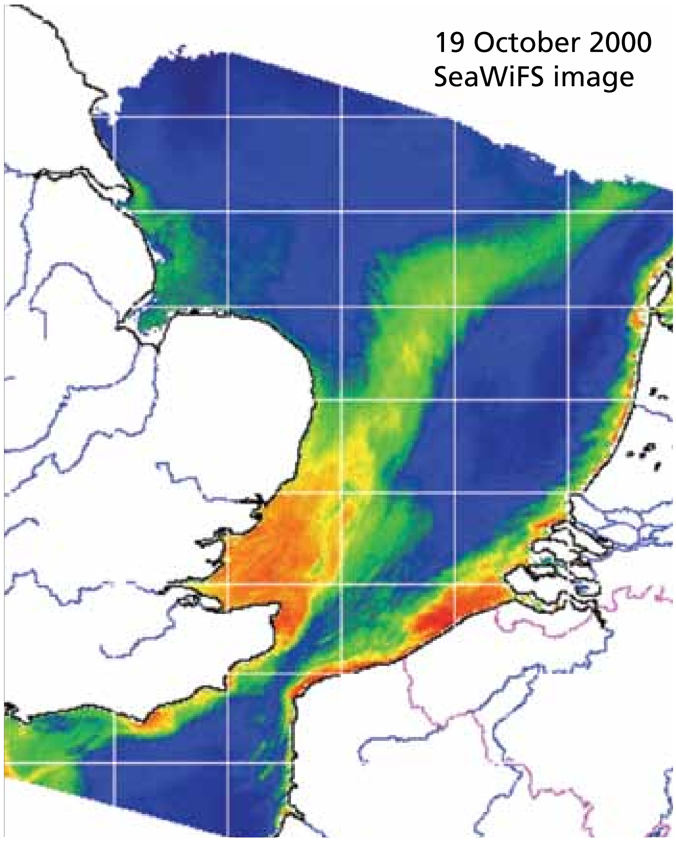


The winter suspended sediment concentrations are higher, generally about double the summer concentrations (Figure 3.151) but with similar patterns in the coastal areas. There is a dominant plume-like feature, reported by Dyer and Moffat (1998); it extends north-east from Norfolk across the North Sea towards the Netherlands and also showed in the modelling for SNS2. This may be due to local resuspension by wave activity but the data density in this region is too low to make definitive judgements. Figure 3.152 shows a SeaWiFS image from 19 October 2000 with a distinctive strong reflectance plume indicative of higher levels of suspended sediment.

A study in the southern North Sea off the Dutch coast illustrates how SPM properties are governed by an interacting combination of physical and biological processes (McCandliss et al., 2002). The study area was in ~ 20 m water depth and influenced by outflow from the Rhine. The observations in spring showed SPM and chlorophyll concentrations characterised by a two-layer structure with low concentration in the surface layer and higher concentrations near the bed. The surface layer, of relatively low salinity, contained larger particles than the more saline bottom layer (Figure 3.153).

Near-surface SPM was characterised by slow-settling particles (modal settling velocity 10^{-4} to 10^{-3} mm/s). Resuspension of relatively small, fast-settling (> 10^{-1} mm/s), predominantly inorganic particles occurred during spring tides and storms. During calm, neap tide periods, settling and deposition occurred (modal settling velocity 10^{-2} mm/s). The remaining SPM was dominated by large slow-settling particles, especially in the surface layer. In spring, phytoplankton formed a major slow-settling component of near-bed SPM, which was maintained in suspension during spring tides and storms but settled to form an aggregated phyto-detrital fluff layer during at least two calm neap tide periods. The observations show the relatively rapid rate at which fluff layers are formed and dispersed, and highlight the need for high frequency measurements during studies of vertical exchange processes.

Figure 3.152 Large-scale transport of suspended matter depicted by a SeaWiFS image from 19 October 2000, clearly showing the extent of the Thames plume. From SNS2 (2002); data supplied by NEODAAS.



Fettweis et al. (2006) showed the strong relationship between the floc size of SPM and the turbulence regime over tidal cycles in the Belgian coastal zone (Figure 3.154). As a result, floc size increases offshore as turbulent stresses diminish.

Resuspension of benthic fluff also occurs in much deeper water. A study in the northern North Sea (water depth > 100 m) shows that a threshold bed shear stress of 0.02 to 0.03 Pa was needed to resuspend fluff so that resuspension occurred on spring tides (Jago et al., 2002). However, peak bottom-layer SPM concentrations preceded peak tides by three days due to a finite supply of fluff at the site. Modal settling velocities of SPM in long-term

Figure 3.153 (a) SPM concentration (mg/l), (b) chlorophyll concentration (mg/m³), (c) median particle diameter (µm) and (d) salinity in the southern North Sea, spring 1999. From McCandliss et al. (2002).

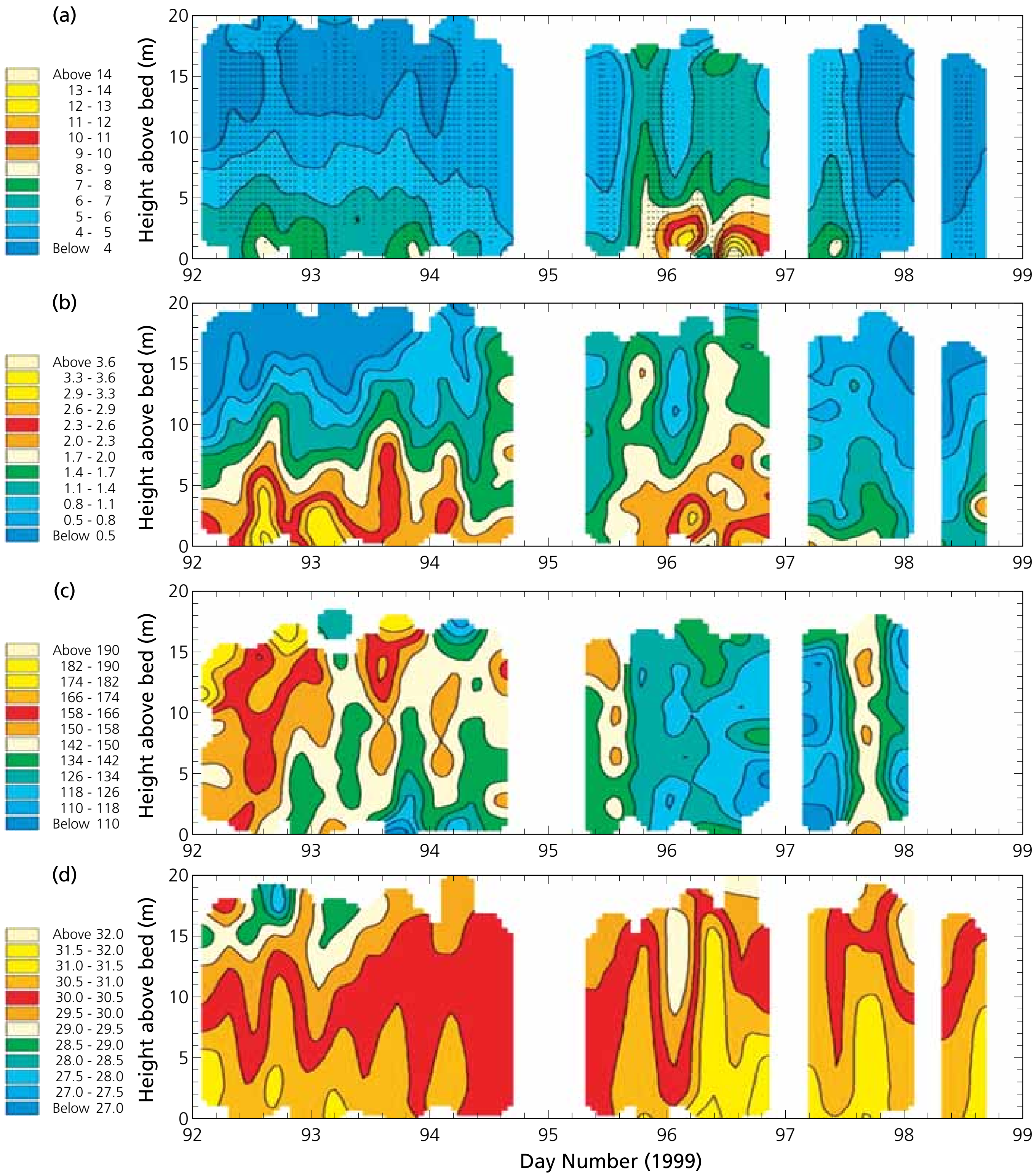
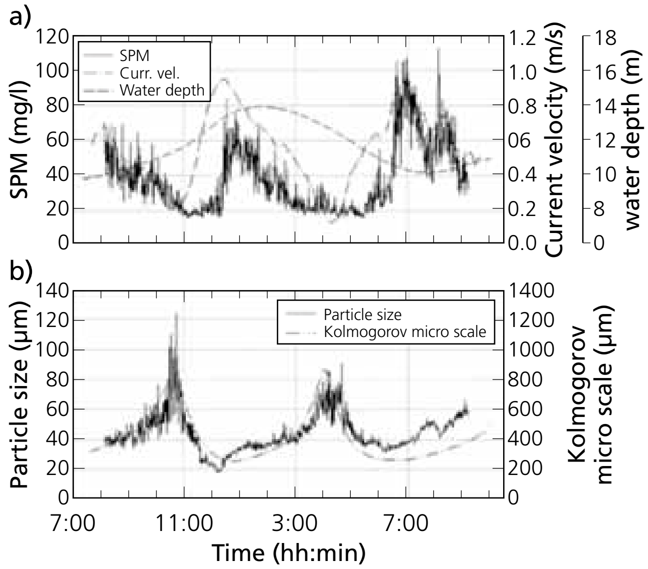


Figure 3.154 Through-tide measurements in September 2003. (a) SPM concentration (mg/l), water depth (m) and vertically averaged current velocity (m/s) and (b) averaged particle size (µm) and Kolmogorov microscale of turbulence (µm; from model result). Measurements at ~ 3 m above bed. From Fettweiss et al. (2006).



suspension were 10^{-4} to 10^{-3} mm/s while the resuspension component had modal values 0.2 to 5.7 mm/s (Figure 3.155).

Cefas SmartBuoy data from the southern North Sea (Figures 3.156 and 3.157) show the time-variation in suspended load, its monthly average, climatology and the anomaly over the seven-year period from December 2001 to September 2008. This shows the annual peaks of suspended load increasing from 2001 to 2007 for Warp (TH1) NMMP, from the outer Thames Estuary, with higher (~ two-fold) concentrations than at West Gabbard to the north. The peak concentrations occur in the winter months, highest in March, with the lowest concentrations occurring after the spring phytoplankton bloom in May/June. All plots indicate that suspended load is highly variable.

3.7.4.3 English Channel

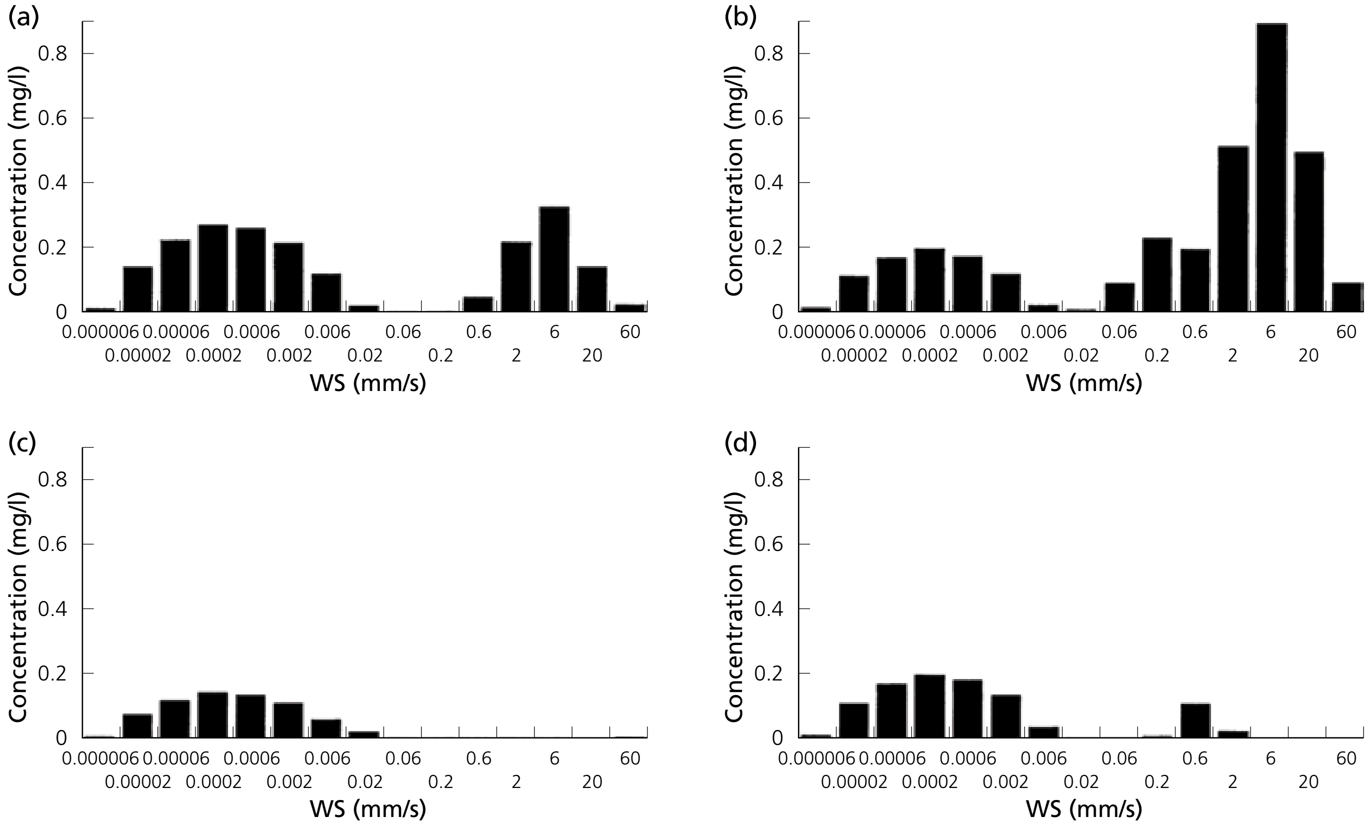
Seasonal observations of the nature and concentration of SPM for the western boundary of the eastern English Channel were reported by Velegrakis et al. (1999). The highest concentrations were found adjacent to the English coastline, with lower concentrations offshore (Figure 3.158). The highest concentrations occurred in winter when SPM was enriched with coarse silt particles. The diatom communities found within SPM indicate that material resuspended in the coastal zone was transported offshore. SPM fluxes (based upon the observed SPM concentrations and the output from a 2-D hydrodynamic model) from the western Channel ranged between 2 and 71 × 10^6 t/y with a mean of around 20 × 10^6 t/y over the period of the observations (1994–1995). These fluxes are comparable to the mean values previously reported (Defra et al., 2005) as output through the Dover Strait. Therefore, it is possible that the eastern English Channel may be characterised as an area of fine-grained sediment bypass.

3.7.5 What the evidence tells us about environmental status

The main changes associated with suspended material and turbidity are from new developments in methods for sensing SPM, for example the LISST, measurements of turbulence, and developments and new sensors in Earth Observation.

- Trends in SPM concentrations and turbidity, identified in *Charting Progress* (Defra et al., 2005), show no significant change.
- Traditional methodologies are still used successfully, although more emphasis is on optical techniques, such as transmissometers and radiometers. Each of these provides

Figure 3.155 Settling velocity spectra (a) near-surface and (b) 1 m above bed showing enhanced tidal resuspension component (fluff) near the bed; (c) near-surface and (d) 1 m above bed four days later at peak spring tide after total removal of the fluff layer, so low SPM concentration and minimal resuspension. From Jago et al. (2002).



limited data due to the current lack of understanding of marine optics, especially in turbid waters. Many optical studies relate to weight of SPM – but particle size is also important.

- New optical instrumentation is now available to study particle size, such as LISST – low-angle laser scattering or laser diffraction instruments. This has increased understanding of the dynamics and processes associated with suspended particles in shelf seas, especially tidal stirring of sediments.
- Remote sensing measurements of ocean colour provide time series for studying variability at a higher resolution than previously. Two parameters are used: water-leaving radiance in the green, for example $nL_w(551)$ and diffuse attenuation, $k_d(490)$. However, these measurements are still hampered by limitations such as weather and by a lack of understanding of the coastal and shelf water marine optics ('Case 2' problem).

Good-quality waters are needed to sustain a fully-functioning healthy ecosystem. Recent data improve understanding of coastal and shelf sea processes, especially with respect to particle size and SPM. Current evidence is that the concentrations of suspended material, and therefore the turbidity, have not significantly changed since *Charting Progress*. Specific, localised, inshore high-turbidity events have been seen following heavy rain events and

Figure 3.156 Warp (TH1) NMMP time series for suspended load from the Cefas SmartBuoy for December 2001 to September 2008. The upper panels show (a) the time-series of half-hourly data and (b) monthly mean and standard deviation (blue error bars) of the half-hourly data. Panel (c) shows the seasonal cycle by mean and standard deviation (red error bars) of the monthly means, and also (blue error bars) the mean monthly standard deviation of the half-hourly data. Panel (d) shows the anomaly time-series of the monthly mean to the climatology. Courtesy of J. van der Molen and N. Greenwood, Cefas.

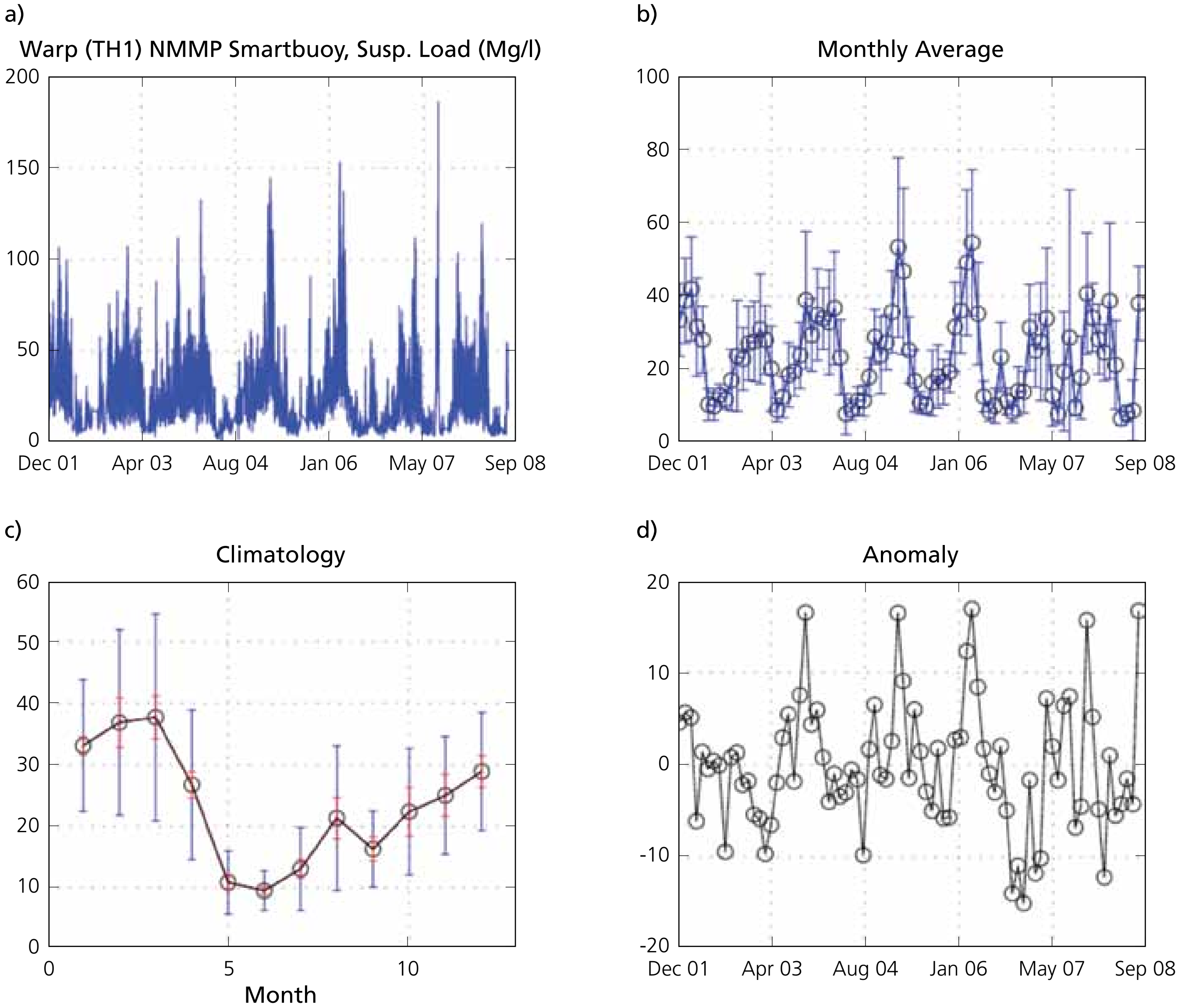
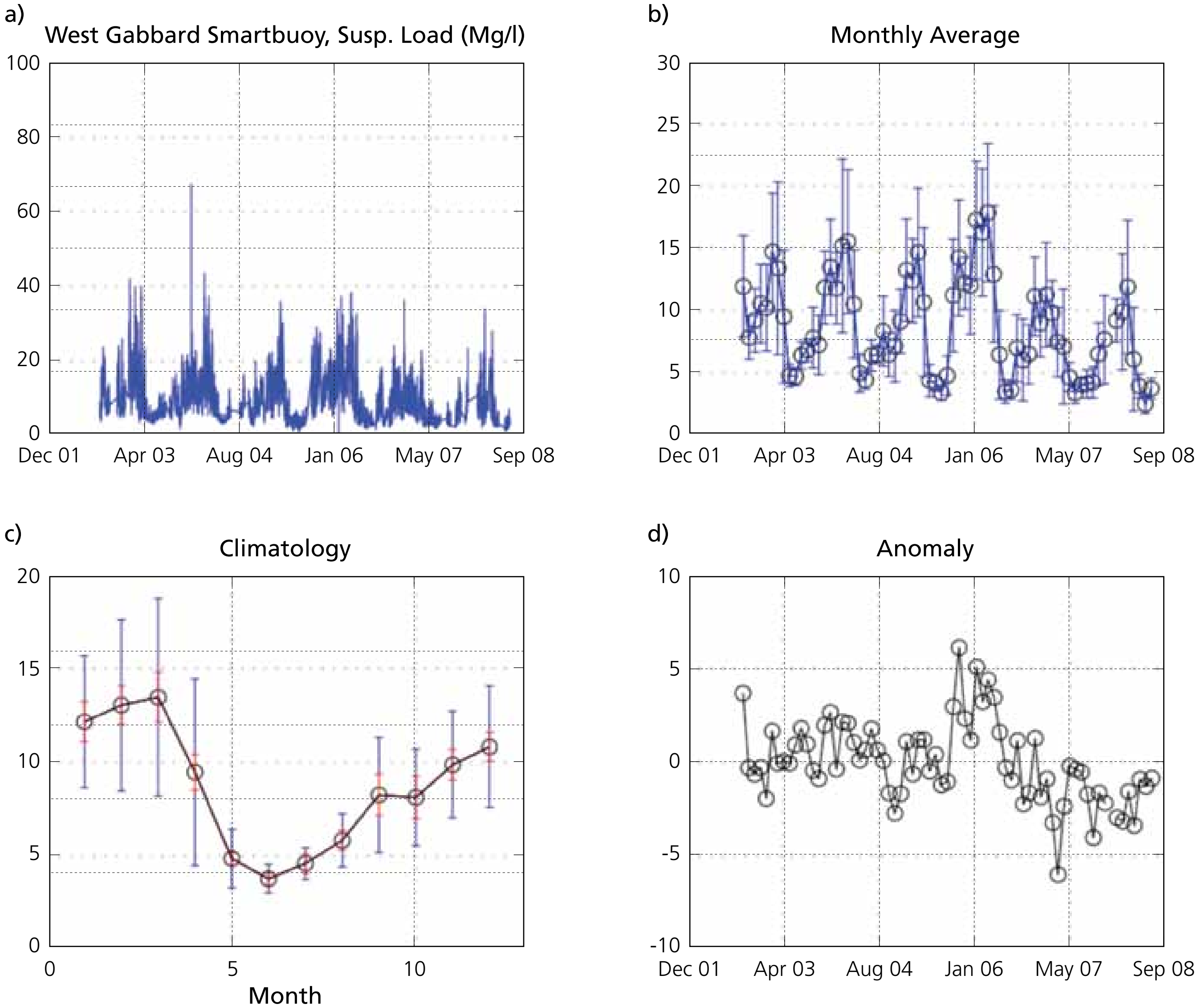


Figure 3.157 West Gabbard time series for suspended load from the Cefas SmartBuoy for December 2001 to September 2008. The upper panels show (a) the time-series of half-hourly data and (b) monthly mean and standard deviation (blue error bars) of the half-hourly data. Panel (c) shows the seasonal cycle by mean and standard deviation (red error bars) of the monthly means, and also (blue error bars) the mean monthly standard deviation of the half-hourly data. Panel (d) shows the anomaly time-series of the monthly mean to the climatology. Courtesy of J. van der Molen and N. Greenwood, Cefas.



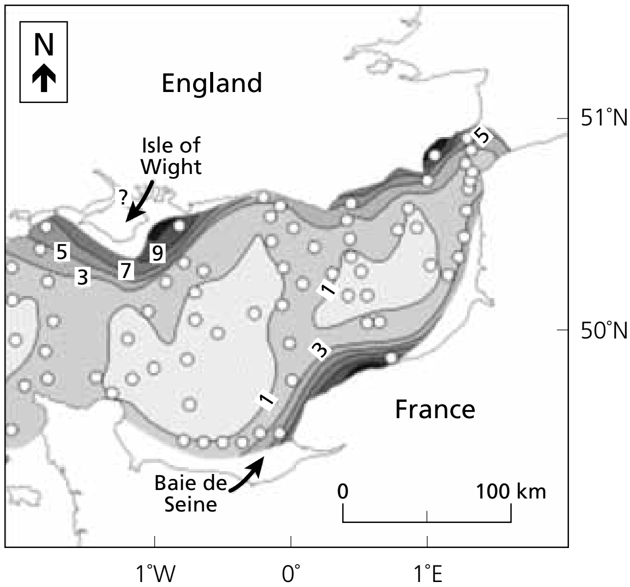
localised flooding, but this has always been the case.

Satellite monitoring, although an attractive approach for broad-scale assessments of water quality with the higher spatial and spectral resolution of current sensors, is limited by the difficulty of obtaining high-quality images, by cloud conditions over the UK shelf seas; also it can only assess surface waters. Despite the limitations, through its easy method, with a good spatial scale for UK shelf seas, the use of colour satellite imagery can be a contributor to monitoring environmental status and its change over time.

The summary table (Table 3.13) includes an assessment of trend but not status ('traffic-light') because (1) no accepted criteria apply for suspended material giving significant risk of adverse effects; and (2) the UK (government), or even the EU, cannot itself take measures to improve the status.

Suspended sediment is subject to a wide range of natural variability on many time scales, reacting quickly to local flow (circulation) and conditions for phytoplankton production. There is no reason to suppose that this variability or typical suspended concentrations have changed significantly to have an impact on the environment or human health. Local construction has the potential to introduce local changes and significant impacts on the spatial scale of the construction, such as in harbours and around wind turbine pylons. Climate change, given the expected changes of sea-level rise and a potential increase in storminess, will impact on suspended load, with many coastal areas becoming more turbid through direct impact of both these scenarios. The higher sea level rises, the more upper-beach/terrestrial sediment will enter the marine environment, adding to the sediment load and potentially changing the type (and particle size) of sediments in suspension in coastal regions. Any increase in storminess through wind and or wave action will impact on shallow water regions in particular by increasing the resuspension of bottom material.

Figure 3.158 SPM concentrations (in mg/l) in the surficial waters of the eastern English Channel (early September 1994). The open circles show the locations of the sampling stations. From Velegrakis et al. (1999).



3.7.6 Forward look and need for further work

Both new and previous data of SPM and turbidity variations in UK waters show that there are gaps in understanding and that a clear picture of the spatial and temporal variability of SPM and turbidity is missing – largely due to the rate of change in the dynamic processes that control these. To assess how this relates to environmental status needs an understanding of the role of SPM in the marine environment. SPM controls the entry of light into the sea,

Table 3.13 Summary assessment of trends.

Parameter	*CP2 Region*	*Key factors and impacts*	*What the evidence shows*	*Trend*	*Confidence in assessment*	*Forward look*
Suspended Particles	1, 2, 3, 4, 5 (North Sea, Channel, Celtic Sea, Irish Sea)	Tides, winds, waves, site. Affects primary production	Varies on short scales	No clear trend	Medium	Nearshore increase?
Suspended Particles	6, 7 (Scottish shelf seas)	Tides, winds, waves, site. Affects primary production	Varies on short scales	No clear trend	Medium – no new data identified	Nearshore increase?
Suspended Particles	8 (Adjacent Atlantic)	Tides, winds, waves, site. Affects primary production	Varies on short scales	No clear trend	Medium – no new data identified	No clear trend

and binds pollutants and nutrients, such as phosphate. Better knowledge is needed of how these bindings occur and under what conditions release occurs.

The main questions to be addressed are therefore:

- What is the role of SPM in determining, and therefore changing, environmental status?
- Are background levels of SPM changing and, if so, is the change significant?
- What is the role of SPM in the diagenetic processes that bind nutrients to it; what happens to these nutrients; how are they released back into the environment?

For the future, the impacts of SPM on environmental quality need to be assessed under climate change scenarios:

- Will increased storminess increase mobilisation of sediments and release pollutants back to the water column and how might this impact on marine ecosystems and human health?
- How could these increased levels of turbidity affect optical properties of the shelf seas and what will be the impact of this on phytoplankton blooms and productivity?
- How might changes in catchment affect coastal waters – impacts of climate change on both catchments and coastal regions?
- How will raised water temperature affect phytoplankton biogeochemistry and how will that feed back upon SPM through flocculation processes?

Advances in marine optics and use of in-water and remotely-sensed data for monitoring SPM and turbidity in coastal and turbid waters highlight areas of uncertainty and limitations in their use. Although improvements have been made, the ‘Case 2’ problem for use of ocean colour satellite data in turbid waters is still unresolved and inhibits the derivation of precise ocean colour data due to a poor atmospheric correction; SPM is a major inhibitor in the ability to derive phytoplankton measurements in sediment-laden waters.

Integrated coastal zone management (ICZM) is being rolled out in many regions, each with ‘new’ indicators for this. For example, the Wales Coastal Maritime Partnership has compiled ICZM indicators for Wales – see the draft list at www.walescoastalpartnership.org.uk/images_client/resource/Draft%20List%20of%20Welsh%20ICZM%20%20Indicators.pdf. These bring to the fore management issues for coastal waters where SPM levels can have negative socio-economic impacts; from impacts on human health to the aesthetics of bathing waters.

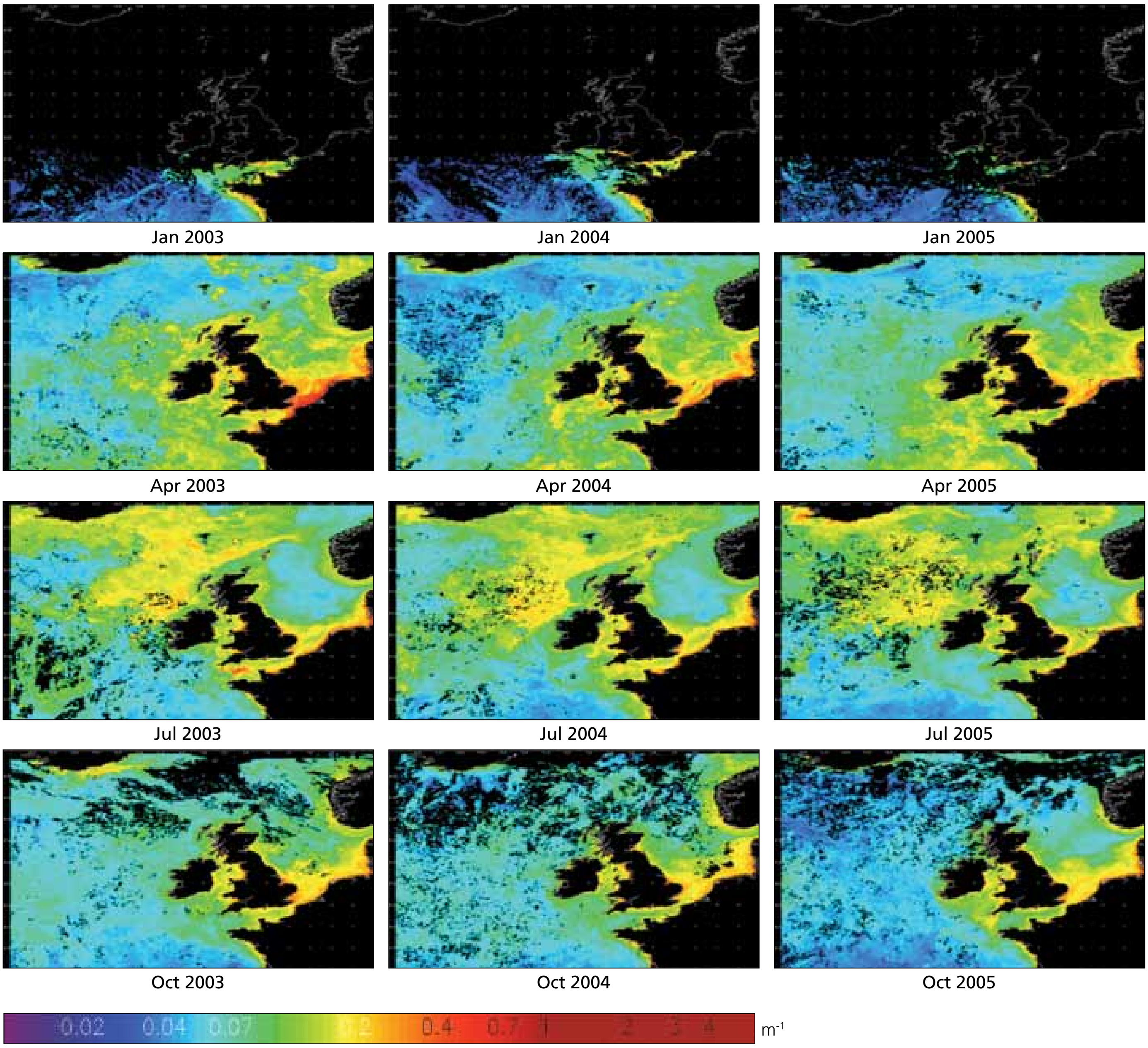
CETaSS – the Wirral Shoreline Management Plan (SMP) – Stage 1 Scoping study (Cell Eleven Tidal and Sediment Study; Faber Maunsell, 2005) recommends the need for more quantitative information, especially on shoreline processes, wave interactions (inshore wave climate) and water flow along coasts for improved shoreline management plans.

3.7.6.1 Conclusions

The present state shows little change since *Charting Progress*. However, given recognised climate change impacts for coastal regions, changes are anticipated in the future. Several proposed studies aim to assess how climate change will impact coastal regions and model the scenarios for this. There is a lot of interest and activity in coastal regions with the EU ICZM recommendations and a number of large EU-funded projects studying turbidity in coastal regions, for example, IMCORE - Innovative Management for Europe's Changing Coastal Resource.

Appendix 1 NEODAAS imagery – nLw(551) and kd(490) for UK Shelf Seas

Figure 3.7.A1 Turbidity maps from Earth Observation data for selected months from each season, 2003-2007. These show Aqua-MODIS diffuse attenuation coefficient kd(490), which indicates the fraction of blue-green light that is attenuated per metre depth. Turbidity indicates the presence of both suspended sediments and phytoplankton, and so there is large interannual variability in this parameter. Low light in January prevents the reliable use of Aqua-MODIS data at higher latitudes. In April the turbidity is dominated by suspended sediment, particularly in the southern North Sea, though the spring bloom is often present in the Celtic Sea. In July the sediment is at a minimum so the turbidity indicates phytoplankton in the NE Atlantic. With less phytoplankton growth, October turbidity is mostly influenced by sediment. Although the seasonal patterns are similar across 2003-2007, bloom events provide the most noticeable differences, for instance in the Atlantic NW Approaches in July 2005 and northern North Sea in April 2007.



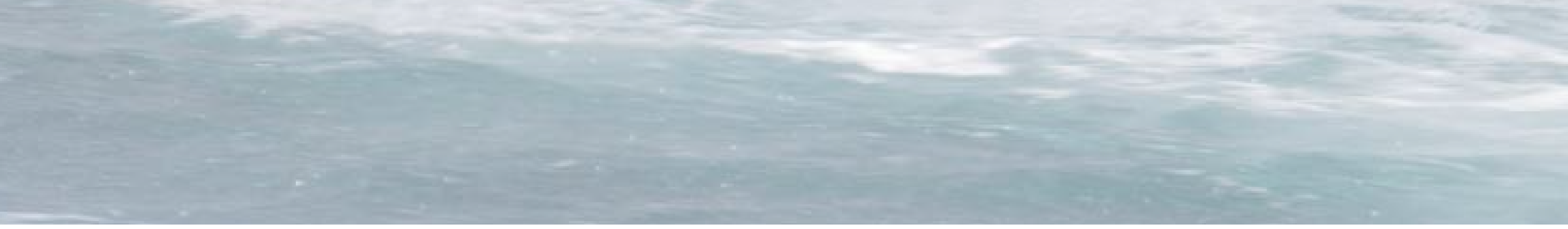


Figure 3.7.A1 continued.

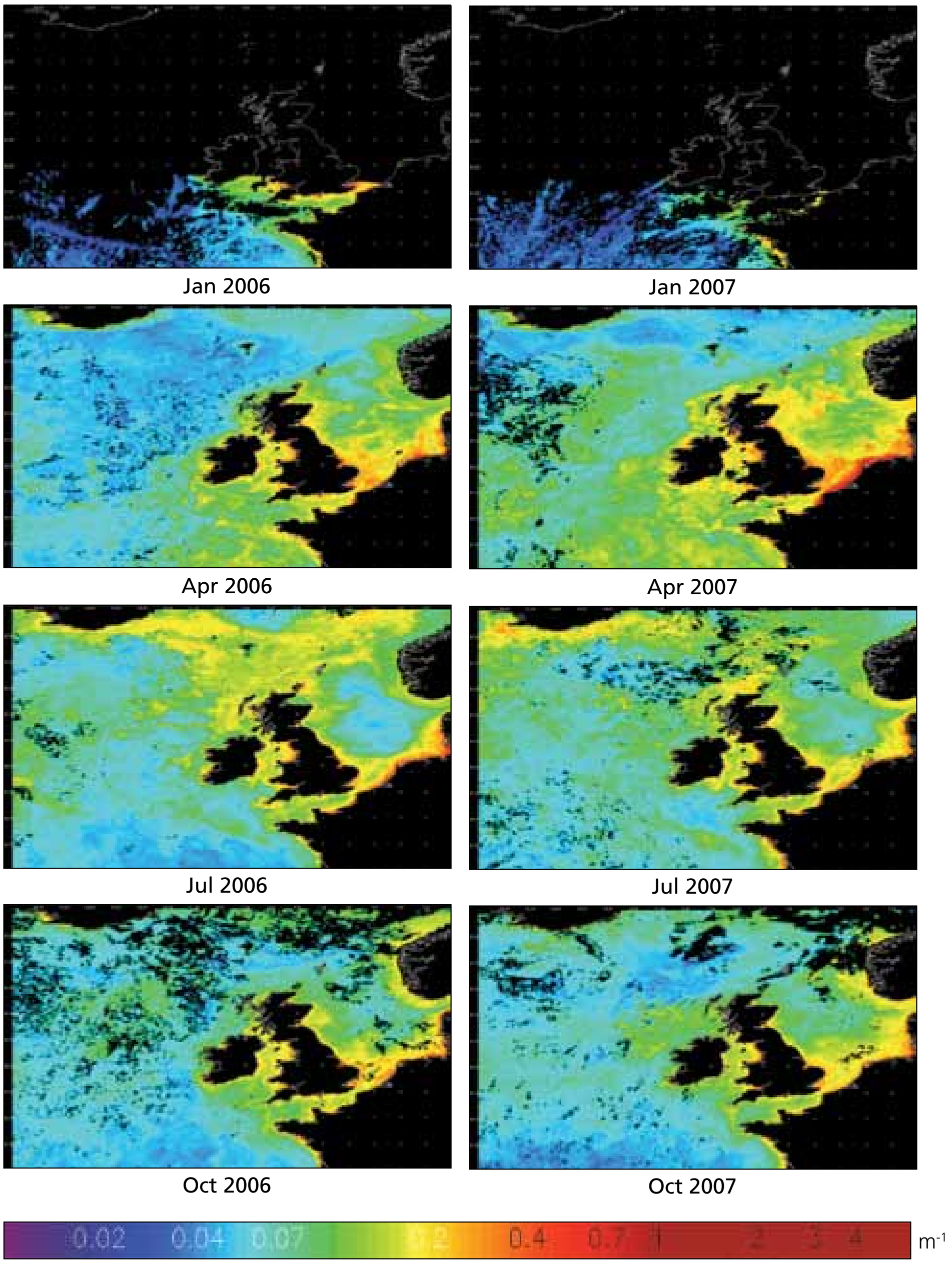


Figure 3.7.A2 Maps of monthly suspended sediment concentration from Earth Observation data. These are Aqua-MODIS water-leaving radiance at 551nm - nLw(551), which may be used as a proxy for suspended sediment, though note that it also highlights scattering particulates such as coccoliths. These maps clearly show the spatial distribution of suspended sediment in UK waters seasonally from 2003 to 2007. The seasonal pattern is consistent across these years, with much less interannual variability than the corresponding turbidity maps. It can be seen that the Irish Sea, southern North Sea, and northern English Channel are subject to high sediment loads for most of the year except summer. Coccolithophore blooms are often present in the North Sea in July.

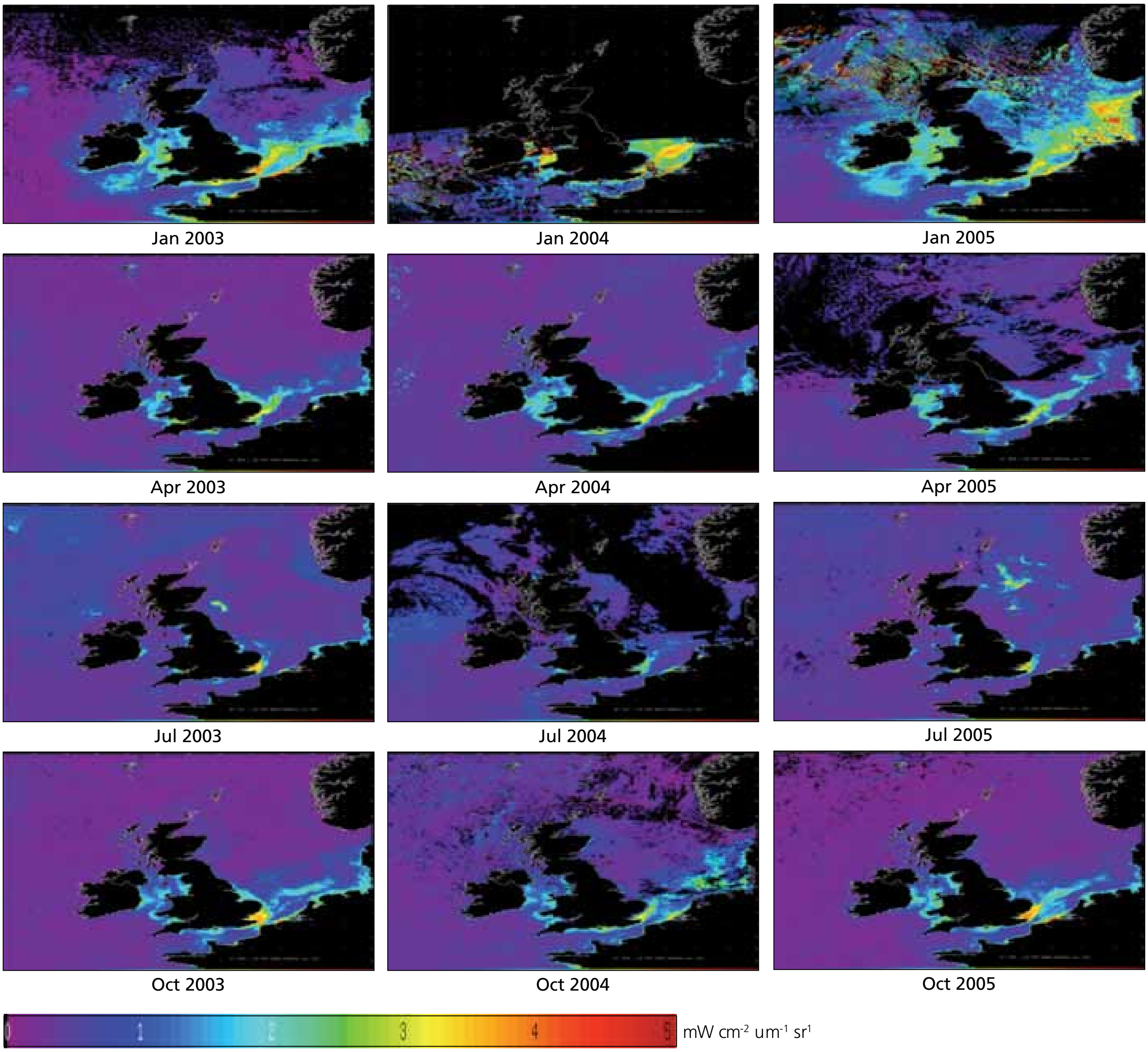
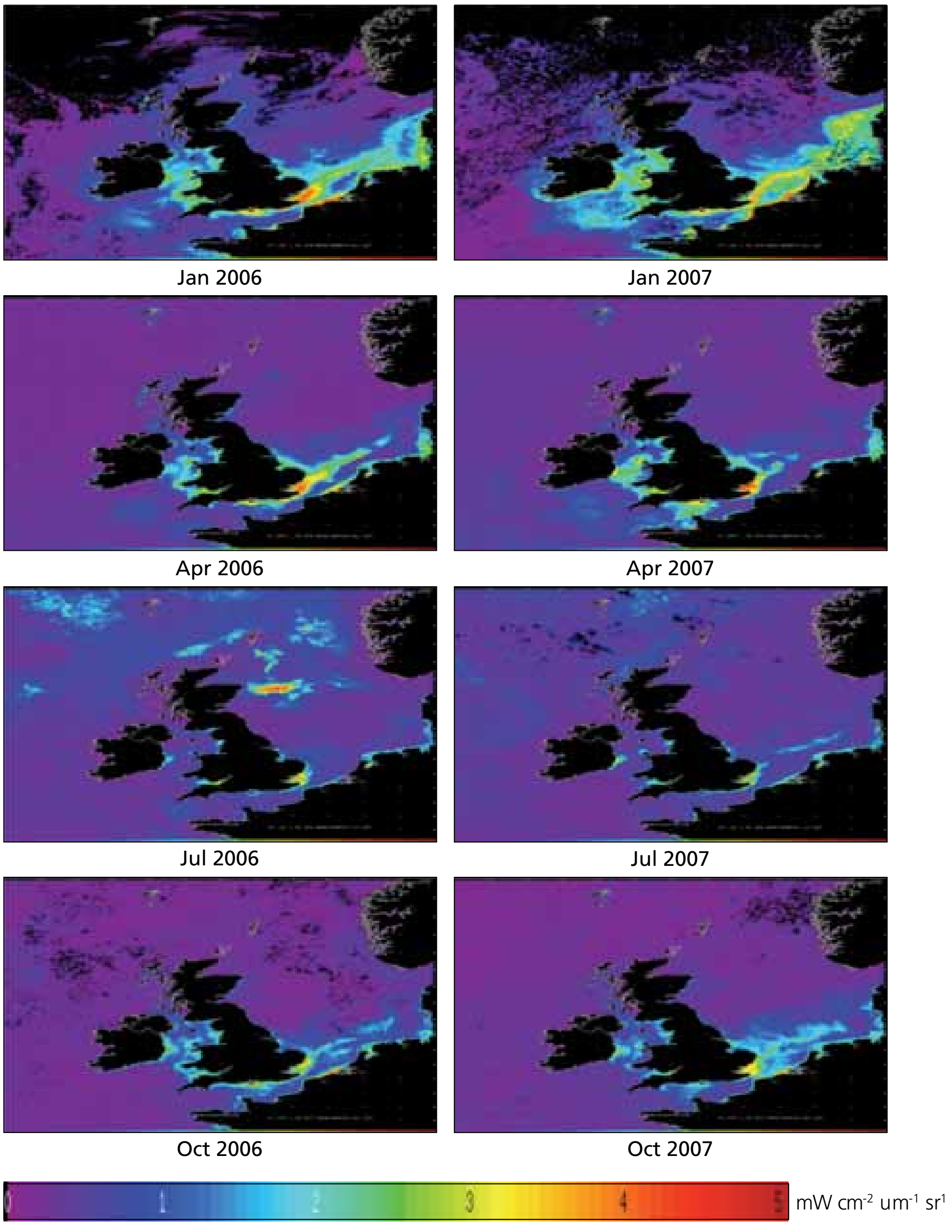


Figure 3.7.A2 continued.



3.8 Sedimentary Processes and Morphology

3.8.1 Key points

i. Introduction

This report focuses on the geology and bathymetry of the seabed across the United Kingdom. The nature of the seabed plays a critical role in the distribution of benthic habitats, which form an integral part of much of ocean life. It underpins much of the biodiversity in the seas around the UK and it is therefore important to understand the seabed as an integral part of the ocean system. Knowledge of the seabed is also a key factor in the location of many marine installations, such as wind farms and aggregate extraction sites. Whereas most of *Charting Progress 2* reports on the environmental pressures and impacts of change in the seas, this section focuses on the growing evidence available on the nature of the seabed, and highlights that in many areas detailed survey information is not yet available.

ii. How has the assessment been undertaken?

Data from many sources, including research programmes and commercial surveys, have been brought together for the first time to give a clearer picture of what is known about the detailed distribution of sediments on the seabed. In areas of relatively rapid coastal erosion there are monitoring projects on the rate of change, but for the offshore environment this report focuses on where and what data exist.

The advent of multibeam echosounder systems (MBES) has provided a new approach to seabed mapping and has provided a technological means of bringing geologists, biologists, archaeologists, engineers and hydrographers together through common data collection and interpretation techniques. MBES data collection programmes have expanded dramatically since *Charting Progress* (Defra et al., 2005). This powerful technology has the potential to revolutionise our understanding of the seabed and, for the first time, provide the data resolution necessary to underpin marine planning. New data have been collected in all regions using MBES, but only a small fraction (around 15% of the whole UK seabed) is covered.

iii. Current and likely future status of sedimentary processes and morphology

In offshore areas the rate of change of the seabed is generally low, with rapid changes restricted to shallow areas where wave action is strong. The area of most change is in the coastal zone where coastal erosion is occurring; along 17% of the UK coastline (30% of England's coastline; 23% Wales; 20% Northern Ireland; 12% Scotland). Almost two-thirds of the intertidal profiles in England and Wales have steepened over the past 100 years. Steepening of the intertidal profile is particularly prevalent on coasts defended against erosion (this represents 46% of England's coastline; 28% Wales; 20% Northern Ireland; 7% Scotland). Both coastal erosion and steepening of intertidal profiles are expected to increase in the future, due to the effects of sea-level rise and changes to wave conditions. In low-lying coastal regions of England it is estimated that at least 40 to 100 hectares of saltmarsh are being lost every year and it is predicted that 'coastal squeeze' and habitat loss will be accelerated by continued sea-level rise.

iv. What has driven change?

Erosion, especially by waves from offshore, and hard rock or inshore structures, combine to steepen intertidal profiles, i.e. reduce intertidal area.

v. What are the uncertainties?

Provision of detailed geological interpretations of the seabed based on multibeam surveys are only just beginning, with small areas linked to specific projects having been completed. In very shallow waters, the time to survey, and therefore the cost, has limited progress; however, it is this coastal 'envelope' (the 'white ribbon') that suffers from a lack of good quality modern survey information. At a national level, the main geological interpretation remains based on pre-multibeam data.

vi. Forward look

The distribution of mobile sediment and how this will react to climate change and development of offshore resources is a topic for future research. Understanding the rates and distribution of coastal erosion and changes to beach dynamics in response to climate change and sea-level rise will be an area for new research and monitoring. The importance of the coastal zone in terms of coastal erosion and flooding, habitats and commercial uses, make this a key area for future work.

With current detailed survey rates in existing programmes, it will be many years before survey coverage is complete. An increase in detailed surveying (in particular with MBES) will provide high quality bathymetric data and form the basis for subsequent geological and habitat analysis to underpin future marine planning and to support commercial exploitation (such as marine renewable energy sources), environmental monitoring, conservation and other legislative drivers.

In the UK there are many collectors of MBES data for a wide range of different uses. This contrasts with countries like Ireland, that have one integrated marine mapping programme, funded to rapidly complete the entire Irish seabed (see www.gsi.ie/Programmes/INFOMAR+Marine+Survey/). Better integration of Government-funded surveys and re-use of commercial data will also increase the efficiency of environmental surveys and assist with spatial planning between different users. Progress is being made in this area through initiatives between different Government organisations.

3.8.2 Introduction

A sound knowledge of the seabed environment, and the processes that shape the seabed characteristics, is important for managing our seas, to develop our marine resources in an economic, efficient and sustainable way, and simultaneously to conserve key areas and maintain biodiversity. In particular, the coastal zone is of crucial importance; here, marine processes interact with the onshore environment. Drivers for coastal evolution include changes in relative sea level, antecedent topography, sediment supply, climate (wave climate, storm surges, rainfall), coastal engineering, renewable energy installations, land use and other anthropogenic factors. The intertidal zone is especially dynamic: beach and shoreface profiles can change rapidly in response to storms; seasonally, beach profiles are typically steeper in winter and broader/less steep in summer. Static bathymetric or sediment distribution maps are therefore misleading, and need to be considered in relation to environment variability and sediment mobility; monitoring is important. (The coastal zone may be defined as the area of land influenced by marine processes together with the offshore area influenced by terrestrial processes, including areas where natural processes or anthropogenic activities have direct impact on processes occurring at the coast; P. Balson, BGS, pers comm.2009).

Although the first Admiralty charts of UK coastal harbours and ports were produced in the early 19th century, marine geological mapping in the UK began in the 1960s after the discovery of hydrocarbons in the North Sea. Geological maps were based on seismic data, seabed samples and cores; in places with oil industry interest, the maps benefited from detailed subsurface data. Collaboration between geologists and hydrographic surveyors was variable, but where available, bathymetric data could provide geomorphological evidence to enhance the interpretation. Links between biologists and geologists were relatively poor and sampling for geology and biology were often parallel and unrelated activities.

The development of multibeam surveys (see Section 3.8.2.2) much improves our knowledge of the seabed. In areas with multibeam coverage, there are the geospatial data necessary to greatly enhance our understanding of the marine environment and put into context much of the environmental monitoring data discussed elsewhere in *Charting Progress 2*.

3.8.2.1 Policy drivers and users of geological and bathymetric data

Policy drivers for collecting detailed bathymetry and developing our understanding of the seabed include underpinning data for developing marine planning, EU Water Framework Directive reporting and implementation of the EU Habitats Directive. There is also increasing pressure from the EU through the Marine Strategy Framework Directive. The cross-cutting and multidisciplinary usage of detailed data is clearly demonstrated in Table 3.14. A recent cost-benefit analysis undertaken in Ireland has demonstrated the value of undertaking a National Seabed Survey based primarily on MBES technology (PriceWaterhouseCoopers, 2008).

3.8.2.2 The multibeam echosounder systems (MBES) technique

Figure 3.159 shows the basic layout for data collection using MBES techniques. Sound waves in discrete beams are transmitted and received at the ship. In shallow water the width of the survey swath is narrower and the spatial resolution is greater. As depths increase the spatial resolution decreases, but swath widths increase. There is therefore a balance between

Figure 3.159 Schematic illustration demonstrating the principles of MBES data collection. Courtesy of the Geological Survey of Norway.

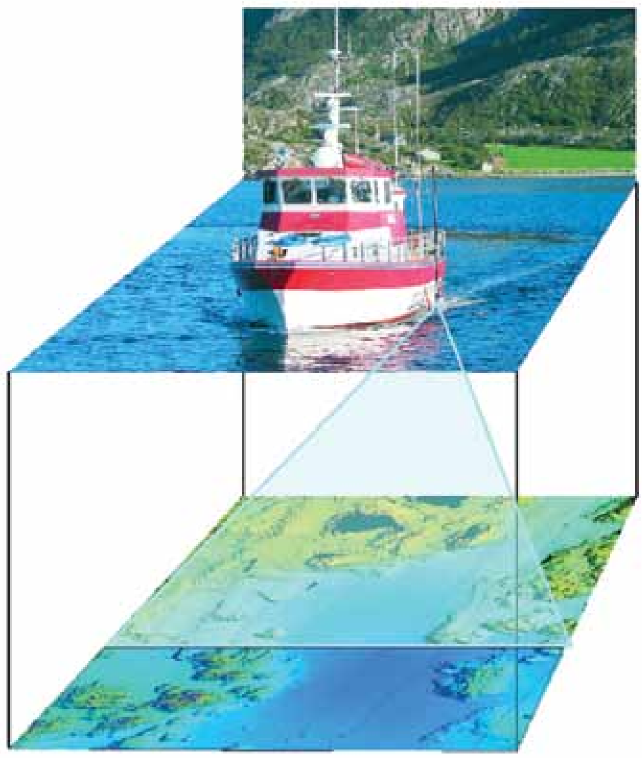


Table 3.14 Users of detailed seabed data and geological models.

Stakeholders and seabed users	*Reasons why detailed seabed data and geological models are required*
Sand and gravel producers	Resource and reserves estimation; monitoring extraction volumes and environmental impacts with repeat surveys
Fishing industry	Fishing in areas with unsuitable seabed conditions results in extra time at sea, the use of inappropriate equipment and unnecessary damage to the seabed and equipment
Aquaculture	Efficiencies can be gained by understanding the detailed bathymetry, seabed geology and hydrodynamics of potential sites
Renewable energy	Sites based on individual studies but difficult to assess in a regional context. Developments undergo detailed studies to assess site selection, risk, hazard and environmental impacts
Shipping	Maintenance of navigation channels and avoidance of hazards to shipping requires detailed charts. Site investigation for harbour developments
Sea defences and beach replenishment	Understanding the geometry of the nearshore environment, the distribution of shallow sediments, bedrock geology and hydrodynamic conditions
Pipelines and cable corridors	Routes based on individual studies but difficult to assess in a regional context. Potential to cut across key areas with other marine resources
Military defence	Bathymetry and seabed texture requirement for defence purposes
Ocean modelling	Improved hydrodynamic models for assessing sediment movement, erosion, deposition and distribution of contaminants
Archaeology and cultural heritage	The detailed distribution of our marine heritage is poorly understood, with few sites fully analysed – identification of wrecks and palaeolandscapes
Ecosystems and conservation	The distribution of benthic habitats relies on geological controls and underpinning information for defining Special Areas of Conservation and Marine Protected areas
Geohazards	Monitoring the seabed for evidence of gas escape (methane and carbon dioxide); defences against storm surge, tsunamis and submarine landslides
Hydrocarbon exploration and production	Site investigation and environmental impacts
Dredging/discharge	Disposal impacts, monitoring with repeat surveys
Tourism	Recreational diving, small boats etc.
Sport	Yacht racing etc.
Education and outreach	A recent survey in the UK demonstrated that the understanding of the marine environment is very poor (Natural England, 2008). MBES data provides an excellent resource for educational purposes

water depth, resolution and swath width, making operations in shallow water areas more time-consuming and expensive compared with deep water. In deep water areas, increased resolution can be obtained by using AUVs (autonomous underwater vehicles) or ROVs (remotely operated vehicles). In shallow water, higher-frequency sound can be used, compared with the lower-frequency systems required in deeper water to ensure sufficient energy in returns from the seabed. The technology was developed initially in the 1960s, and began with deep-ocean application, but it was not until the 1990s that systems began to be used more widely. In the past eight years, national mapping programmes were begun in several countries, including Ireland, Norway and Canada. In the UK, the first MBES tasks associated with the Civil Hydrography Programme began in 2003/04.

MBES was initially designed primarily for collecting detailed bathymetric information. However the technique has developed so that backscatter information can be collected which may be correlated with the physical parameters of the seabed. This provides a crucial tool for geologists, engineers and habitat mappers in enhancing the interpretation of the seabed.

3.8.3 Progress since *Charting Progress*

In 2005, the amount of MBES data in the UK was very limited, datasets were generally not shared and bathymetry and geology was a relatively small part of *Charting Progress* (Defra et al., 2005). During the past five years there have been major advances in the technique, a large increase in the number of survey programmes (Table 3.15) and new challenges have developed in sharing data, building the IT infrastructure to store and manipulate the very large volumes of digital data and in developing the expertise and techniques for achieving the scientific and strategic value from the data. This section provides an overview of progress, with MBES data and in other respects: understanding the bathymetry and geology; capturing single beam bathymetry from the United Kingdom Hydrographic Office (UKHO), from a compilation of data primarily from fishing boats, and from data collected by the oil industry. Details of how these data have been applied in the individual CP2 Regions are given in Section 3.8.4.

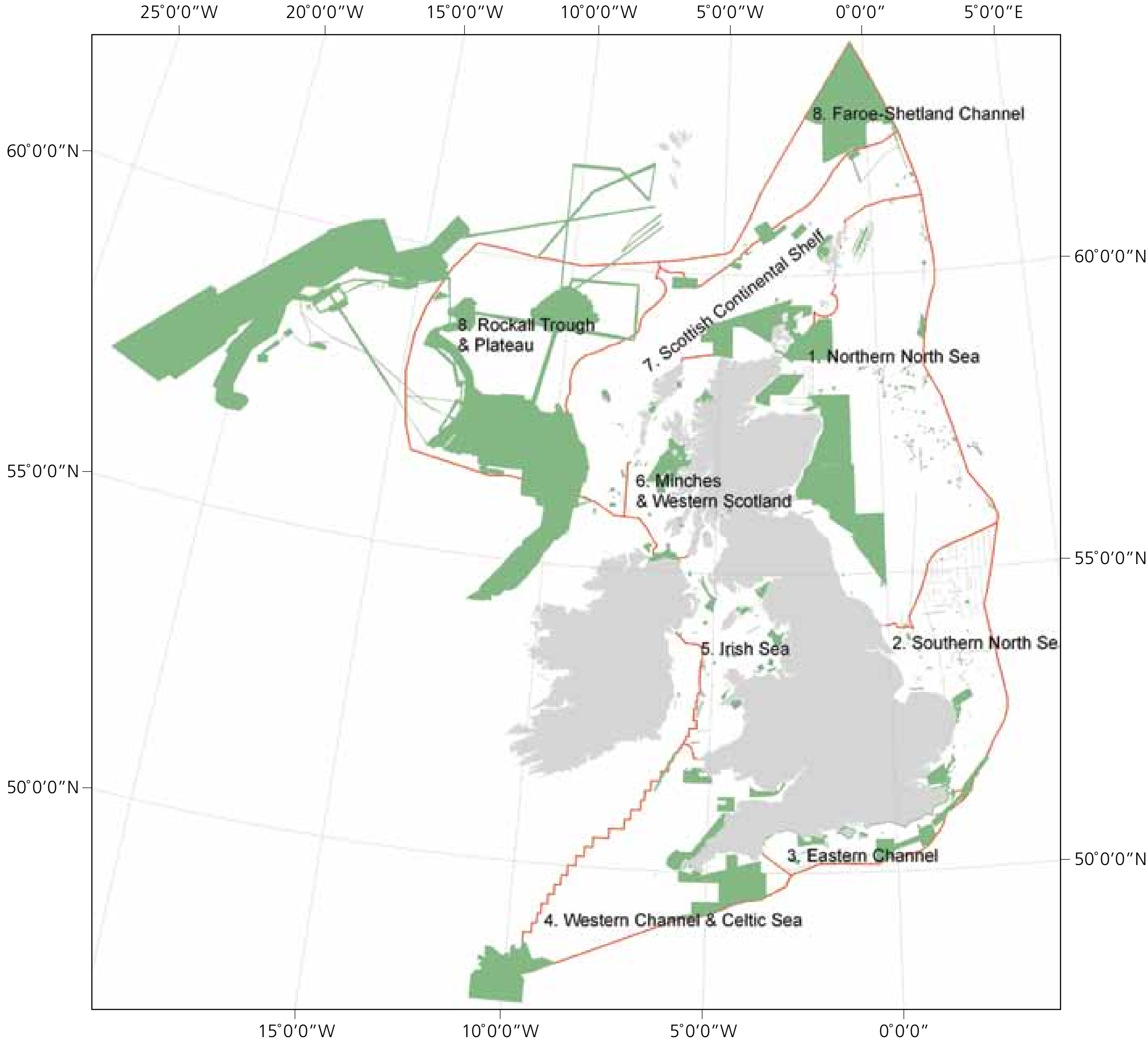
3.8.3.1 MBES coverage

Providing an overview of MBES coverage around the UK is not straightforward because, until recently, there had been no or little co-ordination in terms of surveying, reporting or storage of these data in a national database. However, there are now several excellent initiatives which are beginning to improve co-ordination, including the annual COSH (Committee on Shipping Hydrography) meeting, renamed in 2010 as the Civil Hydrography Annual Seminar, and a new Memorandum of Understanding between several Government organisations (the Department for Environment, Food and Rural Affairs, DEFRA; the Maritime and Coastguard Agency, MCA; UKHO; the Joint Nature Conservation Committee, JNCC; Natural England, NE, the Centre for Environment, Fisheries and Aquaculture Science, CEFAS; the British Geological Survey, BGS) to share data collected to a set standard. It is envisaged that this agreement will be extended to other governmental organisations in the near future following a review of its effectiveness. Figure 3.160 summarises the first comprehensive compilation of data; this was initiated for the purpose of *Charting Progress 2* as well as to develop a case for a National Seabed Survey. Some datasets from the commercial and governmental sectors are not represented, but the database is improving. It is clear from this map that most, perhaps around 85%, of UK marine waters are not covered by modern multibeam data. Most areas highlighted on Figure 3.160 can be classified as having very good bathymetric data, suitable to support geological and habitat mapping to the standard required to underpin environmental and resource assessment and marine planning. In deeper waters, such as Rockall Trough, the resolution of multibeam data is so poor that consideration should be given to follow-up surveys using deep-tow technology or newer high-resolution surface systems.

Table 3.15 Summary of main collectors of multibeam data in the UK.

Programme/project	*Comments*
Civil Hydrography Programme	Largest survey programme in the UK and focused on the main shipping channels in order to meet requirements of SOLAS (the International Convention on the Safety of Life at Sea). The programme is now being broadened via a partnership approach, to include other areas where there are SOLAS considerations
Mapping European Seabed Habitats (MESH)	An EU INTERREG IIIb -funded project to develop methodologies for mapping marine habitats. Several trial areas surveyed
Conservation agencies (Joint Nature Conservation Committee, JNCC; Natural England, NE, Countryside Council for Wales, CCW; Scottish Natural Heritage, SNH; Northern Ireland Environment Agency, NIEA)	Scattered surveys in areas considered for inclusion as Special Areas of Conservation, Marine Parks or Marine Protected Areas
British Geological Survey (BGS)	National geological mapping programme, data in deep water collected in Rockall: new focus on shallow-water near-shore areas. A new initiative called MAREMAP (Marine Environmental Mapping Programme) was launched in 2010 to develop the interpretation of MBES data across the UK continental shelf. This is an initiative led by BGS, the National Oceanography Centre (NOC) and the Scottish Association for marine Science (SAMS) with other partners
Strategic Environmental Assessments (Department of Energy and Climate Change, DECC)	Small survey areas in each of the eight strategic sea areas (i.e. CP2 Regions)
UN Convention on the Law of the Sea (UNCLOS)	Data collected in areas adjacent to the UK Designated Area to support the claim for an extended EEZ.
Fishing agencies (Centre for Environment, Fisheries and Aquaculture Science, CEFAS; the Agri-Food and Biosciences Institute, AFBI and Marine Scotland)	Small survey areas associated with assessment of fishing and pollution studies. Increased activity to support development of marine renewable energy sources
Local authorities and environment agencies	Some surveys in coastal areas, particularly estuaries to support the EU Water Framework Directive reporting and nearshore sediment movement
Ministry of Defence	Additional data collected as part of defence requirements
Aggregate Levy Projects	Several reconnaissance surveys, primarily in the southern North Sea, English Channel and Bristol Channel
Industry	See Table 3.14: surveys collected to support sand and gravel resource assessment, and site investigation work for oil and gas developments, pipeline and cable route studies, port authorities and marine renewables
Academia	Small surveys for geological and biological research, including EU projects such as HERMES (Hotspot Ecosystem Research on the Margins of European Seas)

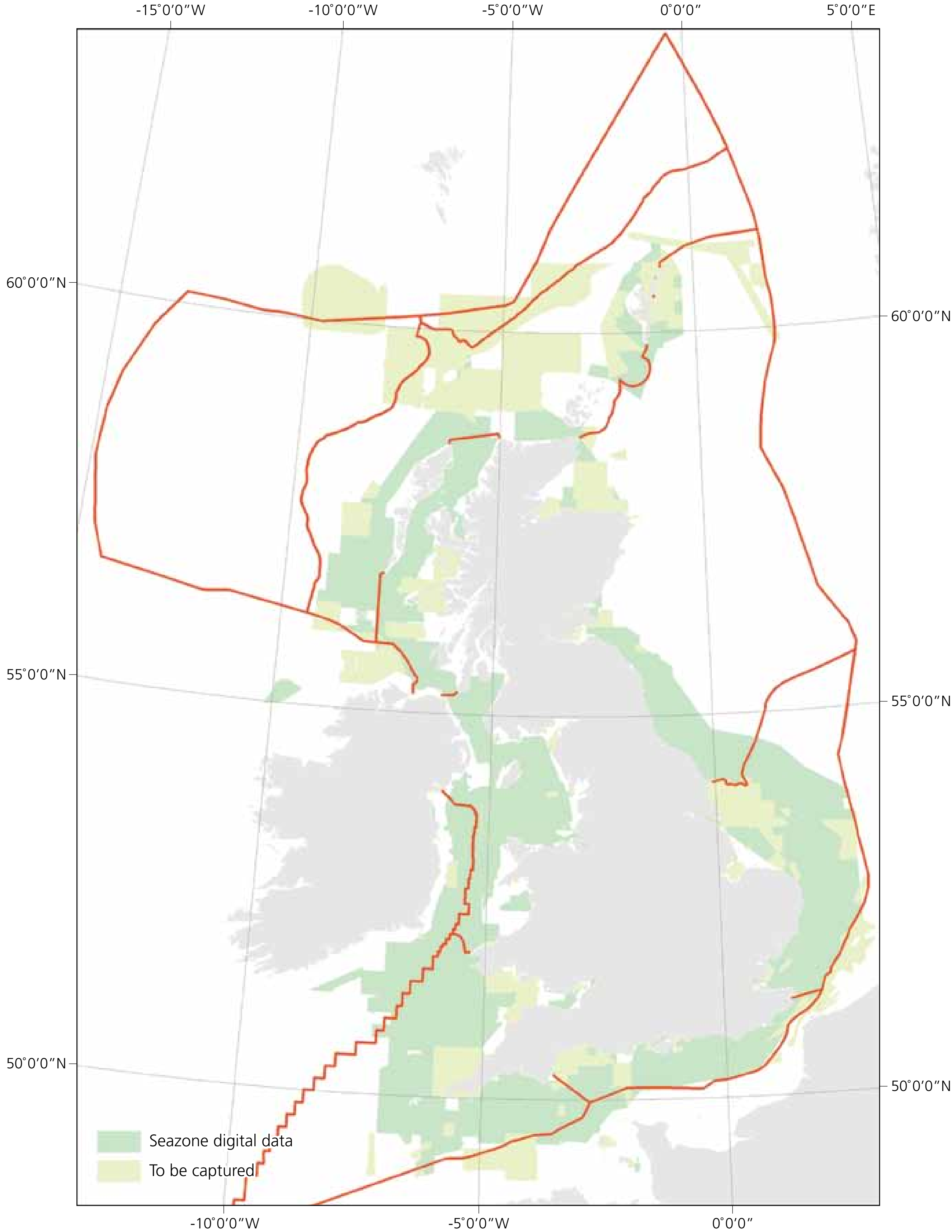
Figure 3.160 Summary of multibeam (MBES) coverage in the United Kingdom. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



3.8.3.2 Digital UKHO single beam data

The UKHO has primarily provided chart information to support the safe passage of shipping. But, until the past few years, most charts were based on single-beam soundings, in some cases at a spacing of more than 100 m. Recently SeaZone Solutions Ltd has taken these data and produced digital xyz data to provide new coverage of bathymetry. Although these data are not as detailed as multibeam bathymetry, they can be used to provide a reasonable understanding of bathymetry to assist with a range of seabed environmental and resource issues. A case study on these data is provided in Section 3.8.4 (see Case Study 4 Page 231). Figure 3.161 summarises the areas where digital bathymetry now exists and other

Figure 3.161 Extent of digital single-beam bathymetry. Prepared by SeaZone Solutions Ltd. Data provided by SeaZone Solutions Limited.

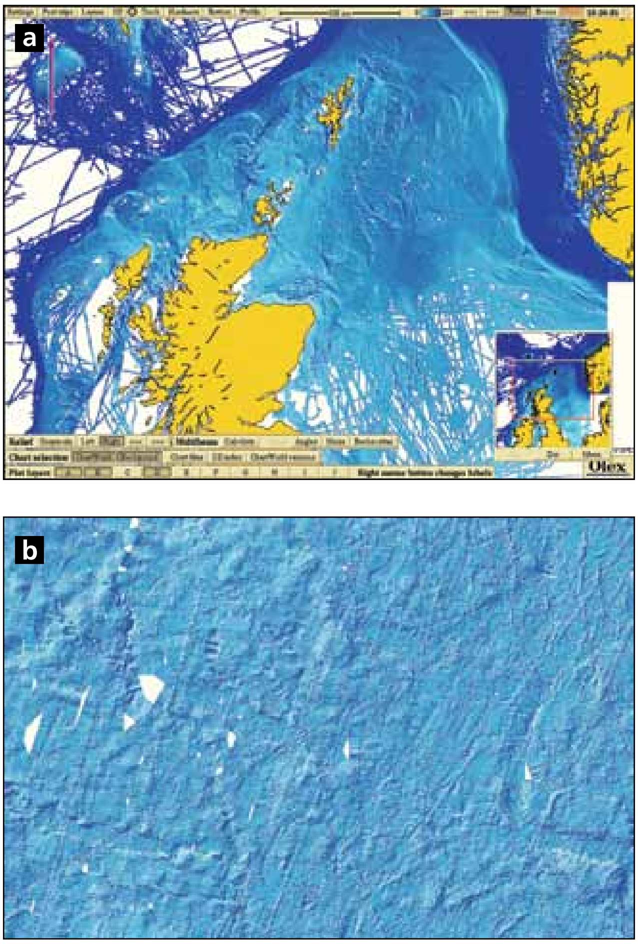


areas where SeaZone are carrying out their processing. For the purposes of assessing the state of bathymetric data in the UK, these data can be graded as of intermediate quality. Two significant omissions from these data are the lack of even this bathymetry in much of the coastal zone and a similar lack of good quality bathymetric information in many of the deeper offshore areas, including much of the North Sea. In these areas, most of which also have no multibeam coverage, the quality of bathymetric information is very poor.

3.8.3.3 Olex data

'Olex data' comprises a bathymetric dataset put together by Olex AS, a Norwegian company. Olex AS provides data recorders to vessels – originally fishing vessels, but increasingly the research fleet and indeed other vessels – which store bathymetric data, which are then returned to Olex AS, who compile the data from the different sources and generate an integrated dataset. The system can also include MBES data. The quality of the data is extremely variable and depends on the density of line coverage. Olex data does not meet hydrographic standards as it is a secondary data source and is often uncalibrated. However the data are a very useful source of broad-scale regional bathymetry and are currently being used to improve geological and geomorphological seabed mapping.

Figure 3.162 Olex bathymetry data from the seas around Scotland (a) regional map (b) zoomed in area highlighting granularity of data in relatively densely surveyed areas. Permission granted by Olex AS.



The dataset is an international compilation with the greatest density of soundings found offshore on the eastern seaboard of Canada, around Iceland and along the coast of Norway. However, the coverage is particularly useful around the Shetland Islands and adjacent areas (Figure 3.162). Nevertheless, even in these areas, although Figure 3.162 appears to show complete coverage, this is not the case as each single beam track is plotted with a very broad plot width (see Figure 3.162b). This is also clearly apparent in the areas of Figure 3.162 with less dense coverage. See Case Study 1.

3.8.3.4 3D Seismic data from the oil industry

Modern seismic exploration data are frequently collected as a 3D survey, with line spacing sometimes as little as 6 m. The first returns provide a seabed image very similar to those from multibeam surveys. The major difference is one of wavelength and frequency: seismic data uses lower-frequency inputs, with the prime objective of evaluating the structure below the

Case Study 1:
Evidence for the extent and structure of the last British Ice Sheet from Olex data (see www.olex.no)

Olex is a shared bathymetry made up of voluntarily contributed data from fishing vessels and an increasing number of other ships. All contributors to the process share all the data, which are located using GPS navigation and vertically referenced to the predicted tides at equinoctial spring low water. Vertical resolution is around ± 1 m in water depths > 100 m and ± 0.1 m at shallower depths. The speed of sound in water is assumed to be 1500 m/s. The resulting bathymetry can be viewed as contours or shaded relief maps.

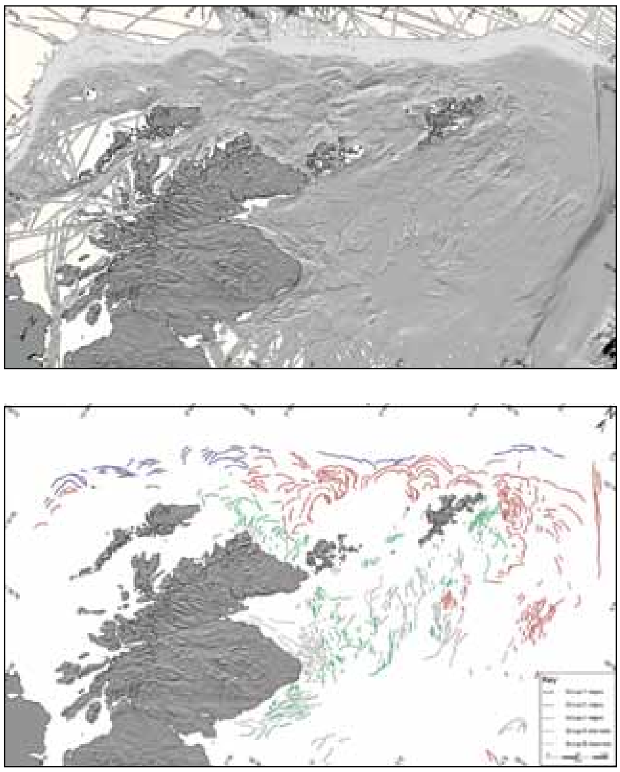
Bradwell et al. (2008) published the first detailed geological analysis of the UK seabed geology based primarily on Olex data. Previous studies of the area around Shetland had interpreted features as moraines (Stoker and Holmes, 1991) and tunnel valleys (Andrews et al., 1990), but no complete picture of the area had been available until the compilation of Olex data was released. The pattern reveals that the British and Fennoscandian ice sheets were joined and provides evidence for how the ice sheet retreated as ice melted. This evidence will help with modelling how the Greenland Ice Sheet may react in the future as climate change continues.

Bradwell et al. (2008) interpreted a series of ridges as retreat moraines and distinguished three phases of moraine development (Figure 3.163) and two groups of channels. The morphology and distribution of the moraines is variable with large arcuate ridges, concave to the east, interpreted as shelf edge moraines (Group A; Stoker et al., 1993), but shorter and more complex cross-cutting patterns (Groups 2 and 3) nearer the present day coast. The channels have an irregular base and vary from 1.5 km to about 60 km in length and trend north to north-west. They are interpreted as tunnel valleys, formed by flow at the base of ice sheets.

Recognising these features is not only important in developing models of ice dynamics in a disintegrating ice sheet, but also provides evidence for the shallow and seabed geology, for example boulders are likely to be concentrated on the moraines, providing localised habitats that differ from the sea floor between the moraine ridges.

A comparison of Figure 3.163 with Figure 3.193, from MBES data, demonstrates the higher resolution achieved using MBES technology. More detail, such as smaller moraines and other sedimentary features, can be seen in the multibeam dataset.

Figure 3.163 Olex data and interpretation, Northern North Sea and adjacent areas. Permission granted by Olex AS.

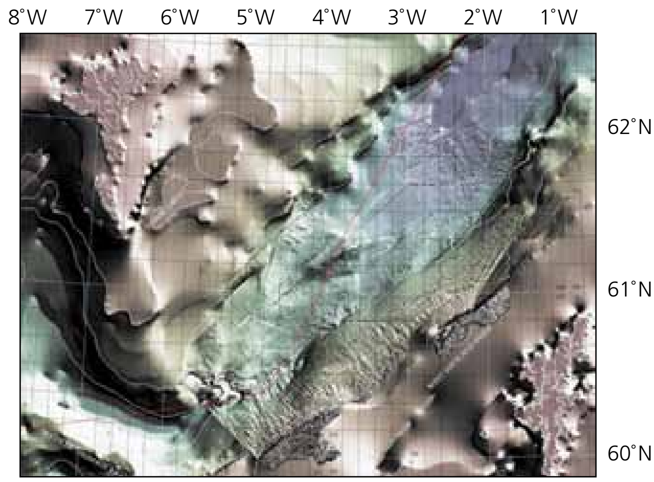


seabed. However, studies in the Faroe-Shetland Basin have demonstrated that the data are very useful for highlighting the geology and topography of the seabed in deeper water areas (Figure 3.164; Long et al., 2004). The dataset may be comparable to multibeam data for assessing geohazards and some aspects of habitats; Bulat (2005) showed a comparison between two datasets in the same area.

3.8.3.5 Coastal zone

In the coastal zone (defined in Section 3.8.2), different techniques for studying geological processes are available. Since 2005, much work has been undertaken in the coastal zone by local authorities and the Environment Agency. In exposed and partially exposed zones, including beaches, open coasts and the margins of estuaries, photographic techniques are available. One of the newer technologies is the use of LIDAR (LIght Detection And Ranging). This can be collected from airborne and ground sources. It is a powerful technique for measuring rates of change in the area of sediment movement and erosion of beaches and cliffs. Case studies are provided in Section 3.8.4 in areas where coastal monitoring is undertaken. In the coastal zone beneath the water, new developments have resulted in marine-penetrating LIDAR that can map the seabed beneath shallow seas. For the systems to work effectively, relatively clear water is required, and hence its effectiveness in UK waters can be limited. The Civil Hydrography Programme commissioned a marine LIDAR survey of the Sound of Harris, but thus far few large-scale marine LIDAR surveys have been undertaken in the UK. However, the INFOMAR programme in Ireland is using this technology extensively to survey bays along the western and southern coasts in conjunction with MBES surveys.

Figure 3.164 An image of the seabed in the Faroe-Shetland Basin. The area of detail in the centre of the figure shows the data from 3D surveys collected by the oil industry. Figure compiled by BGS for the Western Frontiers Association with the support of a consortium of oil companies. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



Local authorities have tended to use a variety of techniques, including standard beach profiling (Simm et al., 1996), and much of the data in areas with significant coastal change are now collected and stored at the Channel Coastal Observatory (CCO), based in Southampton, and at individual local authorities.

In the regional assessments, the issues of coastal erosion and squeeze of coastal environments are of crucial concern, hence the significance of recent research into the implications of enhanced sea-level rise and changes in wave energy at the coast (Walkden and Dickson, 2006; Dawson et al., 2007; Masselink and Russell, 2007). New research has also focused on the theory and modelling of predicted changes on open coasts and in estuaries (e.g. Taylor et al., 2004; Orford and Pethick, 2006).

Charting Progress (Defra et al., 2005) was based on the results of an EU-funded project (see www.eurosion.com) and a major Defra-sponsored project, Futurecoast, which covered the coasts of England and Wales. These projects highlighted the regional areas with greater erosion rates and areas with coastal protection (see Table 3.16). New projects which take the approach further include Risk Analysis of Coastal Erosion (RACE), which was completed by Halcrow and Partners on behalf of Defra and the Environment Agency. The idea was to take the Futurecoast approach forward to include information on coastal defences and provide more detailed information. The final report (Defra, 2008) is available (http://randd.defra.gov.uk/Document.aspx?Document=FD2324_7452_TSM.pdf) on the Defra website. One of the aims of the project was to provide a means for local authorities to provide and integrate their data.

Another project in progress covers coastal geomorphology modelling and is led by HR Wallingford. This project is based on models of a cliff environment and an estuary and attempts to model what will happen in these environments in response to sea-level rise or increased energy/wave input. An inception report was prepared by Whitehouse et al. (2008).

The major current modelling project in the coastal zone is led by the Tyndall Centre and is designed to produce an integrated regional coastal simulator, to help vulnerability assessment and identify mitigation options in response to sea-level rise (Mokrech et al., 2007).

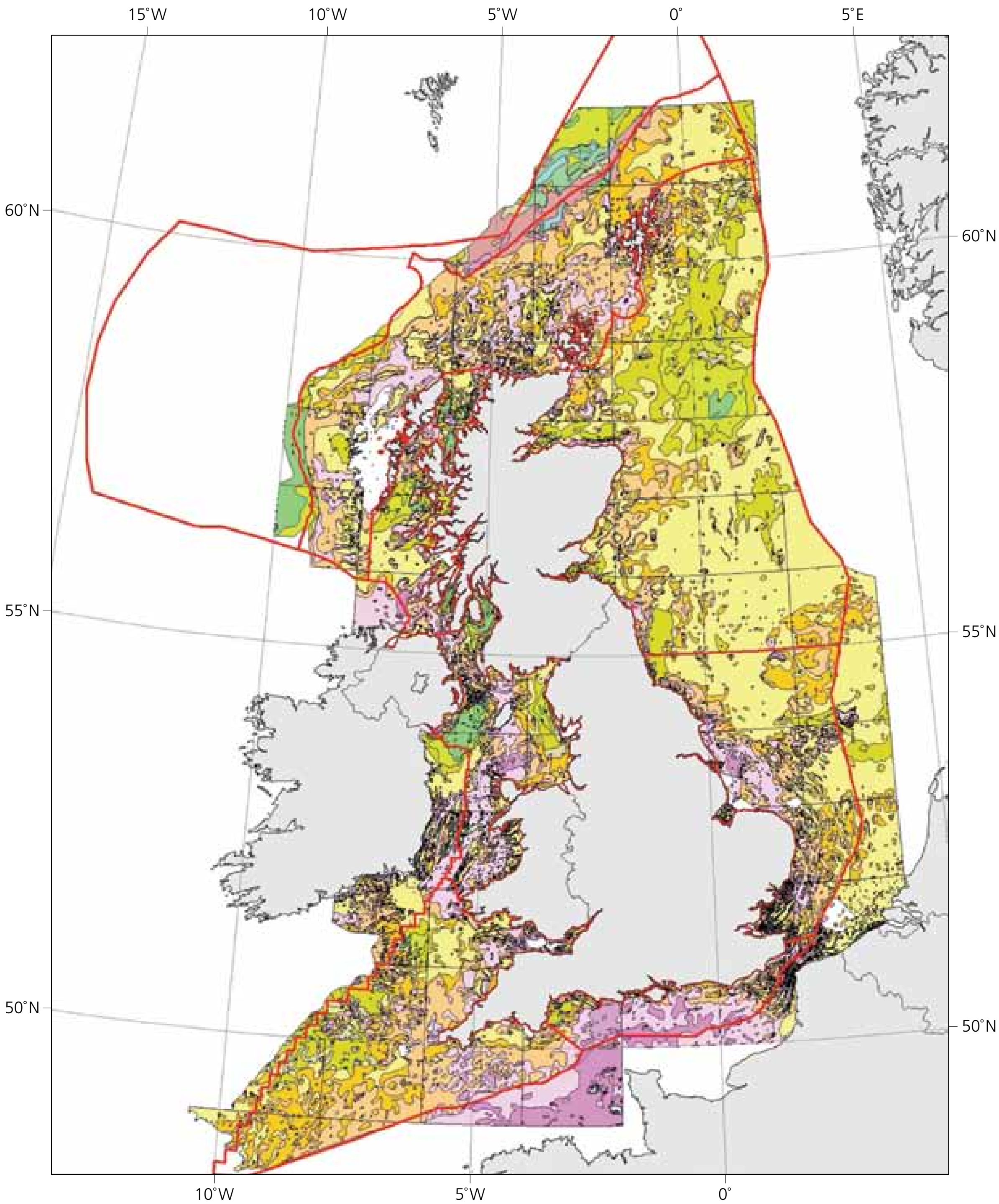
3.8.3.6 Geological maps

The national coverage of seabed geological maps remains similar to that reported in *Charting Progress*. Figure 3.165 shows the existing coverage of the British Geological Survey

Table 3.16 Coastal erosion and protection in the UK. Source: MCCIP, 2008 and www.eurosion.org.

Region	*Coast length*	*Coast length which is eroding*		*Coast length with defence works and artificial beaches*	
	km	*km*	*%*	*km*	*%*
Northeast England	297	80	27	111	37
Northwest England	659	122	19	329	50
Yorkshire & Humber	361	203	56	156	43
East Midlands	234	21	9	234	100
East England	555	168	30	382	69
Southeast England	788	244	31	429	54
Southwest England	1379	437	32	306	22
England	4273	1275	30	1947	46
Wales	1498	346	23	415	28
Scotland	11154	1298	12	733	7
Northern Ireland	456	89	20	90	20
Total	**17381**	**3008**	**17**	**3185**	**18**

Figure 3.165 British Geological Survey seabed sediment map. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



- Mud M
- Sandy mud sM
- Slightly gravelly mud (g)M
- Slightly gravelly sandy mud (g)sM
- Gravelly mud gM
- Sand S
- Sand (French classification)
- Muddy sand mS
- Slightly gravelly sand (g)S
- Slightly gravelly muddy sand (g)mS
- Gravelly muddy sand gmS
- Gravelly sand gS
- Gravelly sand (French classification)
- Gravel G
- Gravel (French classification)
- Muddy gravel mG
- Muddy sandy gravel msG
- Sandy gravel sG
- Sandy gravel (French classification)
- Gravel, sand and silt
- Clay and sand
- Diamicton
- Rock or diamicton
- Mussell deposit
- Rock and sediment
- Undifferentiated solid rock

(BGS) seabed sediment map, available at a scale of 1:250 000 and as a digital model. New studies, primarily using multibeam but also using Olex data and digital single-beam bathymetry, have shown that this map is not detailed enough to define our marine resources and habitats and fails to support efficient marine planning. The BGS has a new project to develop more detailed maps and models, based on new data and including existing multibeam, Olex and sample information. Thus far only a few pilot areas have been completed due to funding constraints. Details of a new approach are given as an example in Section 3.8.4. Improvements to this are in progress, including a new interpretation of areas where sediments are likely to form thin veneers, or be completely absent, which is an important criterion for habitat and site investigation studies. Figure 3.166 shows a simplified seabed sediment map which covers the western approaches, where a more detailed map cannot yet be produced because of a lack of data. This map was used in the MESH project as the basis for the first regional broad-scale habitat map.

3.8.4 Presentation of the evidence and regional assessments

This section includes summaries of recent research and new data in each of the regional seas (i.e. CP2 Regions). Each section is supported by case studies that highlight aspects of recent work. The first part of each section focuses on the coastal zone and highlights projects that have studied coastal processes (primarily erosion) and near-shore bathymetry; the second part focuses on studies further offshore. The issues of coastal erosion and squeeze of coastal environments are of crucial concern. Assessment of the areas experiencing significant impacts were highlighted in *Charting Progress* and these are not repeated here. However, the text begins with a summary of coastal erosion and defences (Table 3.16).

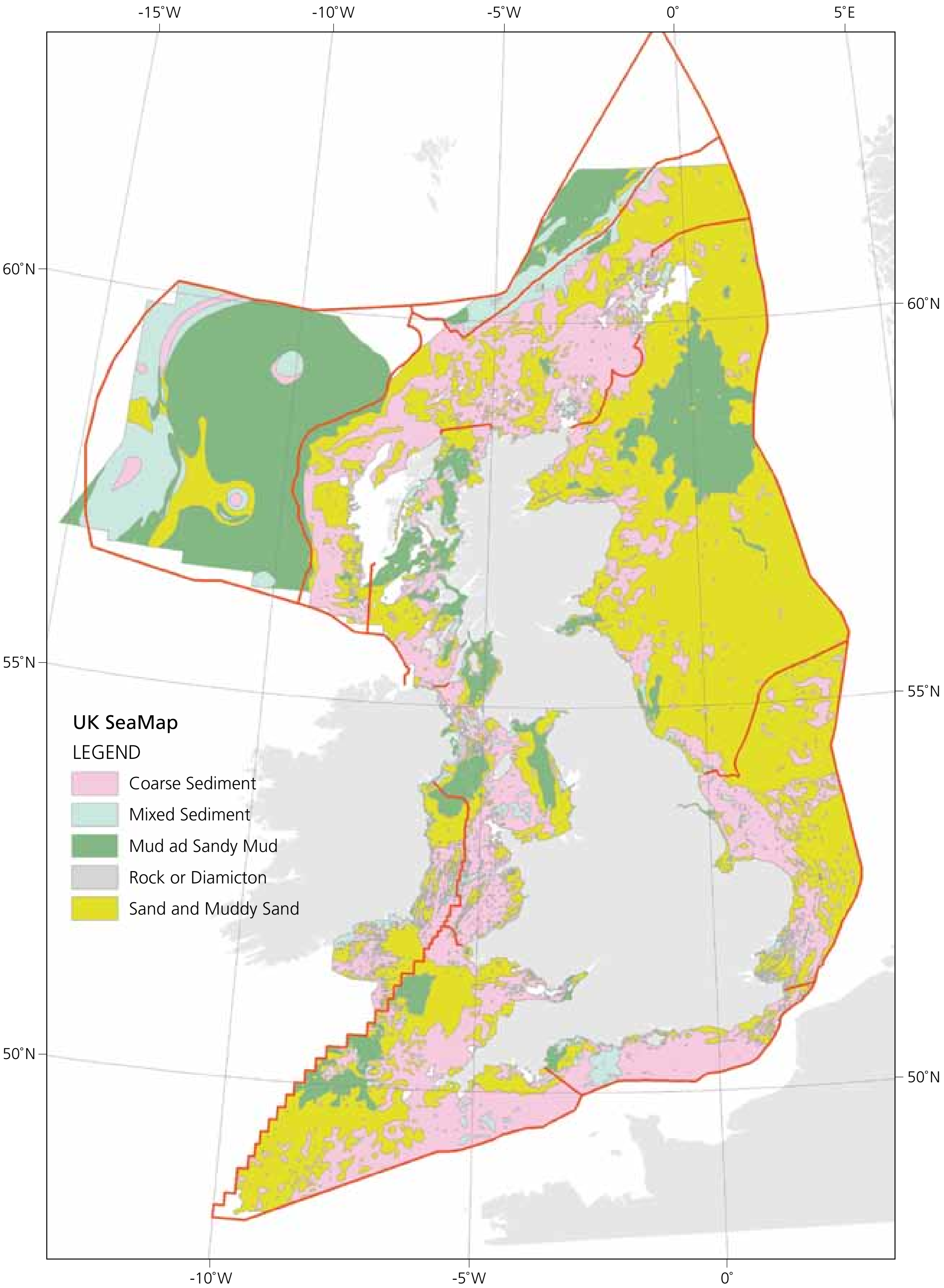
3.8.4.1 Northern North Sea (Region 1)

3.8.4.1.1 Coastal zone

The east coast of England has significant areas of coastal erosion, with locally larger landslips and higher rates of erosion along the Yorkshire coast compared with the coasts further north (see www.eurosion.com). In Scotland there are examples of erosion on the soft parts of the east coasts, although zones of concern are more localised than further south (see www.eurosion.com). Scottish Natural Heritage (SNH) is supporting a review of historical geomorphological change of the Scottish coastline, which seeks to use beach and dune aerial photography coupled with digital terrain models to provide quantitative measurements of geomorphological changes for a selected set of beach and dune areas across Scotland. A second SNH study is assessing the evidence for coastal squeeze and beach steepening around Scotland. A scoping study looking at the evidence for coastal flooding risk around Scotland was prepared for Sniffer (Ball et al., 2008). A summary of the state of Scotland’s seas has also been published (Baxter et al., 2008).

In the nearshore areas there has been relatively little surveying, although BGS, in partnership with Forth Ports, has collected some multibeam data in the Forth (Figure 3.167), and these data are being utilised in the planning for the proposed new Forth Bridge. Further work to complete a bathymetric and sediment model to assess the hydrodynamics of the Forth is proposed in conjunction with the Scottish Environment Protection Agency (SEPA). Note the gap in data between the edge of the multibeam and the coast in Figure 3.167, where data are

Figure 3.166 Simplified seabed sediment map covering the Atlantic Margin. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



difficult to collect due to the shallow water. In this area the zone of no data may be reduced through LIDAR surveys from the air, or indeed from land-based systems mounted on the Forth rail bridge.

3.8.4.1.2 Offshore

Away from the coast some new data have been collected as part of the SEAS programme (e. g. the Sandy Riddle area in the Moray Firth; Figure 3.168), and part of the Forth Approaches has been surveyed by the Civil Hydrography Programme, but these data are yet to be integrated into detailed geological mapping. In this area there are many small patches of multibeam data collected by the oil industry through site investigation surveys. The northern part of this area is also covered by Olex data (see Case Study 1 Page 220).

3.8.4.2 Southern North Sea (Region 2)

3.8.4.2.1 Coastal zone

The coastal zone adjacent to the southern North Sea is the area of the UK where erosion rates are highest. This is mainly due to the soft sediments that make up the coastal zone. There are several monitoring projects in this area, led by local authorities and the Environment Agency, and this is the area with probably the longest records of evidence of coastal change (Balson, P., BGS, pers. comm., 2009). BGS monitors cliffs on the Norfolk coast at Happisburgh, where erosion is in part governed by man-made sea defences, and at Sidestrand, which is a more natural environment (see Case Study 2). The low-lying estuaries are another area where risks of flooding and loss of coastal habitats are of serious concern. Case Study 3 demonstrates the measures that are being implemented to manage realignment in the Humber.

Figure 3.167 Multibeam image of the seabed in the Firth of Forth. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

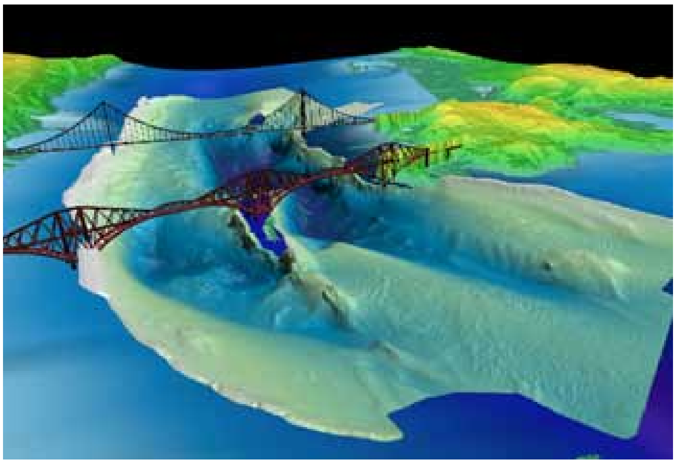
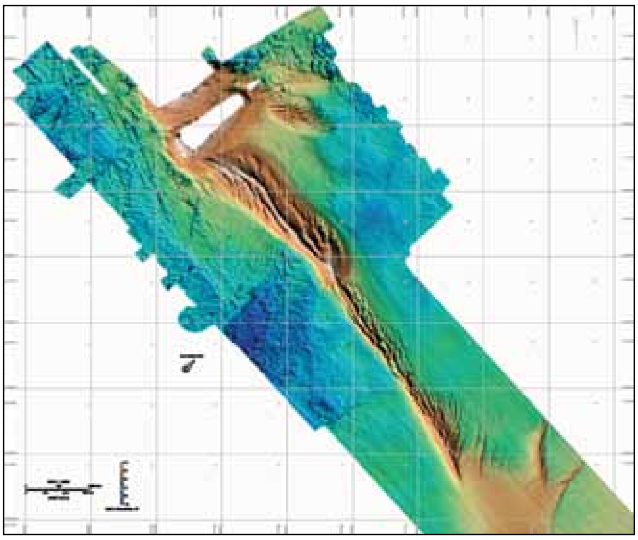


Figure 3.168 MBES image of the Sandy Riddle, to the south east of the Pentland Firth. Data collected as part of the Strategic Environmental Assessment (SEAs) programme, Department of Energy and Climate Change.



Case Study 2: Norfolk Coastal evolution

The coasts of East Anglia include many of the most rapidly retreating sections of Britain's coastline, and the North Norfolk cliffs between Weybourne and Winterton Ness (about 75 km distance) produce around 500 000 m^3/y of sand (HR Wallingford, 2001). This is a much greater volume of new sediment on the coast than that provided by fluvial input. The rate of erosion and pattern of sediment dispersal is crucial in terms of coastal erosion, beach nourishment and natural protection from flooding.

Modern techniques for measuring rates of retreat are based on low-level airborne LIDAR/GPS systems that can rapidly monitor rates of retreat. However, more detailed studies that attempt to quantify coastal recession in 3D to understand the geomorphological processes have been undertaken over six years at three Norfolk sites (Weybourne, Sidestrand and Happisburgh), using terrestrial systems (Hobbs et al., 2008), and integrated with detailed geological analysis.

At Weybourne there has been little landslide activity and little beach recession. The exposure of chalk at the base of the cliffs provides some additional strength, but another key feature is the protection from wave energy provided by the steep, permanent shingle beach in front of the cliff (Figure 3.169). The most significant activity is small sand runs or flows initiated by wind erosion and rainfall (Figure 3.169).

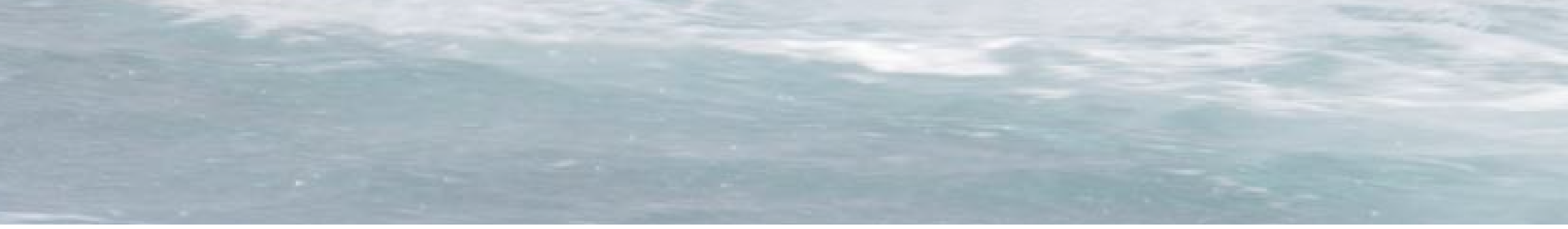
At Sidestrand the cliffs are up to 60 m high and there has been considerable landslide activity which is linked to embayment development and drainage, although the complex glacial geology provides difficulties for generalised extrapolation along the coast. A key feature at Sidestrand is the occurrence of several deep-seated landslides

Figure 3.169 Sand run and protective shingle beach at Weybourne. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

that produced large debris flows which then remain on the platform for several months, providing the cliffs with temporary protection from the sea. Results show a complex pattern of volume change and cliff retreat, reflecting the complex landslide processes, and extended time to remove fallen material from the beach (Table 3.17; Figure 3.170).

Figure 3.170 summarises the differences following major landslides on 28 September 2006, following heavy rainfall. The most noticeable changes are the landslide scars on the cliffs (in red), debris material at the foot of the cliffs (in blue, A and B; Figure 3.170), and erosion of material at the base of the cliff (C).

The spectacular rates of erosion at Happisburgh may be artificially accelerated following the failure of sea defences in the 1990s, but a model



of embayment development related to the cliff and platform stratigraphy and beach profiles has been developed. The cliffs are between 6 and 10 m high and are made of glacial sediments. Results show an average of 16 800 m^3 of sediment is lost per year from a 200 m section of cliff. However, the results from year to year are variable (Table 3.18). The increase in volume in 2005–2006 is the result of increased sediment on the beach.

Figure 3.171 shows the differences in rates of erosion to the north, where sea defences are in place, and in the monitored area to the south with no sea defences. This figure includes data from old maps and photos in addition to the LIDAR results. During the period 2001 to 2006 the loss of land was about 6 to 8 m/y. In the past 121 years the coast has retreated approximately 145 m, but since the loss of some of the sea defences in the early 1990s, rates of erosion have increased to an average of about 8 m/y.

Table 3.17 Volume change for a 200 m and a 100 m section of cliff at Sidestrand.

Period	*Volume removed per 200 m cliff, m^3*	*Volume removed per 100 m cliff, m^3*
2000–2001		45 670
2001–2002	64 790	43 367
2002–2003	1 414	-11 124
2003–2004	4 132	2 357
2004–2005	12 084	1 896
2005–2006	38 880	9 600

Table 3.18 Volume change for a 200 m section of cliff at Happisburgh.

Period	*Volume removed per 200 m cliff, m^3*
2002–2003	21 000
2003–2004	12 600
2004–2005	36 785
2005–2006	-3 193

Figure 3.170 Height change model for Sidestrand between 2005 and 2006. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

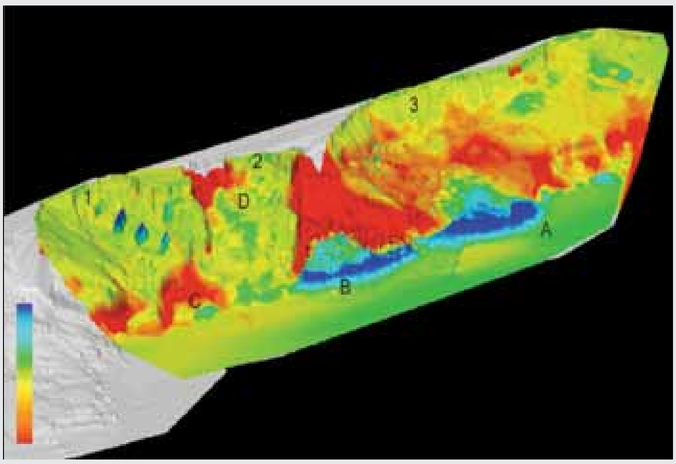
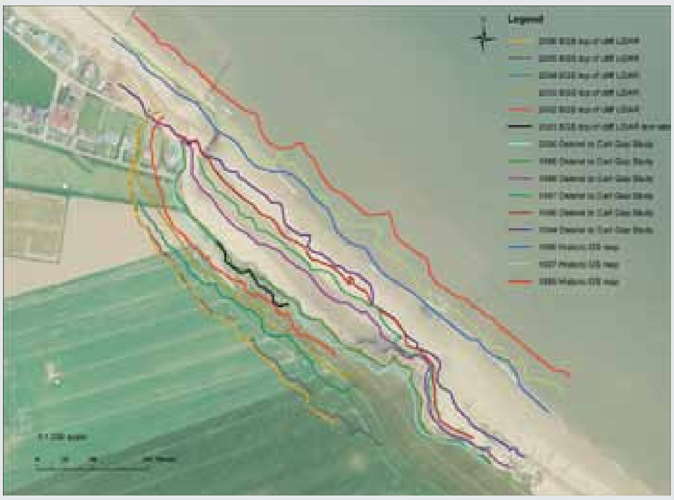


Figure 3.171 A 1999 aerial photograph with lines showing the position of the top of the cliff measured by BGS between 2001-2006 plus historical data extracted from data collected by HR Wallingford on cliff top position between 1994-2000 (HR Wallingford, 2001) and Ordnance Survey maps. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



Case Study 3: Alkborough Flats – managed realignment

Since the late 1990s the Environment Agency has been developing a long-term strategy for the management of flood risk on the Humber Estuary under the banner 'Planning for the Rising Tides'. The strategy has been developed in response to the increasing challenges brought about by climate change and sea-level rise in an estuary where more than 300 000 people live and work below the highest tide levels. Key actions from the strategy include both traditional raising and strengthening of the existing defences as well as managed realignment to provide more space for water in the estuary and to safeguard the internationally important nature conservation resource. Work undertaken as part of the development of the strategy identified that over the next 50 years sea-level rise will lead to the loss of more than 700 hectares of intertidal habitat through the effects of 'coastal squeeze' (i.e. the inability of intertidal habitats to migrate inland in response to rising sea levels).

Alkborough Flats was identified as one of the key sites on the Humber Estuary where the managed realignment of tidal defences can provide both nature conservation (habitat creation) and flood risk management benefits. The site is located on the south bank of the Estuary, to the east (downstream) of the confluence between the Humber and the River Trent. The land at Alkborough has been reclaimed from the estuary over many years with the most recent phase of reclamation in the 1950s. See Figures 3.172, 3.173 and 3.174.

From the outset the project at Alkborough has been managed and promoted by a core management group of organisations comprising:

- Environment Agency (lead partner)
- The Countryside Agency (now part of Natural England)
- English Nature (now part of Natural England)
- North Lincolnshire Council
- Associated British Ports

Figure 3.172 Aerial view of Alkborough Flats prior to works.

Figure 3.173 Breach structure.

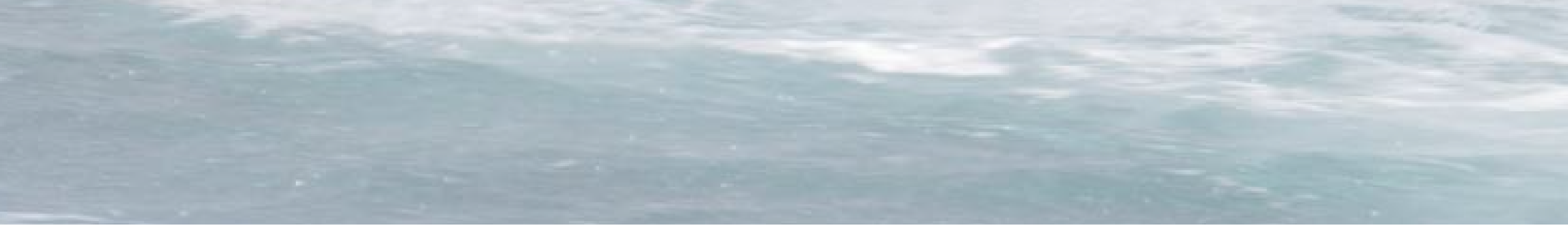


Figure 3.174 Inundation after high tides (October 2006).

The management group has been supported and assisted throughout the development of the site by a much larger group of organisations and individuals adding their expertise across a wide range of subjects including nature conservation, recreation, access, education and livestock management. The partners spent a good deal of time at the start of this project to agree a set of high level objectives for the project, the following being particular to the seabed and its character:

- To contribute to the practical implementation of the Humber Estuary Shoreline Management Plan and Coastal Habitat Management Plan
- To demonstrate sustainable flood defence planning and implementation in response to sea level rise
- To create new intertidal habitats, which contribute to UK Biodiversity Action Plan targets and help to maintain favourable conservation status of the Special Protection Area
- To create a new National Nature Reserve (subject to designation by English Nature's Council)

3.8.4.2.2 Offshore

Three new major seabed mapping projects funded through the Aggregate Levy Sustainability Fund (ALSF) have recently started in the Outer Thames, off the coast of East Anglia and further north near the Humber and Dogger Bank. Additional data have recently been collected on behalf of the JNCC on the Dogger Bank, and these data will provide a new level of understanding of the resource potential (sand and gravel), ground conditions for renewable energy infrastructure, and habitats. An evaluation of the archaeological heritage in these areas will also be undertaken.

The coastal area adjacent to Norfolk is the site of the first detailed geological map of the seabed developed by integrating data from MBES surveys (Civil Hydrography Programme data), SeaZone digital bathymetry and BGS to provide a detailed seamless map from onshore to offshore (Case Study 4).

Case Study 4: SeaBed Geology

It is now possible to prepare more detailed geological maps and models that underpin the efficient and sustainable development of our marine resources. Ideally, areas with multibeam data supported by samples and seismic data provide the most efficient and detailed datasets from which high quality interpretations can be generated. BGS has studied an area of the southern North Sea off the coast of East Anglia where, despite there being only partial MBES swath coverage, there exist other datasets (Figure 3.175) that have been combined into a detailed interpretation of the complex geomorphology. In this area the single beam echo sounder derived digital bathymetry prepared by SeaZone Solutions Ltd was used to infill areas without MBES multibeam data.

The project has generated a seamless new onshore-offshore dataset – SeaBed Geology at 1:50 000 resolution, with data presented in a format that is easily interoperable with other datasets. It utilises all best available data and provides detailed classification in vector format with metadata, attempting to account for sediment variability with time by defining environments in zones with high sediment mobility.

The final map (Figure 3.176) is supported by additional digital layers (Figure 3.177) and full attributes, which record sources of data, time of survey etc. The geology is classified using a hierarchical database, with each layer representing a different resolution, scale or feature.

Rather than use the Folk or Wentworth systems, as used on the BGS seabed sediment maps, an indication of the dominant sediment fraction is used instead. This makes for visual clarity and provides solid baseline interpretation for users such as habitat mappers.

The product is flexible, allowing many different layers of data, according to the user interests, to be overlain onto a solid geological and geomorphological interpretation. In this way, the whole marine landscape can be defined, from the solid bedrock, through surficial sediment and bedform distributions, to information on anthropogenic activities and structures, hydrodynamic regimes, sediment transport regimes, and habitat delineations etc. Because each layer is geo-referenced, 3D images can be created and examined in more detail (where the client has the software).

Figure 3.175 Selection of data used in the generation of Seabed Geology. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

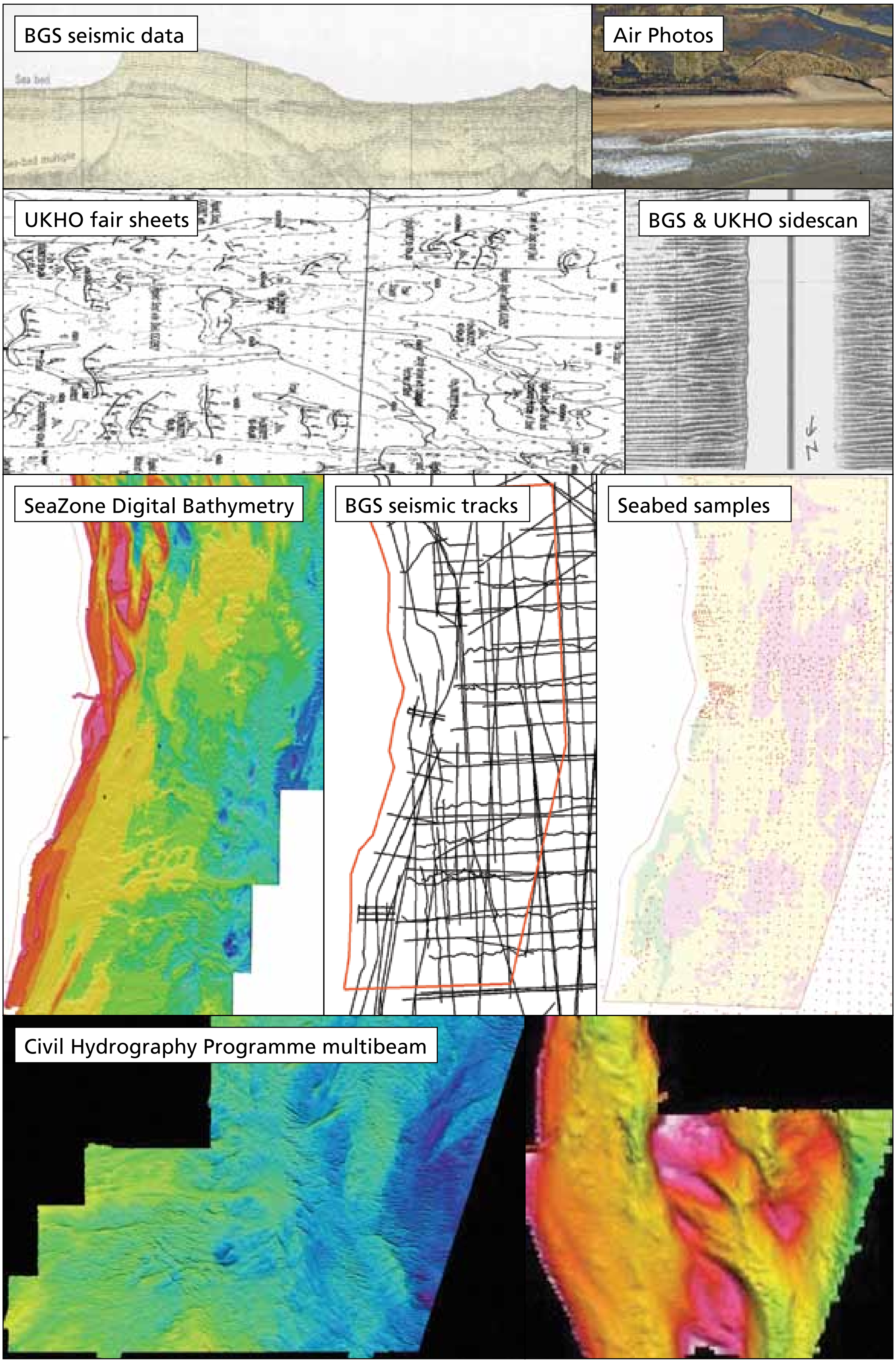


Figure 3.176 SeaBed Geology Map: part of the East Anglian coast. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

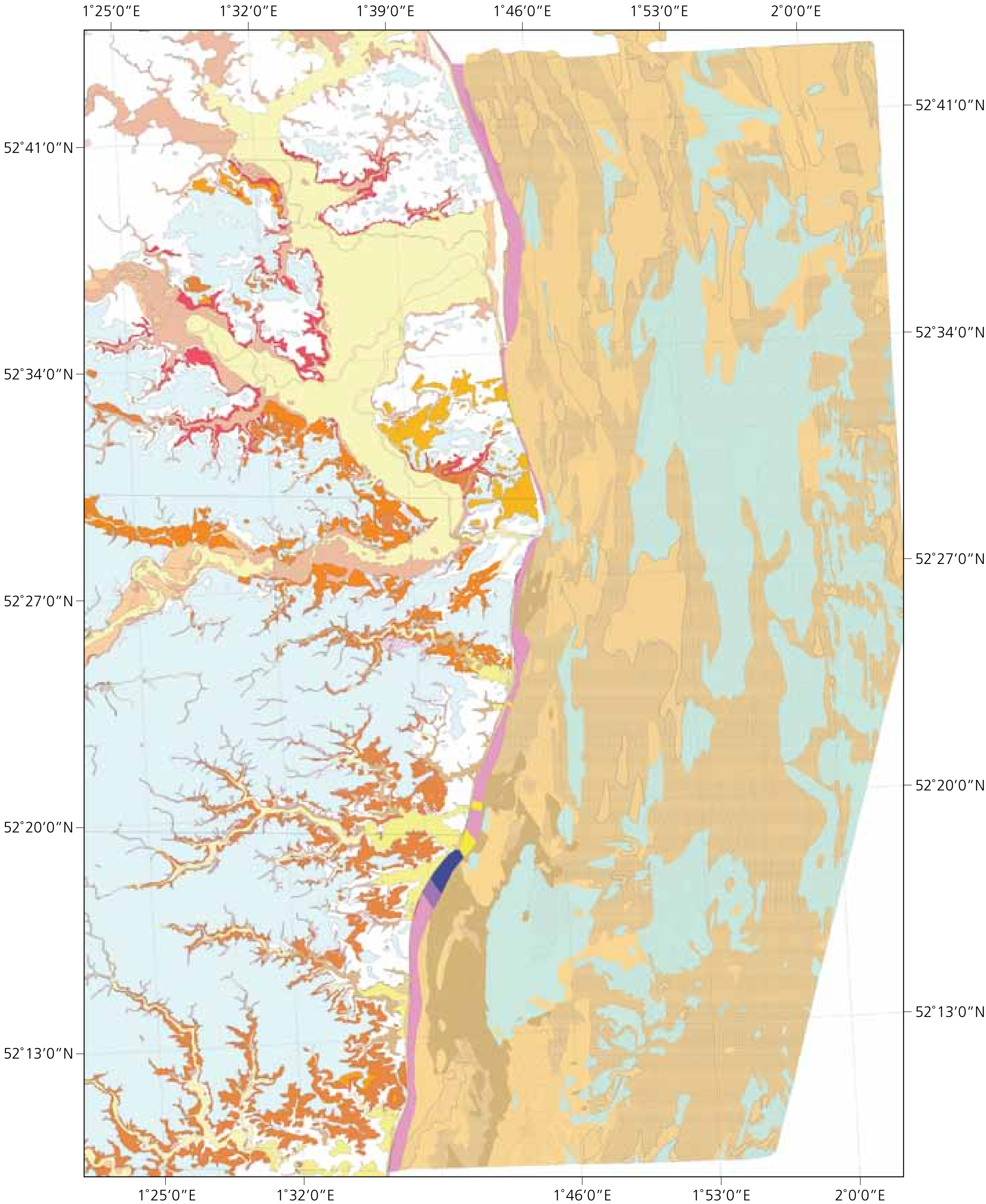
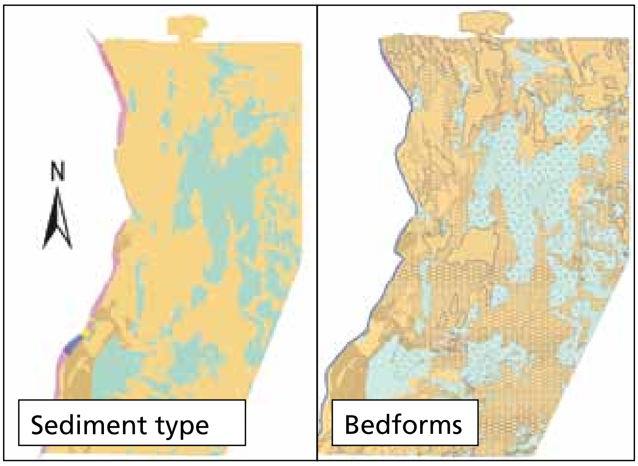


Figure 3.177 Different layers of data within SeaBed Geology. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



3.8.4.3 Eastern English Channel (Region 3)

3.8.4.3.1 Coastal Zone

Continued rising eustatic sea levels, compounded by subsidence of the land mass, makes this area more likely to suffer coastal flooding and erosion of beach areas. Monitoring surveys undertaken by the Channel Coastal Observatory are summarised in Case Study 5. Currently these are based mainly on single-beam surveys (Southeast Strategic Regional Coastal Monitoring Programme Annual Survey Reports, 2008). These surveys are gradually being extended around the coast of England and Wales and provide the main evidence base for changes in beach profiles and other aspects of coastal squeeze. A new MBES joint survey between Dorset Wildlife Trust, the MCA and the New Forest District Council of the Dorset coast (known as the DORIS programme) was completed in late 2008, with financial contributions from Viridor Credits.

Case Study 5: Coastal monitoring in southern England – a strategic approach

The Southeast and Southwest Strategic Regional Coastal Monitoring Programmes were established in 2002 and 2005 respectively, to provide coherent and cost-effective delivery of the coastal monitoring data required for sound decision-making at both strategic and operational levels. The Coastal Monitoring Programmes are grant-aided by Defra and, between them, provide a seamless data source for the coastal zone from the Isle of Grain (Thames Estuary) to Avonmouth (Bristol Channel). The Programme partners are the 48 maritime Local Authorities together with the Environment Agency (Southern and Southwest Regions). The Channel Coastal Observatory has been set up as the data management centre for the Programmes, and also has responsibility for their Coastal Wave Network and tide gauges.

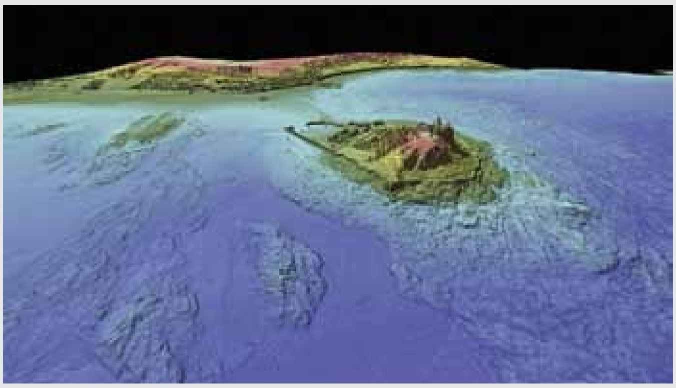
Coastal monitoring consists of topographic and bathymetric surveys, LIDAR and aerial photography – these can be said to monitor the 'response' of the coast. The 'forcing' is measured by a Coastal Wave Network of 20 Directional Waverider buoys, in roughly 10 to 12 m depth (referred to Chart Datum), together with seven high quality tide gauges (which also measure non-directional waves) and meteorological stations.

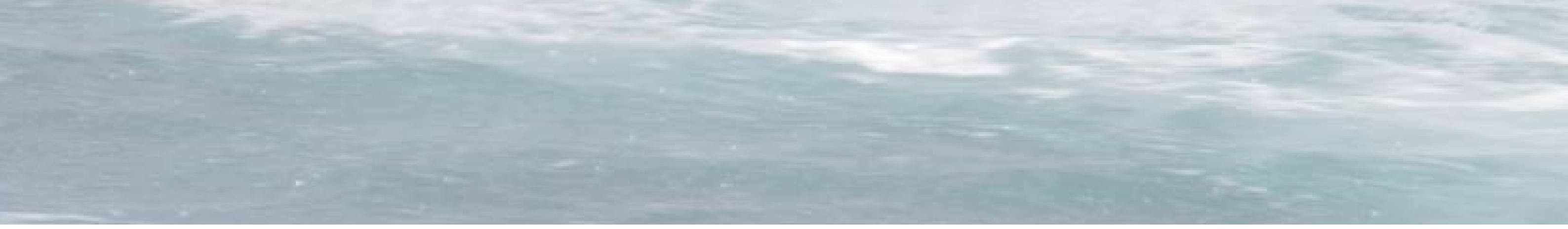
The type of monitoring and the spatial and temporal frequency of surveys for each section of coast is determined on a risk basis, considering geomorphology, exposure, defence type and coastal erosion and flood risk. Typically, a beach with a 'Hold the Line' coastal defence policy will receive two topographic profile surveys a year, with profiles spaced every 100 to 200 m. Every five years, the entire stretch of coastline receives an ortho-rectified aerial survey and a LIDAR survey to the Mean Low Water Springs (MLWS) contour, plus a topographic baseline (spot height) survey of accessible beaches. Inaccessible areas, such as cliffs or saltmarshes and mudflats can receive annual LIDAR surveys. A nearshore bathymetric survey is also conducted every five years, with annual surveys along selected, highly-managed frontages. This is the region of the 'White Ribbon' – the phrase coined by BGS to describe the nearshore coastal strip where traditionally very little data are collected due to both the operational difficulty and expense.

An important facet of the Coastal Monitoring Programmes is that all data are collected using consistent specifications and subject to rigorous quality-control procedures. Furthermore, a detailed survey control network has been installed, which is used for all types of data collection, so that different types of data can be merged (within the accuracies of each type of equipment), as shown in Figure 3.178, where unfiltered LIDAR data have been merged with multibeam bathymetric data.

The MBES survey was conducted jointly by the Southwest Coastal Monitoring Programme and the UK Civil Hydrography Programme.

Figure 3.178 Combined MBES and LIDAR data for Mount's Bay. Image courtesy of NetSurvey.





Analysis of the five-yearly topographic baseline surveys has identified areas of coastal change which can be missed by examining only year-on-year changes shown by profiles (as shown in Figure 3.179).

The Coastal Wave Network was designed primarily to provide wave climate in the nearshore region where, again, traditionally there are very few data and where the wave transformation processes are most significant, so that modelled, transformed data are least reliable for design criteria. Wave exceedance values are also useful as an indicator of potential increase in storminess, although there is no evidence for that in the 12 year record at Milford-on-Sea (Figure 3.180).

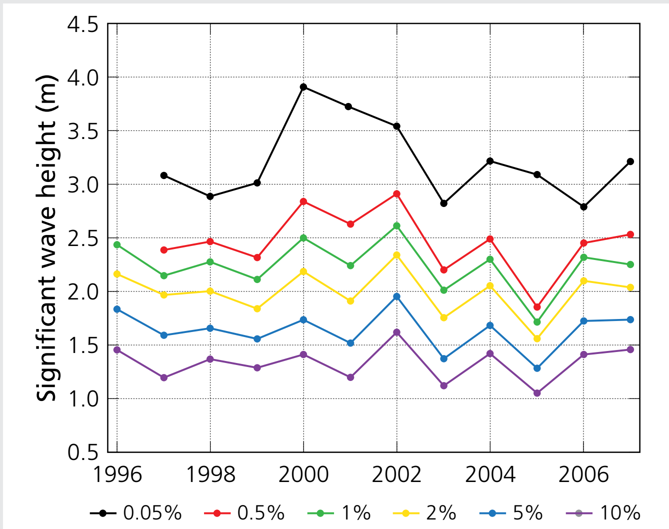
Intertidal zones of saltmarsh and mudflat have been disappearing with a typical rate of loss of 1% to 1.5% per year on a systematic region-wide (Cell 5) basis, over a period of more than 50 years. This loss is linked, though not solely attributable, to coastal squeeze. The trend seems likely to continue.

The regional beach survey programme is relatively immature at present and long-term trends cannot be predicted reliably. Net losses of beach material above MLWS, arising from natural processes within the central south coast (cell 5), exceed 1.35 million m^3 over a period of about 5 years. (The net change in measured beach volumes suggests that beaches have accreted by about 0.75 million m^3; however, this figure is distorted by the regional pattern of beach recharge which has introduced more than 2.1 million m^3 over a 5 year period.) Erosion hotspots are evident at a number of locations, often associated with beach recharge sites including much of Poole Bay, Medmerry and Hayling Island.

All data collected by the Coastal Monitoring Programmes are freely available, with full metadata, directly from the Programmes' website (www.channelcoast.org). This ease of access to high quality data has proved to be one of the most appreciated 'add-on' benefits of the Coastal Monitoring Programmes and the data have been widely used for ecological mapping, Shoreline Management Plans and design of new beach management programmes, and by other Government agencies such as the UK Hydrographic Office as well as for strategic (Defra) and university research programmes.

Figure 3.179 Difference model for Gull Island, West Solent. Courtesy of the Channel Coastal Observatory.

Figure 3.180 Significant wave height exceedance at Milford-on-Sea, 1996-2007. Courtesy of the Channel Coastal Observatory.

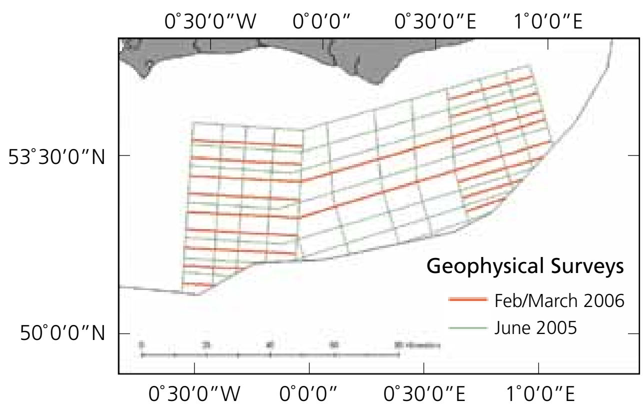


3.8.4.3.2 Offshore

The Eastern English Channel is one of the key areas for UK marine aggregate extraction, and several new surveys and studies have been undertaken in this area. A major project funded by the ALSF has recently been completed (James et al., 2007), and new projects are underway extending this style of work, which provides a much better understanding of the underlying bedrock structure, the thickness and distribution of sediments and distribution of habitats than previously possible. One disadvantage of these projects is the corridor approach to multibeam data collection. In these projects SeaZone digital bathymetry has been used to guide interpretation between the corridors (Figure 3.181), but future complete MBES coverage will be required to meet modern hydrographic standards, to provide more comprehensive habitat maps and for full resource assessment.

The Eastern English Channel is an area with much new data collected by aggregate companies and the Civil Hydrography Programme; these data have not yet been fully integrated or interpreted with existing geological data. These new data have led to new scientific publications. Gupta et al. (2007) suggested that the bathymetry and sediments in the Eastern English Channel were catastrophically affected by a flooding event associated with break-through of a pro-glacial lake in the southern North Sea.

Figure 3.181 Corridor approach to multibeam collection used in the Eastern English Channel Habitat Map project. From James et al. (2007). Courtesy of the Channel Coastal Observatory.



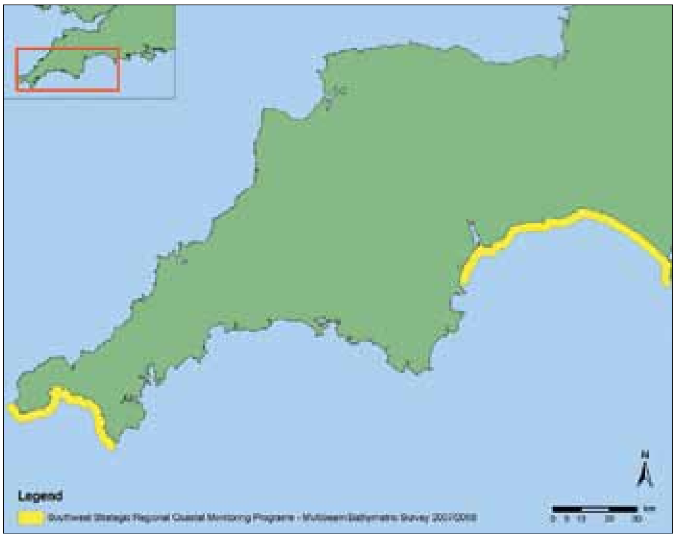
3.8.4.4 Western English Channel, Celtic Seas and South West Approaches (Region 4)

3.8.4.4.1 Coastal zone

In 2008 there was a major landslip at Lyme Regis. Similar events are more common in coastal areas where Jurassic sediments crop out compared with the harder cliffs formed in the older rocks. In the rest of this area, erosion is less of a problem and is generally confined to changes in beach profiles and intertidal zones of the estuaries around the south west peninsula. Assessment of the coast in this area is now included in the Southwest Strategic Regional Coastal Monitoring Programme. Previously this was based on beach profiles and single-beam bathymetry, but in 2008 the SW programme was upgraded to MBES (IHO Order 1) in collaboration with the Civil Hydrography Programme (Figure 3.182).

On the south coast of Wales, the Countryside Council for Wales (CCW) has completed a ten-year study of the intertidal zone which, although focussed on biota, provides a summary of the intertidal substrate and will form a key dataset for monitoring future coastal change.

Figure 3.182 Outline of Southwest Strategic Regional Coastal Monitoring Programme multibeam around the SW Peninsula. Courtesy of the Channel Coastal Observatory.



3.8.4.4.2 Shelf seas

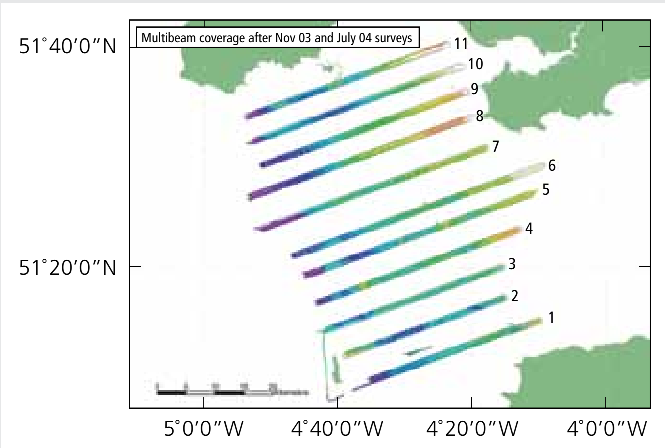
New multibeam surveys have been collected as part of the Civil Hydrography Programme and by Natural England along parts of the nearshore area around Cornwall. The geological analyses of these data are not yet complete. In the Bristol Channel there is significant interest in improved models of the bathymetry and geology of the seabed, as this is a key area for future aggregate extraction, wind energy and tidal power schemes. New data have been collected by BGS and DECC as part of the Strategic Environmental Assessment (SEAs) programme (see www.offshore-sea.org.uk), and a major project funded by the ALSF was completed in the outer Bristol Channel (see Case Study 6; Mackie et al., 2006). The dredging licensees are also required to undertake monitoring of extraction areas, including Helwick and Nash banks (Kemp and Brampton, 2007).

Case Study 6: Bristol Channel Habitat Study

The Bristol Channel Habitat Study was undertaken by BGS and the National Museum of Wales (NMW) to produce a marine habitat study with the aim of addressing the lack of regional-scale biological and geological data in the outer Bristol Channel. The area covers approximately 2400 km^2 of the seabed from Carmarthen Bay to Lundy Island, with water depths up to 60 m. The area has a very high tidal range, reaching over 7 m in the study area. A primary aim of the study was to gather high resolution data on the character and nature of the seabed through use of multibeam coverage of the main bedforms, habitats and biotopes. The survey consisted of eleven 25–40 km long and one-km-wide corridors with complete multibeam and sidescan coverage, separated by 5 km between the corridor centre-lines (Figure 3.183).

Bedforms have been mapped at a large scale (sand waves; Figure 3.184). Superimposed smaller-scale wave forms (megaripples) can be seen on sidescan data. The integration of seismic

Figure 3.183 Corridors of multibeam data collected in the Outer Bristol Channel. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



data with the MBES provided the data required for a 3D model of the mobile and young sediments above bedrock (Figure 3.185).

Although the corridor approach provides better data and enhanced interpretations at a regional level, it does not provide full coverage or meet modern hydrographic requirements. Further work will be required to infill between the corridors and clearly define aggregate resources and the distribution of habitats.

Figure 3.184 Sand waves in the Outer Bristol Channel. The largest feature has an amplitude of about 10 m. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

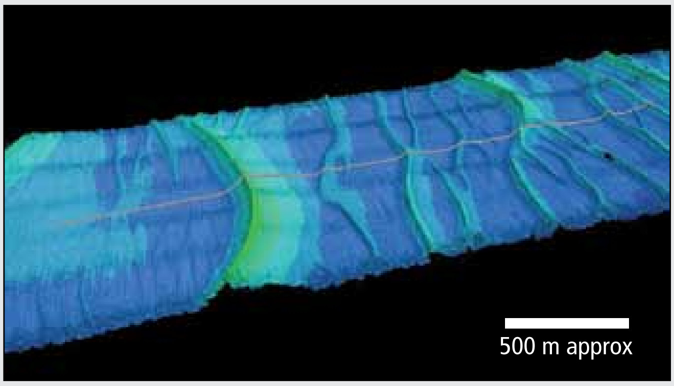
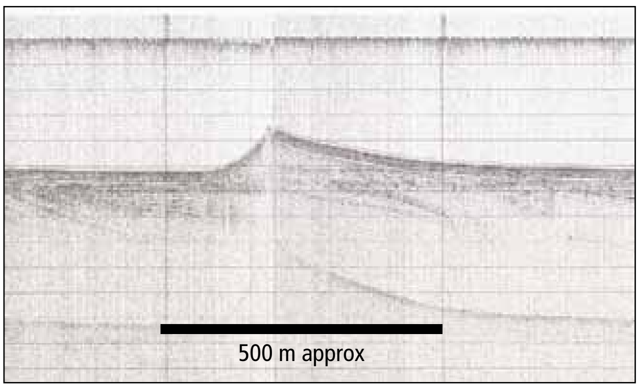


Figure 3.185 Boomer seismic data demonstrating internal structure of sand wave and thickness of sediments above dipping bedrock. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved



3.8.4.4.3 South West continental margin

A small sector of the continental margin extends into UK waters in the far west of the SW Approaches. In 2007 the UK, in collaboration with Ireland, France and Spain, submitted a joint claim for an extended exclusive economic zone (EEZ) in this area, based on considerable new multibeam and seismic data collected outside the designated area. Within the designated zone, the MESH project collected new geophysical data to undertake a trial habitat mapping project on the canyon (Figure 3.186). Publications from this work are in progress.

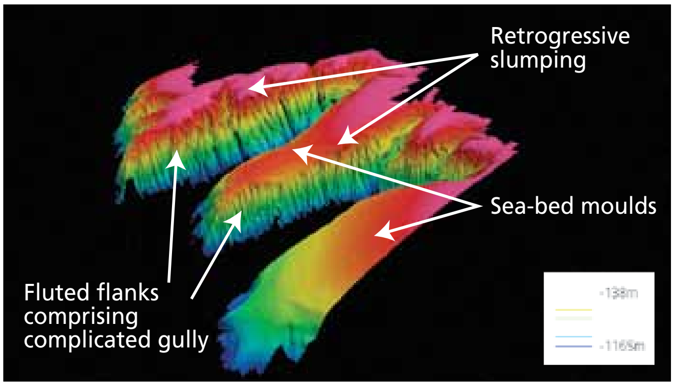
3.8.4.5 Irish Sea (Region 5)

3.8.4.5.1 Coastal zone

The Irish Sea is an area of strong tidal activity and high sediment mobility; sediment transport and evolution of the estuaries are key topics of study. The Dee Estuary has been a focus for research undertaken by the National Oceanography Centre (NOC) (see Case Study 7). On the south bank of the Ribble Estuary, the Environment Agency has led a project to develop 168 hectares of new saltmarsh on land formerly drained and intensively farmed. The appoach is two-fold: (1) to generate new saltmarsh to replace areas lost as 'coastal squeeze' continues, and (2) to environmentally assist with flood risk management, as the scheme achieves the same level of protection as a traditional flood defence scheme.

Around the coast of Wales, CCW has undertaken a ten-year study of the intertidal zone which will provide new evidence on coastal change and sediment distribution in the coastal zone.

Figure 3.186 Multibeam bathymetry on the South West Continental Margin collected as part of the MESH project. Courtesy of JNCC.



Additional MBES data, shallow seismic data and cores have been collected in the Clyde to support a BGS geochemistry study looking at the anthropogenic impacts from urban, industrial and recreational activities upstream, along shores and in the adjacent coastal zone.

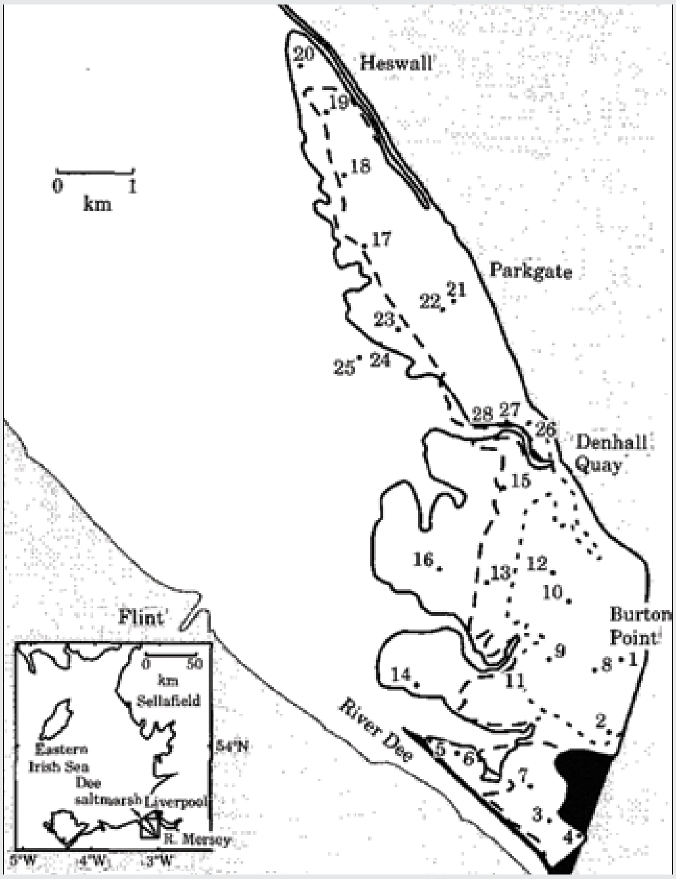
3.8.4.5.2 Offshore

NOC has led research in the area through continued monitoring of a sector near Liverpool as an oceanographic observatory. In 2008, BGS extended the data coverage by collecting multibeam data in the area. Additional site investigation surveys have been collected for the extensive developments of offshore wind farms. Other areas of multibeam and supporting shallow seismic data have been collected by CCW (www.habmap.org; Robinson et al., 2007), Agri-Food and Biosciences Institute (AFBI) and the SEAs programme.

Case Study 7: Changes in sedimentation in the Dee Estuary

The Dee Estuary in NW England/North Wales is a macrotidal coastal plain estuary. It was possibly over-deepened by glaciation during the Ice Age. It has a long history of management from Roman times to the present day. Chester was the predominant port in the NW of Britain from the 11th to the 14th century, by which time navigation was affected by siltation. In the 16th century ships used Neston and Parkgate on the English shore. In the 18th and 19th century there was major land reclamation downstream of Chester following construction of the 'New Cut' (a canalized section aimed at improving navigation to Chester) with the last reclamation ending in 1916. During the 20th century there has been substantial siltation and establishment of saltmarsh on the English side of the estuary (see Figure 3.187), with continuing interventions. The soft boulder-clay cliffs near the mouth on the English side are eroding; Caldy Golf Club deployed armourstone in 1993 to prevent further losses. The severe storms of February 1990 caused significant erosion at Flint Point and a coastal defence was built. Some work on the training wall was carried out in 1993/4. Further recent work on bridges at Flint and Queensferry has led to some local changes in scour and deposition. Now the main port is at Mostyn on the Welsh shore. The Port of Mostyn has commissioned substantial surveys and modelling studies in recent years, to understand the effects of dredging and spoil deposition in the Welsh channel on the estuarine biota, and monitoring is carried out as part of the licensing procedure. Water abstraction from the river over many years has led to reduced sediment load from the landward side. Thus it is difficult to disentangle natural and anthropogenic effects

Figure 3.187 Changes in extent of salt marsh. The dotted line indicates edge in 1904, dashed line 1948 and solid line 1970-80. Black shaded area is land claim of 1962 and 1987. From Hutchinson and Prandle (1994).



on the morphological evolution of the estuary. Marker (1967) carried out a detailed study of the history of siltation.

The estuary contains extensive areas of intertidal sand and mudflats which support a variable but characteristic benthic fauna depending on the nature of the substrate. Large areas of saltmarsh also occur at its head and along part of its north-eastern shore. The estuary continues to accrete and further saltmarshes are developing, particularly on the English shoreline. Locally, on the Welsh shoreline, saltmarsh continues to erode, particularly between Greenfield and Flint. Within the estuary, the three small sandstone islands of Hilbre, Middle and Little Eye provide the only hard natural rock coast habitat along this section of coastline. A largely unvegetated shingle ridge occurs at the Point of Ayr. Although yellow embryo dunes occur at its western end, these are susceptible to erosion from wave action (www.wirral.gov.uk/LGCL/100006/200073/1008/content_0000986.html).

There are several different types of habitat and the estuary is of international importance for birds. It is designated as a Special Area of Conservation (SAC) and has some Sites of Special Scientific Interest (SSSIs) and Special Protection Area (SPA) status. It is also a Ramsar site (wetland of international importance designated under the Ramsar Convention).

Hutchinson and Prandle (1994) studied the record of saltmarsh deposition from a series of shallow cores extracted at 28 locations which were analysed for caesium-137 (^{137}Cs) content at 2-cm intervals. These depth profiles of ^{137}Cs were correlated against a 40-year record of ^{137}Cs discharges from the nuclear fuel reprocessing plant at Sellafield, some 130 km to the north. Over the last 20 years, net deposition ranged from 5 cm at the head of the estuary to 60 cm at the offshore edge closest to the sea. The deposition rates decreased steadily over this 40-year period with net deposition over the last 20 years only half that of the first 20 years. Huckle et al. (2005) also studied the evolution of the saltmarsh over 40 years from the 1950s to 1997 using various remote sensing techniques. At the apex of the saltmarshes on the English shore of the Dee Estuary, the marsh expanded dramatically to 1975, and consisted predominantly of pioneer and low marsh vegetation types. Between 1975 and 1997, however, there was only a slight increase in saltmarsh area, but with an increase in mid-and high marsh vegetation, replacing pioneer marsh. In a second area of the saltmarsh on the English shore, a different pattern of saltmarsh expansion was observed. The area occupied by marsh continued to increase right up to 1997, with extensive pioneer vegetation suggesting a process of continuing expansion. However, the pattern of marsh colonisation appeared to be different in 1997 compared to 1975.

The Defra/EA Estuaries Research Programme (1997–2008) has investigated morphological estuary models. A review of models and their results is given by Huthnance et al. (2008).

The Dee Estuary (as is the case for most others) appears to be infilling as it traps fine sediment (Prandle, 2004). Different models predict different rates of infill, which will proceed until a dynamic equilibrium can be reached where the estuary switches from a flood-dominant importer of sediment to an ebb-dominant exporter.

Moore et al. (2008) have examined the processes of present day change using hydrodynamic models and LIDAR data to examine the effects of tidal asymmetry. Moore and co-workers found that the shallower intertidal areas (sand and mud banks) were the most tidally asymmetric, showing flood dominance. The main navigation channels showed some ebb dominance but the tides were relatively undistorted. This overall flood dominance is likely to induce net sediment import to the Dee, which explains known historical morphological changes (large-scale accretion over the past two centuries) and also recent morphological changes as seen from the LIDAR surveys (which show predominantly net accretion between 2003 and 2006, see Figure 3.188). Hypsometrical analysis suggests the Dee may be approaching equilibrium, and that the flood dominance and sedimentation rate may therefore decrease in the future. In

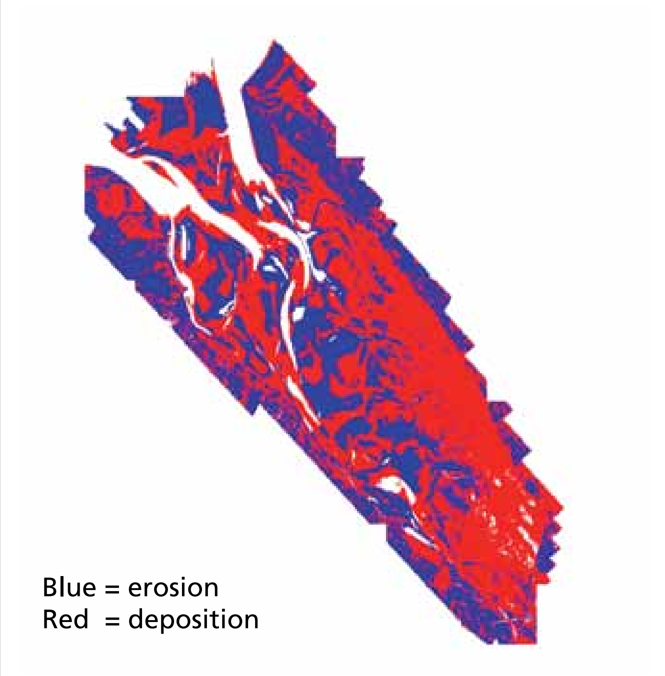


Figure 3.188 Bathymetric changes from LIDAR surveys 2003-2006. From Moore et al. (2008).

an infilling estuary, an increase in the area and elevation of tidal flats can eventually shift an estuary towards ebb dominance, as shown by previous research and by ‘idealised estuary’ modelling results presented in this study. The large tidal amplitude to hydraulic depth ratio of the Dee, however, suggests that the tidal flats would have to be very extensive indeed for this to occur.

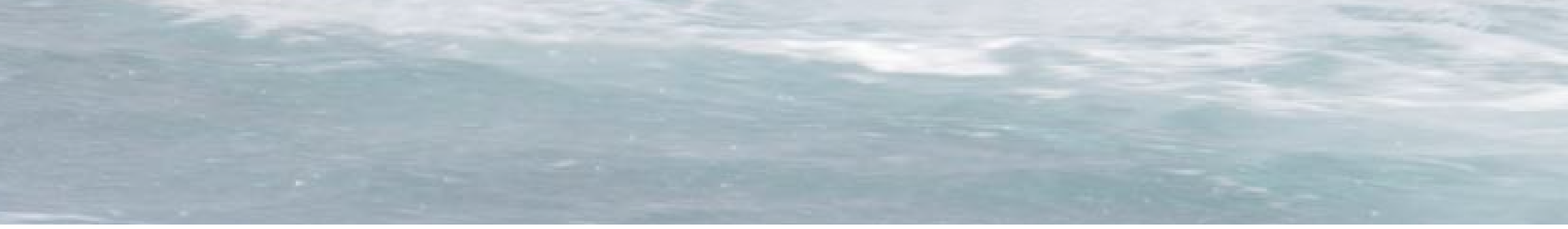
Residuals due to wind and freshwater flow, as well as tidal residuals, will be important in determining the net direction of coarse and fine sediment transport; 3D models are required to investigate these processes fully. Ongoing work in the Dee includes a regular measurement campaign by NOC under the Oceans2025 science programme (Souza, 2006) as well as development of the Liverpool Bay POLCOMS model, which includes the Dee, Mersey and Ribble estuaries. Wolf (2003) used the SWAN model to examine wave effects in the Dee, which may be important near the mouth. The Telemac/Tomawac/Sisyphe model system is being used to investigate sediment transport in the Dee and the Mersey, especially related to impacts of proposed tidal energy barrages. The recently-funded NERC FORMOST project is also investigating sediment transport in the Dee using models and measurements.

Prandle (2006) showed that, on average, the 'dynamical' adjustment to a 25% change in river flows may change depths as much as the projected sea-level rise; this effect is reduced in smaller estuaries and significantly increased in larger ones. The resulting changes in estuarine lengths and breadths follow similar patterns with the biggest 'dynamical' changes occurring in the largest estuaries where they are significantly greater than those due to sea-level rise. This should include the Dee Estuary. There is some uncertainty as to whether the rate of infill can keep pace with sea-level rise.

3.8.4.6 West Scotland including The Minch (Region 6)

3.8.4.6.1 Coastal zone

The hard rocky shorelines around the islands and along The Minch result in very little coastal erosion. However the coastal waters are highly productive and are a focus for aquaculture and inshore fishing. This is also a key area for understanding the dynamics of the last British Ice Sheet. New multibeam, seismic and sampling around the Summer Isles makes this area the first of the sea lochs to have detailed bathymetric coverage (Stoker et al., 2006; Case Study 8). The area is a focus for research by the Scottish Association for Marine Science (SAMS; near Oban) and BGS.



Case Study 8: Summer Isles

Figures 3.189 and 3.190 demonstrate the paucity of detailed bathymetric surveys in the sea lochs along the west coast of Scotland. In 2005, BGS commissioned a survey in the Summer Isles area (Figure 3.189). This was followed up by collecting seismic data and a series of cores in 2006 and 2007. Analysis is in progress in conjunction with the SAMS.

The prime reason for collecting the data was to study the evidence for the history of the last glaciation and the evidence for a palaeo-ice stream which passed through the area and round the north of Lewis to the edge of the Continental Slope. Figure 3.190 highlights some of the glacial features, including moraines and the distribution of late glacial sediments within the area. The moraine features are important as they are likely to have boulders exposed on the surface and provide a different habitat. Other features that have been recognised include submarine landslides and gas escape features (Figure 3.190). The recognition of areas where these occur, and the potential for assessing risks of future events, will help with marine planning for both aquaculture and development of marine renewable energy sources.

The new bathymetry will also allow for better modelling of oceanographic features, such as tidal currents and wave energy, which will provide better data to support better identification of sites for aquaculture.

Figure 3.189 MBES data coverage n the sea lochs around the Summer Isles, NW Scotland. The area outlined is highlighted in Figure 3.190. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

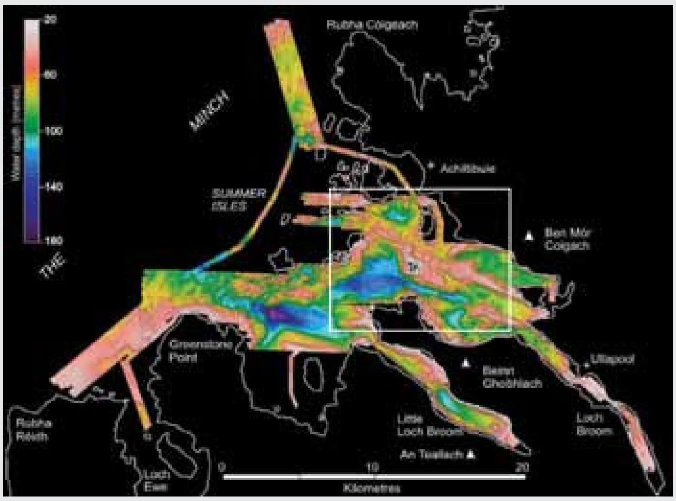
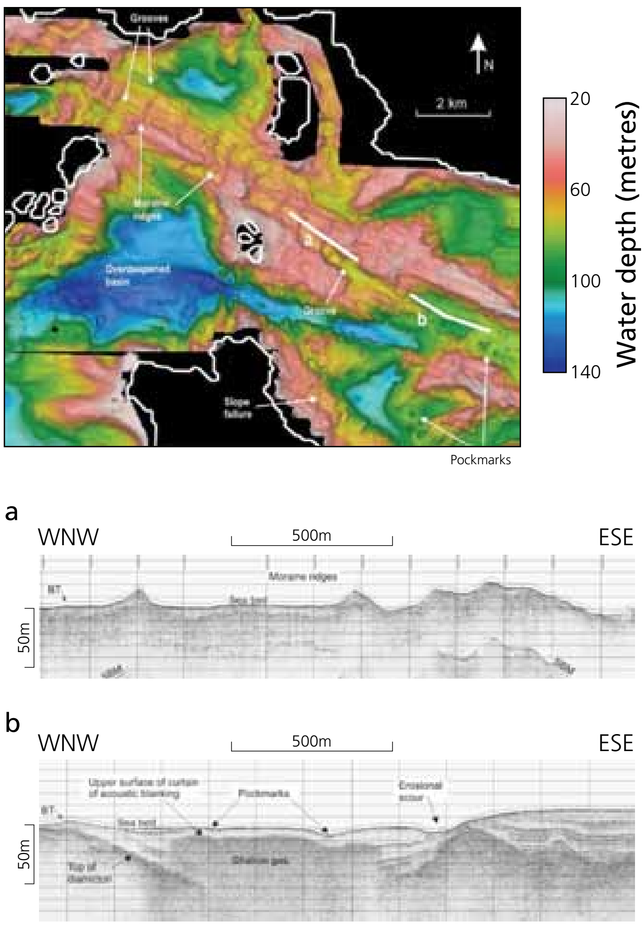


Figure 3.190 Detail of part of the Summer Isles data, highlighting moraine ridges, pock marks and a submarine slope failure. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



3.8.4.6.2 Offshore

The Minch is an important area for aquaculture and fishing and has great potential for marine renewable energy. A strong case can be made for considerably extending detailed surveying in this area to help define ground conditions and improve hydrodynamic modelling.

Only small areas of MBES data have been collected thus far and these are mainly focussed on the reefs to the East of Mingulay, where several surveys and research programmes are studying cold-water coral reef habitats.

At the southern end of this region a major new survey was completed in September 2008 along the northern coast of Northern Ireland (Figure 3.191). This was supported financially by the EU INTERREG IIIa Programme of work as a joint project between groups in the Republic of Ireland and Northern Ireland, led by the Maritime and Coastguard Agency. The project was called JIBS (Joint Irish Bathymetric Survey). The data will support marine planning in the area and be used to produce new charts, geological maps and models and habitat maps. Discoveries include the recognition of underwater caves in areas of limestone at the seabed, several wrecks, and a series of symmetrical sand waves (Figure 3.192).

Figure 3.191 The JIBS multibeam data set, Northern Ireland. Courtesy of the Maritime and Coastguard Agency.

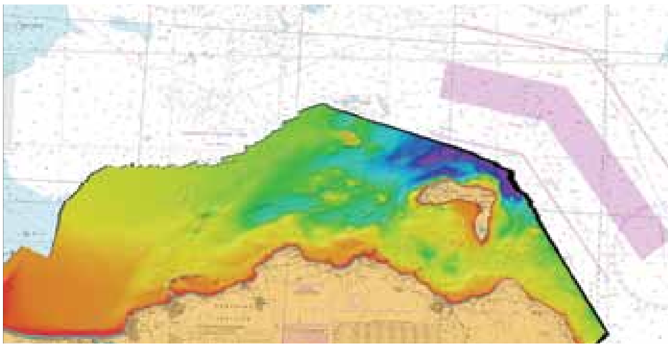
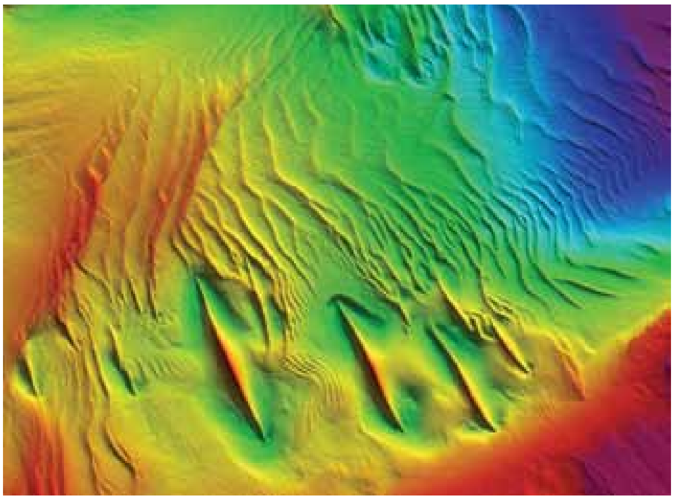


Figure 3.192 Complex patterns of sand waves north east of Portrush. Courtesy of the Maritime and Coastguard Agency.



3.8.4.7 Scottish Continental Shelf (Region 7)

3.8.4.7.1 Coastal zone

The hard rocky shorelines around the islands and along The Minch result in very little coastal erosion. However the coastal waters are highly productive and are a focus for aquaculture and inshore fishing.

3.8.4.7.2 Offshore

New surveys in the offshore area have been undertaken as part of the Civil Hydrography Programme with large areas completed around Orkney and north of Cape Wrath. The data from the area around Nun Rock have provided sites for shallow drilling and sampling of ancient rocks at the seabed and have increased our knowledge of the geology of the area (Figure 3.193). Note the detail of the seabed on this image and the presence of several trends in cross-cutting

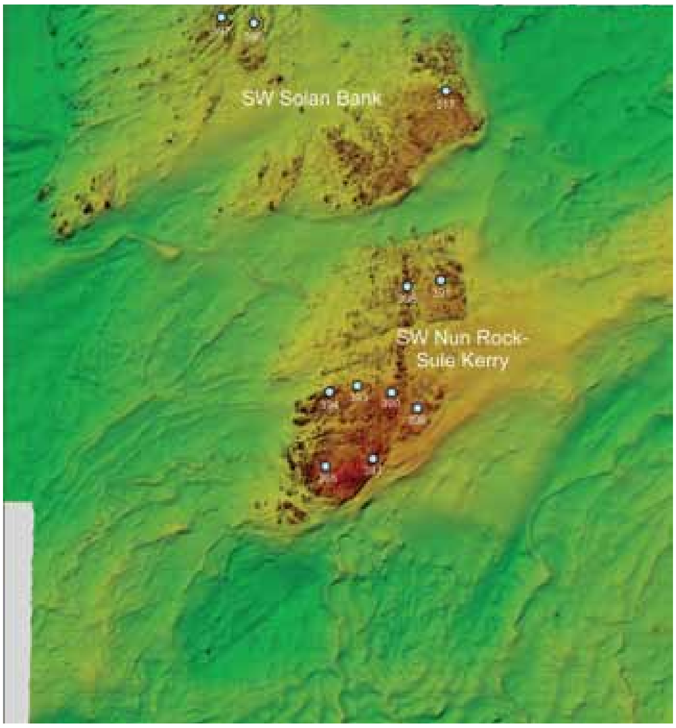


Figure 3.193 Multibeam data from the area around Nun Rock. Multibeam data provided by the Maritime and Coastguard Agency. Borehole locations from the British Geological Survey.

moraines, leading to new scientific publications (Bradwell et al., in press). These data are much more detailed than those provided by Olex for the same area (see Figure 3.163). Other small areas of MBES data have been collected in this region as part of the MESH project.

A new MBES survey was completed in 2008 by the Fisheries Research Laboratory in the Pentland Firth, which is a target for tidal energy schemes.

These data, collected as part of the Civil Hydrography Programme, were used to site a series of shallow boreholes and video footage of the seabed for habitat studies.

3.8.4.8 Rockall Trough and Faroe-Shetland Channel (Region 8)

3.8.4.8.1 Rockall Trough and adjacent areas

The offshore area around Rockall is characterised by deep water with isolated seamounts, such as Anton Dohrn and Rosemary Bank, and the large relatively shallow Rockall Bank and Hatton Bank (Figure 3.194). The geology in this area is less well known with fewer samples (Figure 3.195) and fewer shallow seismic data (Figure 3.196). Most of the existing seabed and shallow seismic data have been collected by BGS with support from the oil industry and DECC through the Rockall Project. In the past few years new data, including multibeam data, have been collected to support the JNCC habitats work and the DECC Strategic Environmental Assessments (see Figure 3.160). Further offshore, outside the UK designated zone, additional data have been collected in support of the UK EEZ claim which will be submitted to UNCLOS in the near future. Unlike in the SW Approaches, in this area there are complex boundary issues with claims from Iceland and the Faroe Islands authorities for parts of the Rockall and Hatton areas.

3.8.4.8.2 Faroe-Shetland Basin

The amount of data in the Faroe-Shetland Basin is greater than in the Rockall area as a result of greater oil and gas exploration activity. There are some large areas of multibeam data, collected primarily as part of the SEAs programme and to support the JNCC habitats study. In the north of the area a series of mud diapirs appear on the seabed and are well imaged on the multibeam bathymetry (Figure 3.197). These can be demonstrated to be associated with Neogene compressional tectonics (Ritchie et al., 2008).

Figure 3.194 Regional bathymetry of the area. Data courtesy of Gebco. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

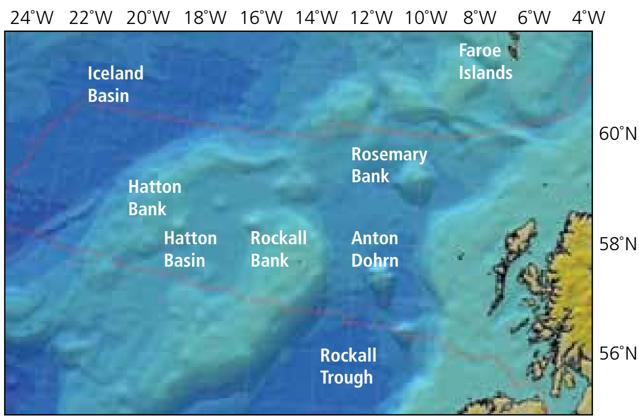


Figure 3.195 BGS Shallow samples in the Rockall Area. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

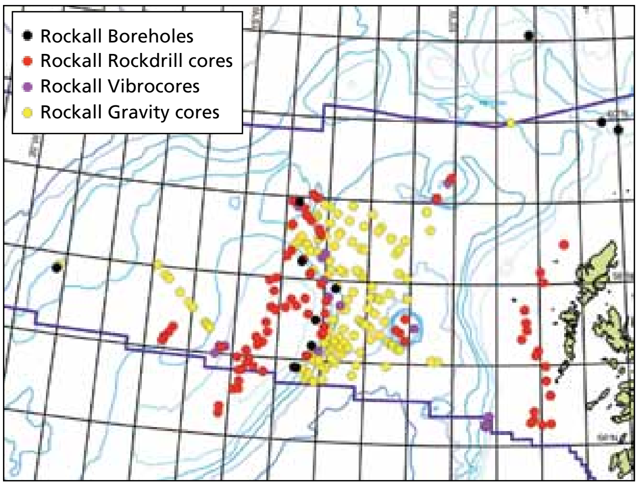


Figure 3.163 highlighted the seabed imagery generated from 3D seismic data in this area. There is evidence for major submarine landslides (Figure 3.198), active faulting at the seabed, strong bottom currents and deep water erosion. Figure 3.199 demonstrates a comparison between the seismic image and TOBI (Towed Ocean Bottom Instrument) sidescan data. Note that the clarity of the submarine fans is much

Figure 3.196 BGS shallow seismic data in the Rockall area. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

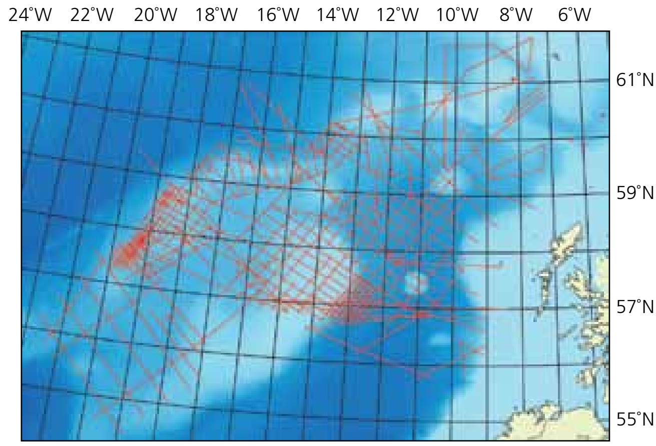
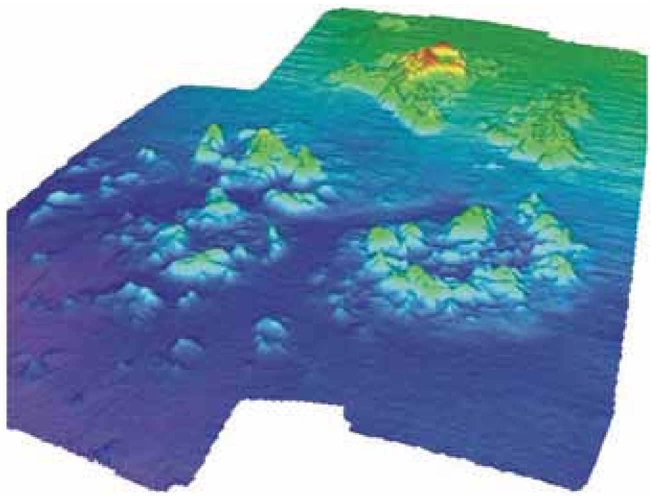


Figure 3.197 MBES image of mud diapirs on the seabed in the area North of 62° N. Data from the DECC Strategic Environmental Assessment (SEAs) surveys. North to left of image. Department of Energy and Climate Change.



reduced on the high resolution TOBI data, which is picking out the details of the seabed. The lower frequency seismic data do not image the seabed but include data from close to the seabed, which in this case suggests that the submarine fan systems are partially covered by recent sediments.

Figure 3.198 Detail of seabed image of the Faroe-Shetland Basin showing the Afen slide. A series of failures transported sediments towards the north west down slope. The feature is about 15 km long. Sampling through the toe of the debris deposit indicates that the slide took place around 2500 years ago. Seismic data indicates that the slip plane is along bedding planes within well sorted contourite deposits. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.

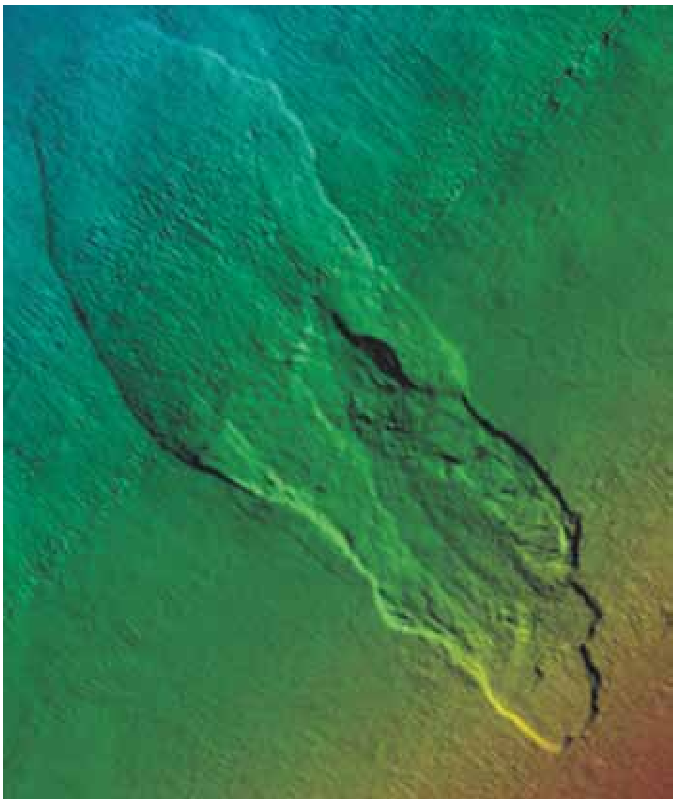
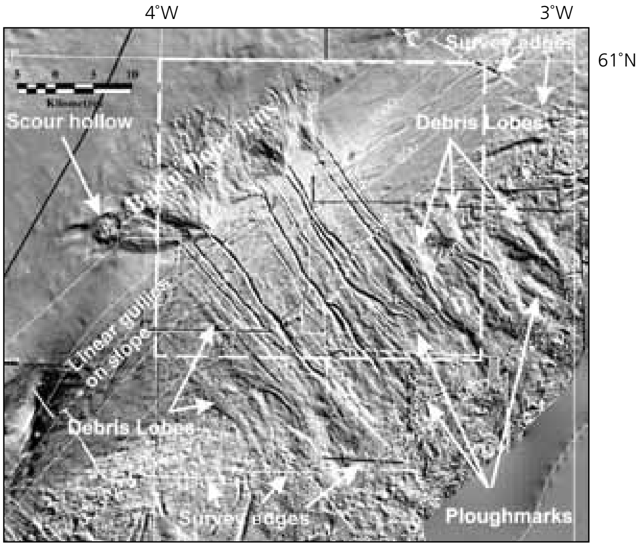
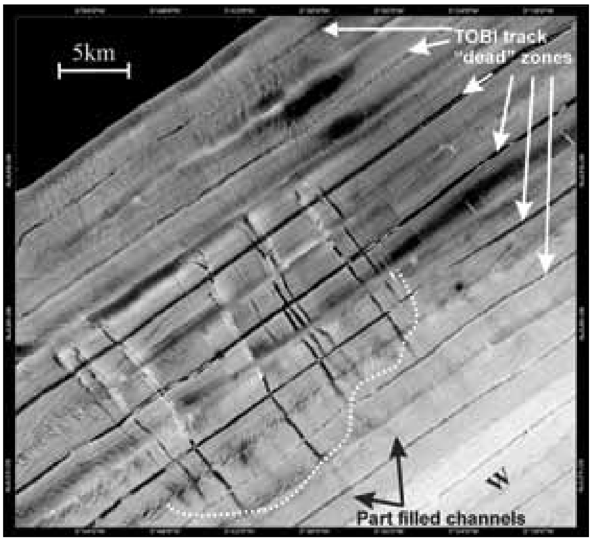


Figure 3.199 Comparison of deep-tow TOBI data and an extract from the 3D seismic montage. After Bulat (2005). TOBI data collected as part of the AFEN project.



(A) Seabed image



(B) TOBI sidescan image

3.8.5 Status of sedimentary process studies and geomorphology

In common with other Ocean Process topics, sedimentary processes and geomorphology may show trends, but status ('traffic-light') cannot be assigned to variables because (1) no accepted criteria apply; and (2) there is limited (usually only local) scope for improvement measures. There are trends of erosion and reduction of intertidal area along a significant proportion of the coast.

This assessment has demonstrated the rapid increase in the coverage of MBES data across the UK seas over the past five years. However, coverage remains at only around 15%, although there are a few additional surveys, primarily site investigations, that are not yet included in Figure 3.160. Geological analysis and interpretation is some way behind the collection of bathymetric data, with only an initial programme of interpretation underway.

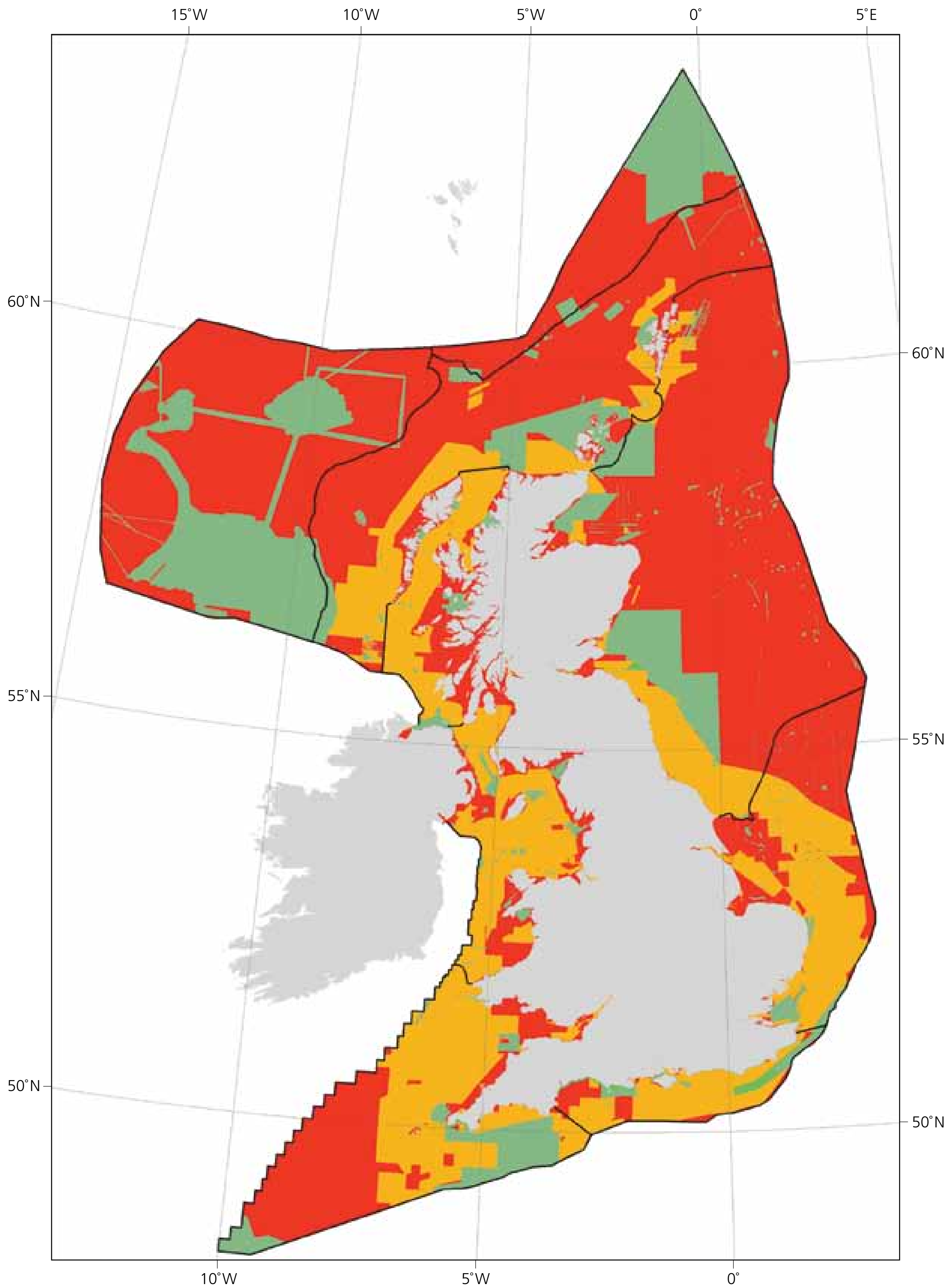
At present there are numerous government-funded and industry surveys which remain largely uncoordinated and piecemeal in nature. Collaboration is improving through the annual COSH meeting (henceforth Civil Hydrography Annual Seminar), although the remit of this meeting needs to be broadened to include the full range of marine mapping activities, including geology and habitats. There is also no integrated database or co-ordinated interpretation programme. Two initiatives in this area include the new Memorandum of Understanding to collect and share data between several Government organisations, and the advent of specialised Data Archive Centres (DACs) under the Marine Environmental Data and Information Network (MEDIN) programme. Through MEDIN, the UKHO will act as the de-facto centre of expertise for all government-sponsored bathymetric data-collection programmes on the UK continental shelf, and BGS will hold geological data and an archive of backscatter information. One of the key challenges is to include and integrate into these archives the extensive commercial surveys, primarily site investigations.

The largest survey programme remains the Civil Hydrography Programme, with a strong emphasis on SOLAS (safety of life at sea). However, other work programmes (e.g. CCO) can increasingly be folded into a single programme of work, through collaborative planning and execution, to ensure that data collected once might be used many times for hydrography, geology and good science. The next-largest programmes, which are not wide-area activities, are associated with habitat and environmental studies and typically are undertaken, for example, by JNCC, Cefas and Natural England.

Figure 3.200 summarises the current status of bathymetric information in UK waters. For the purposes of this assessment, areas in green are covered by multibeam data, areas in amber are covered by digital single beam bathymetry and areas in red are areas with little or no bathymetric coverage (e.g. only Lead Line).

One of the features of Figure 3.200 is that larger areas covered by MBES surveys tend to be in deep water where survey times are short as the swath widths are wide with commensurate reduced resolution. In the shallower near shore areas most MBES surveys cover small areas at high resolution, but are time-consuming and therefore more expensive because of the narrower swath widths. Figure 3.200 also demonstrates that the digital single-beam bathymetric surveys tend to be close to the shore, but miss the nearshore areas, where

Figure 3.200 Summary map of the state of bathymetry in UK waters. Green: 100% multibeam data coverage. Amber: single-beam digital bathymetry available: Red: reconnaissance bathymetry only. Reproduced with the permission of the British Geological Survey © NERC. All rights Reserved.



large vessels cannot work with safety. This is very apparent around the Scottish sea lochs and along the west coast of the Irish Sea. The scale of the map does not demonstrate the effect so clearly along the North Sea coast, but there is usually a ribbon with no, or very poor, data. This is also true for geological information and is a reflection on the difficulties of working very close to shore. New surveys, utilising new small vessels equipped with multibeam, are now tackling some of these areas. In shallow areas with low turbidity, areas may also be surveyed by airborne means (i.e. LIDAR).

3.8.6 Forward look and need for further work

The distribution of mobile sediment, and how this will react to climate change and the development of offshore resources, is a topic for future research. The importance of the coastal zone in terms of coastal erosion and flooding, habitats and commercial uses, make this a key area for future work, especially to understand the rates and distribution of coastal erosion, and changes to beach dynamics, in response to climate change and sea-level rise. Monitoring of coastal change is crucially important in view of the coastal zone's dynamic character and the consequent limitations of static bathymetric or sediment distribution maps. Long-term and repeat surveys are needed as modelling is unlikely to provide site specific answers. With continued sea-level rise and changes in wave energy, long-term data sets (such as those maintained by the Channel Coastal Observatory and some Local Authorities) will become crucial in understanding the impacts of climate change, in particular risks of flooding and rates of coastal erosion, and for developing strategies to manage the effects along the UK's extensive coasts.

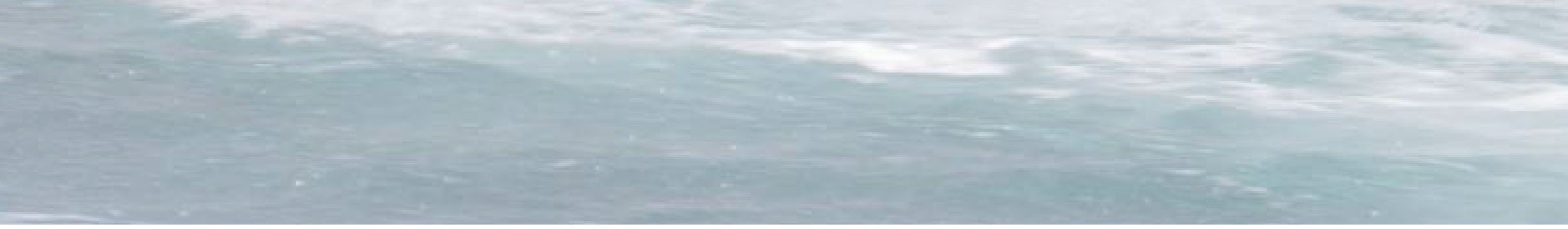
With current detailed survey rates in existing programmes, it will be many years before survey coverage is complete. By increasing the rate of coverage of MBES surveys, the understanding of the seas around the UK will be greatly increased; for example, the Western Approaches is an area requiring more detailed surveys to improve understanding (Section 3.8.3.6). An increase in the use of MBES technology will provide high quality bathymetric data and form the basis for subsequent geological and habitat analysis to underpin future marine planning and to support commercial exploitation (such as marine renewable energy sources), environmental monitoring, conservation and other legislative drivers.

In the UK there are many collectors of MBES data for a wide range of different uses. This contrasts with countries like Ireland, that have one integrated marine mapping programme, funded to rapidly complete the entire Irish seabed (see www.gsi.ie/Programmes/INFOMAR+Marine+Survey/). Work to integrate government-funded survey programmes, and integrate commercial survey data, will increase the efficiency of environmental surveys. Work to develop the next generation of geological maps and models, habitat maps, detailed bathymetry, marine mapping and charts, will better underpin spatial planning between different users and future sustainable development of the marine environment.

Abbreviations

ADCP	Acoustic Doppler Current Profiler
AFBINI	Agri-Food and Biosciences Institute, Northern Ireland
ALSF	Aggregate Levy Sustainability Fund
AMOC	Atlantic Meridional Overturning Circulation
AR4	IPCC Fourth Assessment Report (2007)
AUV	Autonomous underwater vehicle
BCP	Biological carbon pump
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
CANOBA	Carbon and Nutrient Cycling in the North Sea and the Baltic Sea
CASIX	Centre for observation of Air-Sea Interactions and fluxes
CAVASSOO	Carbon Variability Studies by Ships of Opportunity
CCO	Channel Coastal Observatory
CCW	Countryside Council for Wales
CDOM	Coloured dissolved organic matter
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CET	Central England Temperature
CHAS	Civil Hydrography Annual Seminar
CO_2	Carbon dioxide
COSH	Committee on Shipping Hydrography
CP2	*Charting Progress 2* (2010)
DAC	Data Archive Centre
DECC	Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DIC	Dissolved inorganic carbon
DJFM	December to March
EA	Environment Agency
EEZ	Exclusive economic zone
ENSO	El Niño – Southern Oscillation
EPOCA	European Project on Ocean Acidification
ERSEM	European Regional Seas Ecosystem Model
EU	European Union
FLY	Free-falling Light Yo-yo (profiler for microstructure)
FOAM	Forecasting Ocean Atmosphere Model (Met Office)
GCOS	Global Climate Observing System
GHG	Greenhouse gas
GLOSS	Global Sea Level Observing System
GOOS	Global Ocean Observing System
GPS	Global Positioning System
HERMES	Hotspot Ecosystem Research on the Margins of European Seas
HF	High Frequency (radar)
H_s	Significant wave height ~ average peak-trough height of highest third of waves
ICES	International Council for the Exploration of the Sea
ICOS	Integrated Carbon Observation System
ICZM	Integrated coastal zone management

IOCCP	International Ocean Carbon Coordination Project
IoMGL	Isle of Man Government Laboratory
IOPs	Inherent optical properties
IPCC	Intergovernmental Panel on Climate Change
JIBS	Joint Irish Bathymetric Survey
JNCC	Joint Nature Conservation Committee
LIDAR	LIght Detection And Ranging
LISST	Laser In-Situ Scattering and Transmissometery
LOIS	NERC Land-Ocean Interaction Study
LSSW	Low-salinity surface waters
LV	Light Vessel
M_2	Tidal constituent, two tides per lunar day
MAREMAP	Marine Environmental Mapping Programme
MAWS	Marine Automatic Weather Stations
MBA	Marine Biological Association
MBES	Multibeam echosounder system
MCA	Maritime and Coastguard Agency
MEDIN	Marine Environmental Data and Information Network
MESH	Mapping European Seabed Habitats
MLWS	Mean Low Water Springs
MSL	Mean sea level
MSS	Mineral suspended matter
NAO	North Atlantic Oscillation
NCC	Norwegian Coastal Current
NCOF	National Centre for Ocean Forecasting
NE	Natural England
NEODAAS	NERC Earth Observation Data Acquisition and Analysis Service
NERC	Natural Environment Research Council
NGU	Geological Survey of Norway
NIEA	Northern Ireland Environment Agency
NIOZ	Netherlands Institute for study of the Sea
NMW	National Museum of Wales
NOC	National Oceanography Centre
OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis
OWS	Ocean Weather Ship
pCO_2	Partial pressure (in sea) of CO_2
PFT	Plankton functional type
PML	Plymouth Marine Laboratory
POLCOMS	POL (now NOC, q.v.) Coastal Ocean Modelling System
PSMSL	Permanent Service for Mean Sea Level
RACE	Risk Analysis of Coastal Erosion
RAPID	NERC Rapid Climate Change programme name
RIKZ	Dutch National Institute for Coastal and Marine Management
RIZA	Dutch Institute for Inland Water Management and Waste Water treatment



RLR	Revised Local Reference
RMS	Root mean square
ROV	Remotely operated vehicles
S_2	Tidal constituent, two tides per solar day
SAC	Special Area of Conservation
SAMS	Scottish Association for Marine Science
SCC	Scottish Coastal Current
SEA	Strategic Environmental Assessment
SEPA	Scottish Environment Protection Agency
SLP	Sea-level pressure
SMP	Shoreline Management Plan
SNH	Scottish Natural Heritage
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
SNS2	Southern North Sea Sediment Transport Study Phase 2
SOLAS	Safety of life at sea
SOO	Ship of opportunity
SPA	Special Protection Area
SPM	Suspended Particulate Matter
SSC	Suspended sediment concentration
SSSI	Site of Special Scientific Interest
SST	Sea surface temperature
TA	Total Alkalinity
TAR	IPCC Third Assessment Report (2001)
TOBI	Towed Ocean Bottom Instrument
Tp, Tz	Wave periods: peak of spectrum, average of zero-upcross interval respectively
UEA	University of East Anglia
UHI	University of the Highlands and Islands
UKCIP	UK Climate Impacts Programme
UKCP09	UK Climate Projections 2009
UKDMOS	United Kingdom Directory of the Marine-observing Systems
UKHO	United Kingdom Hydrographic Office
UKMMAS	UK Marine Monitoring and Assessment Strategy
UNCLOS	UN Convention on the Law of the Sea
VOS	Voluntary Observing Ships
WMO	World Meteorological Organisation

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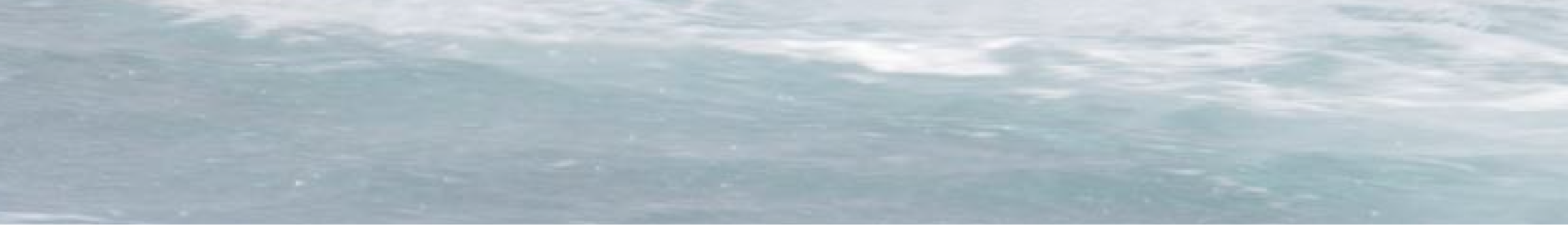

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