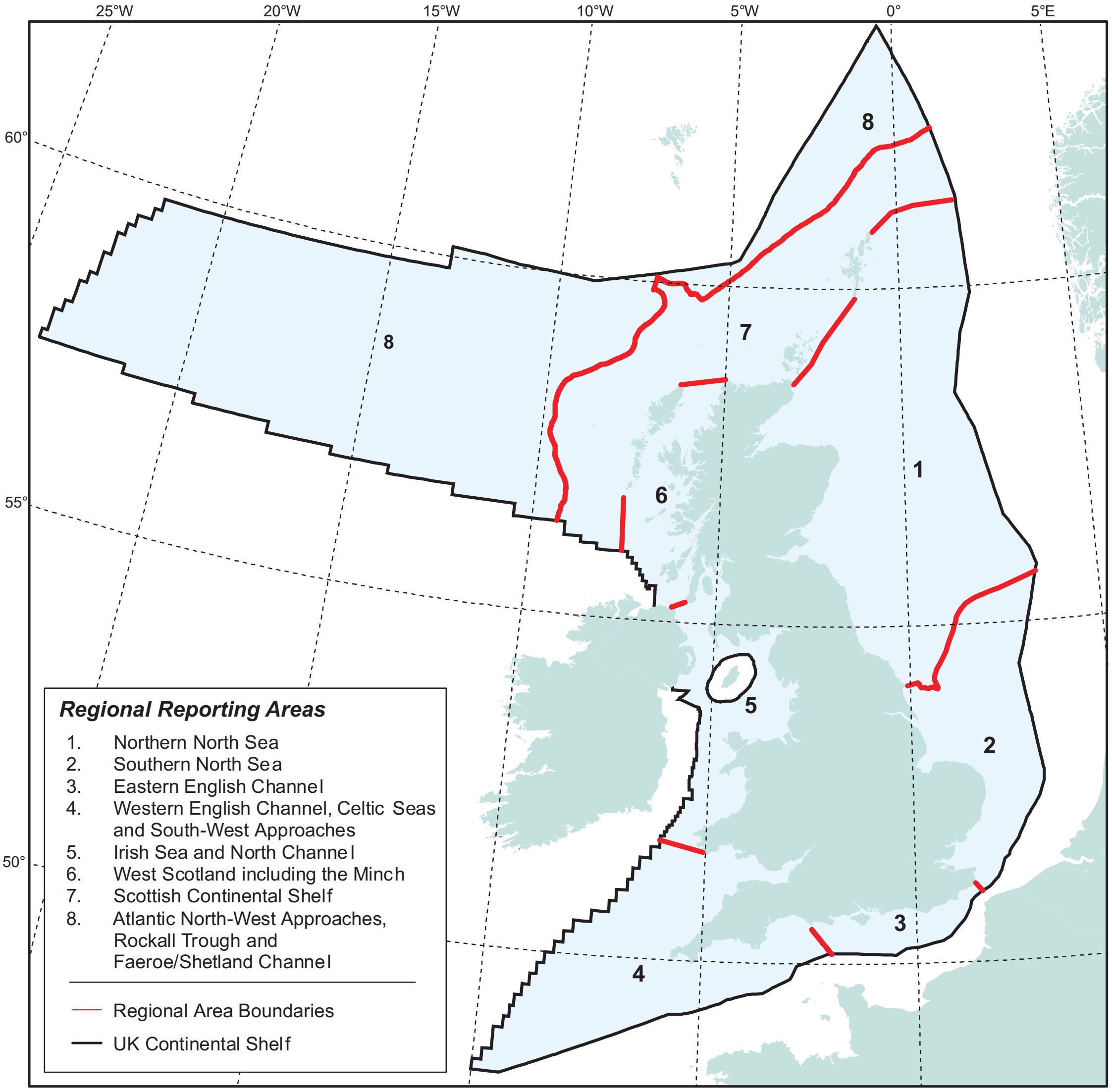
2: Marine Processes and Climate

IACMST contribution to
Charting Progress - an Integrated Assessment
of the State of UK Seas
(The 2nd of 5 Reports)



Note: The exact limits of the UK Continental Shelf are set out in orders made in Section 1(7) of the Continental Shelf Act 1994.

The Regional Reporting Areas around the UK

This report is one of five that have been produced to provide detailed scientific assessment in support of '*Charting Progress – an Integrated Assessment of the State of the UK Seas*'; published by the Department for Environment, Food and Rural Affairs on behalf of the UK Government and Devolved Administrations in March 2005.

The five reports in the series are as follows:

1: Marine Environment Quality
2: Marine Processes and Climate
3: Marine Habitats and Species
4: Marine Fish and Fisheries
5: Integrated Regional Assessment

All reports can be found on the Defra website: www.defra.gov.uk

The 2nd of 5 reports produced to support **Charting Progress** –
an Integrated Assessment of the State of UK Seas

Marine Processes and Climate

Inter-Agency Committee on Marine Science and Technology

2005

Contents

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Top left: Alexander Mustard, Southampton Oceanography Centre.
Bottom left: Mike Meredith, British Antarctic Survey.
Bottom right: Jonathan Sharples, Proudman Oceanographic Laboratory.

Foreword

The Inter-Agency Committee on Marine Science and Technology (IACMST) is a UK Government Committee that maintains an over-view of marine-related activities across Government and internationally. Its role is to identify issues for more detailed consideration, particularly with respect to co-ordination and interaction between science and user interests. IACMST supports two Action Groups – the Marine Environmental Data (MED) AG works to improve the accessibility and availability of UK data relating to the marine environment, and the Global Ocean Observing System (GOOS) AG co-ordinates monitoring, modelling and the assessment of change related to marine processes and climate, as well as the UK contribution to international GOOS programmes. Both Groups include representatives from Government Departments and Agencies, industry and other marine user groups. The Government's first Marine Stewardship Report - 'Safeguarding our Seas' was published in 2002 and set out a framework for action to improve the effective and sustainable management of the UK's marine environment. Two initiatives ensued: a Marine Monitoring Programme and an investigation of the State of the Seas. Both initiatives are being undertaken on a sectoral basis but with coordination of sectoral activities. IACMST has responsibility for contributing the Marine Processes and Climate input to the State of the Seas 2004 report; the other sectoral groups are Marine Environmental Quality, Marine Fisheries, and Marine Nature Conservation. The underlying philosophy behind the Marine Stewardship Report is the move towards a more integrated approach to managing the marine resource. This has motivated the adoption of an ecosystem-based approach to our understanding of the complex interactions in the marine environment and to then make use of this understanding within the policy and decision making frameworks. An important first step is to understand the current state of knowledge, the coverage of ongoing monitoring programmes and how work in the different sectors can be integrated to provide a more comprehensive picture. The first State of the Seas report should help to develop this picture and guide the development of a more comprehensive and integrated strategy for future monitoring in support of the ecosystem approach. We present here the full report on Marine Processes and Climate (MPC), which will be used to provide input to the State of the Seas Report. It is an updated and expanded version of the IACMST report on Climate Status and Trends published in 2001, available on the web (http://www.oceannet.org/UKclimate-status).

I. Townend.

Ian Townend
Action Group

M. J. Cowling

Mike Cowling
Chair of MED Action Group

Trevor Guymer

Trevor Guymer Chair of GOOS
Secretary of IACMST

Executive summary

This report describes the present status, trends and changes in marine processes and climate in UK waters. It covers weather and climate, sea temperature, salinity, sea level, waves, circulation, sediments and changes to the coast and sea bed. The main conclusions are summarised below.

- The annual mean Central England Temperature has increased by about 0.5°C during the 20th Century. The 30-year mean of annual mean temperature in Northern Ireland and Scotland increased by about 0.3°C from 1873 - 1902 to 1961 - 1990. (Weather & Climate, section 3.3)
- The average number of storms in October to March at UK stations has increased significantly over the past 50 years. However, the magnitude of storminess at the end of the 20th century was similar to that at the start. (Weather & Climate, section 3.5)
- There is a tendency towards wetter winters in north-east England and drier summers in south-east England. There were no statistically significant trends in precipitation in Northern Ireland for the period from 1931-2000. (Weather & Climate, section 3.6)
- Annual sea surface temperature averaged around the UK coastline has increased by about 0.5°C for the period 1871 to 2000, with most coastal sites showing a warming trend. (Sea Temperature, section 4.3)
- Sea surface salinity (SSS) averaged over the northern North Sea from 1950 to 2002 shows decreasing salinity since the 1970s. There is no discernible trend in mean SSS in the English Channel from 1900 to the early 1980s. SSS averaged over the Irish Sea from 1950 to 2002 shows a decrease in both winter and summer. (Salinity, section 5.3)
- There are local short-term variations in tide and surge levels at UK sites but no long-term trends. (Sea Level, section 6.2)
- After adjusting for land movements, ‘absolute’ mean sea level (MSL) around the UK coast has increased by about 1 mm per year during the 20th Century. ‘Relative’ MSL, due to the combined effect of absolute MSL changes and land movements, is increasing around most of the UK coast but remains constant or is decreasing along some northern coasts. (Sea Level, section 6.3)
- UK MSL shows an increase in the rate of rise towards the second half of the 19th Century but is now rising on average less fast, i.e. there has been a decrease in the rate of rise in the 20th Century. Trends in UK extreme sea levels match MSL trends closely. (Sea Level, section 6.3)
- Wave data from ships and buoys indicate that the mean winter wave height in the northeast Atlantic increased significantly between the 1960s and 1980s. Satellite data confirm that this increase continued into the early 1990s. (Waves, section 7.4)
- In the northern North Sea, there was an upward trend of about 5-10 per cent (0.2-0.3 m) in mean significant wave height (Hs) for January–March for the period 1973-1995, but a decrease thereafter. In the central North Sea, the trend in Hs for January–March was upwards until 1993/94, with a decrease thereafter. In the southern North Sea, there is no discernible trend in Hs for January–March from 1973 to date. (Waves, section 7.4)
- At Sevenstones LV, off Land’s End, the acceptable value is an increase of 0.02 m/yr in mean wave height over a period of about 25 years. This trend seems to have persisted into the early 1990s at least, although recent winters have suggested a levelling off. (Waves, section 7.4)
- Two pulses of inflow into the North Sea in 1988/89 and 1998 coincided with unusually strong northward transport of anomalously warm water through the Rockall Trough. (Circulation, section 8.4)
- Coastal flow conditions from the Irish Sea to Scottish coastal waters changed considerably after 1977, with a further change in Irish Sea outflow during 1980 to 1981, after which the flow pattern returned to that of 1977-1980. (Circulation, section 8.4)
- The North Sea has both southerly and northerly offshore transport of sediment. The nearshore sediment transport is predominantly southerly on the N-S orientated sections and westerly on E-W orientated sections. (Sediment Concentration & Transport, section 9.2.1)

- The English Channel has both westerly and easterly offshore transport of sediment. The nearshore sediment transport is predominantly easterly, with some reversals in the lee of headlands. (Sediment Concentration & Transport, section 9.2.2)
- The Celtic Sea has a variable offshore transport of sediment. The nearshore sediment transport is predominantly northerly on the N-S orientated coasts and easterly on E-W orientated coasts. (Sediment Concentration & Transport, section 9.2.2)
- The Irish Sea has southerly and south-westerly offshore transport of sediment on the North Wales coast south of the Lleyn Peninsula and northerly and north easterly offshore transport north of the Lleyn Peninsula (Bardsey Sound). The nearshore sediment transport is predominantly northerly on the N-S orientated sections of the coast and easterly on E-W orientated sections. (Sediment Concentration & Transport, section 9.2.3)
- Turbidity (water clarity) in the Menai Straits (Irish Sea) deteriorated from the mid 1960s to the late 1980s. There was no overall trend turbidity in the Irish Sea between 1987 and 1997. (Sediment Concentration & Transport, section 9.2.3)
- Coastal changes in Scotland were mainly accretional during the early and mid-nineteenth century. In most places accretion rates fell and erosional conditions ensued around the turn of the century but there was a general recovery to slight accretion during the period 1920 to 1960. Between 1969 and 1981, approximately 40 per cent of sandy beaches over 100 m in length in Scotland were eroding, 22 per cent were stable, 11 per cent were advancing, 18 per cent showed evidence of both advance and retreat and 9 per cent were protected or backed by some other stable feature such as rocks. (Changes to Coast & Seabed, section 10.2.1)
- The northern coastline of Northern Ireland is principally hard rock, so coastal erosion is minor and localized. The coast to the west of the Bann River is an area of deposition. East coast beaches are generally of late-Holocene age and are not being renewed at a constant rate to match current sea-level rise, with some consequent beach loss. (Changes to Coast & Seabed, section 10.2.3)
- In England, the largest erosion rates (i.e. greater than 1 m/yr) are along the east coast, with nearly 20 per cent of the locations in East England so categorised. Some 13 of the 18 locations in North East England, where erosion exceeds 1 m/yr, fall along the South Yorkshire coast. By comparison, less than 5 per cent of locations in all other regions have such high rates and this is particularly noticeable in South West England and Wales. (Changes to Coast & Seabed, section 10.2.2)

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1. Introduction

This report describes the present status, trends and changes in marine processes and climate in UK waters. It covers weather and climate, sea temperature, salinity, sea level, waves, circulation, sediments and changes to the coast and sea bed. The term marine is used here to mean the whole of the marine environment from the coastal zone to offshore. Some data from adjacent areas is included to provide a global and regional context.

In addition to updating and expanding the IACMST Information Document 'Climate of UK Waters at the Millennium: Status and Trends' (IACMST, 2001), one of the aims of this report is to demonstrate the value of long-term marine measurements in aiding the effective management of the UK's marine environment; thus encouraging their commencement, their continuation or their restoration.

It should be noted that the data included in this report have been assembled from a wide range of sources. These data were originally collected for a number different purposes using a variety of techniques and sampling strategies. The spatial and temporal coverage of UK waters is by no means complete.

One major specific aim is to provide input on Marine Processes and Climate to the Government's 'State of the Seas Report', together with other sector reports on Environmental Quality, Fish and Fisheries, and Habitats and Species. (Plankton, chlorophyll and nutrients are not covered in this report but are included in other sector reports.)

Further specific aims are:
- to stimulate further scientific study of the parameters and their interactions;
- to increase public awareness of the present status and trends in UK waters;
- to enhance marine data inventories, e.g. the existing UK Inventory of Marine Monitoring Measurements and the EU-funded European Directory of the Initial Ocean-observing System (EDIOS, http://www.edios-project.de);
- to provide reference to measurements for the validation of, and assimilation into, operational marine forecasting models (EuroGOOS, 1996); and - to enhance the use of marine indicators of climate change (Hulme *et al*., 2002; Law *et al*., 2003).

This report should be read in the context of other reports on the UK's marine environment, concerning:
- the status of the ocean climate and fisheries in Scottish waters (FRS, 2003);
- the quality of UK coastal waters (Defra, 2002a; ICES, 2003b; MPMMG, 1998);
- the quality status of the NE Atlantic by the Oslo-Paris Commission (OSPAR, 2000); and
- assessments made by the Intergovernmental Panel on Climate Change on the science of climate change (IPCC, 2001a).

REFERENCES

Defra (2002a). Safeguarding our Seas; a Strategy for the Conservation and Sustainable Development of Our Marine Environment. Defra, London, 80pp.

FRS (2003). Scottish Ocean Climate Status Report 2000 - 2001. Fisheries Research Services Report 05/03, Marine Laboratory, Aberdeen, 20pp.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald. R. and Hill, S. (2002). Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK, 120pp.

IACMST (2001). Climate of UK Waters at the Millennium: Status and Trends. Edited by Graham Alcock and Lesley Rickards. IACMST Information Document No. 9. (Also available at http://www.oceannet.org/UKclmate-status).

ICES (2003b). Environmental status of the European seas. Edited by Neil Fletcher. Retrieved 26th September 2003 from the World Wide Web: http://www.ices.dk/reports/germanqsr/23222_ICES_Report_samme.pdf

IPCC (2001a). Climate Change 2001, the scientific basis. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M , van der Linden, P.J. and Xiaosu, D. Editors, Cambridge Univ. Press.

Law, F.M., Farquharson, F., Brampton, A., Dale, M. and Flather, R.A. (2003). Environmental change indicators (including those related to climate change) relevant to flood management and coastal defence. Defra/EA R & D technical report FD2311-TR, 80pp.

MPMMG, (Marine Pollution Monitoring Management Group) (1998). National Monitoring Programme – Survey of the Quality of UK Coastal Waters. MPMMG, Aberdeen, 80pp.

OSPAR Commission (2000). Quality Status Report 2000, Region II - Greater North Sea. OSPAR (Oslo-Paris Commission), London, 136pp.

2. Monitoring networks

MONITORING NETWORKS FOR MARINE PHYSICS AND CLIMATE

Data on MPC parameters have been collected during many projects and studies of limited duration. Use http://www.oceannet.org to access easy to use online search interfaces for the various catalogues and inventories maintained by the IACMST's Marine Environmental Data Network. This includes information on how to access data from the BNSC JERICHO project (waves), the EU's projects on Ocean Margin Exchange (temperature, salinity, currents and circulation, sediment/turbidity) and Processes of Vertical Exchange in Shelf Seas (temperature, salinity, currents and circulation, sediment/turbidity), the IOC's GLOSS project (sea level) and the NERC's Bristol Channel Project (temperature, salinity, sediment/turbidity), Land Ocean Interaction Study (temperature, salinity, waves, sediment/turbidity, coastal data) and North Sea Project (temperature, salinity, currents and circulation, sediment/turbidity).

The following networks measure MPC parameters on a regular basis. Some have been set up with the primary aim of measuring biological and chemical parameters, but all measure some physical parameters. Most of the information has been obtained from Defra (2001), IACMST (2001), the MIC website (http://www.ukmarine.org) or the web sites of relevant organisations.

Further detailed information relating to these networks can also be found in the UK Inventory of Marine Monitoring Observations maintained by MED AG on behalf of GOOS AG. In addition, the EU-funded European Directory of the Initial Ocean-observing System (EDIOS), a web-based searchable and regularly updated marine directory of the ocean observing, measuring, and monitoring systems operating in Europe, contains similar information for all European countries (see http://www.edios-project.de).

The International Argo Project

The international Argo project, which is sponsored by the World Meteorological Organisation and the Intergovernmental Oceanographic Commission, is deploying a global array of profiling floats to measure the temperature and salinity of the upper 2,000 m of the ocean and is well into its initial deployment phase. At present over 1,000 floats have been deployed and expectations are that the target of 3,000 floats will be achieved in 2006.

The UK Argo programme is undertaken by a partnership between the Met Office (who also manage the project), SOC, BODC and the UK Hydrographic Office (http://www.metoffice.com/research/ocean/argo). Over the last 3 years UK has deployed over 100 (Argo and Argo-equivalent) floats; 29 in 2001, 38 in 2002 and 37 in 2003, across a wide range of ocean regions including the North Atlantic (Irminger Basin, Rockall Trough, Iceland Basin), the Norwegian Sea, the South Atlantic and Southern Ocean, the south Indian Ocean and Arabian Sea (http://www.metoffice.com/research/ocean/argo/ukfloats.html).

A key feature of Argo is that all Argo data are freely available to anyone without restriction. UK float data are available via the UK Argo Data Centre at BODC (http://www.bodc.ac.uk/projects/argo.html) and the global data are available via the two Argo Global Data Assembly Centres (Coriolis Data Centre http://www.coriolis.eu.org/coriolis and the US GODAE server http://www.usgodae.org/argo/argo.html).

CEFAS Coastal Temperature Network

The CEFAS Coastal Temperature Network has recorded near-surface sea temperature at selected locations since the mid 1960s. Nineteen stations are sampled by CEFAS observers, approximately six to 12 times per month, and the rest by various other authorities, varying from monthly means to daily values. Copies of reports tabulating monthly, annual and grand monthly mean sea surface temperature measured until December 1989 for 99 stations and for the 38 locations still in use after 1989 are available on the CEFAS website (http://www.cefas.co.uk/publications/catalogue.htm).

CEFAS Marine Environmental Real-time Observation System (MEROS)

The CEFAS Marine Environmental Real-time Observation System (MEROS) uses 'SmartBuoys' to measure data on water quality (including sea surface temperature and suspended sediment concentration) and meteorology (wind speed direction, air temperature, pressure). See http://www.cefas.co.uk/monitoring for details of all measurements and deployments. There are free conditions of access to the data.

The SmartBuoys at Gabbard, West Gabbard (Southern North Sea) and Warp Anchorage (Thames Estuary) are part of the National Marine Monitoring Programme (NMMP). SmartBuoys are incorporated in the Meteorological Office Marine Automatic Weather Station (MAWS) Network buoy K4 and the Liverpool Bay Coastal Observatory's COA mooring position.

Continuous Plankton Recorder (CPR)

The Continuous Plankton Recorder (CPR) programme is operated by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) and covers most sea areas around the British Isles, the North Atlantic and the North Pacific. Its database contains over 2 million records of plankton taxa from 1946 onwards. On some routes, CTD and fluorescence measurements have been added in recent years and Minipack temperature recorders have been attached to some CPRs from 2003. Data are freely available for research to anyone under a Data Licence Agreement. Monthly-mean data for some parameters are available to download from the SAHFOS web site (http://www.sahfos.org/standard_areas.htm). Currently, the temperature data are only available by application to SAHFOS but it is planned to have these data to download from the Internet in early 2004.

DARD(NI) Coastal Monitoring Programme

The DARD(NI) Coastal Monitoring Programme consists of a network of sites around Northern Ireland and is a collaborative project between the Environment and Heritage Service and the Department of Agriculture and Rural Development in Northern Ireland (DARD(NI)). All sites measure chlorophyll-a concentration, salinity and temperature; with turbidity measured at Belfast Lough and Strangford Lough and oxygen concentration at River Lagan Impoundment and Quoile Pondage. Two additional systems will be installed in Lough Foyle and Carlingford Lough in early 2004. All sites use GSM (Global System for Mobile communications) networks for data telemetry.

As part of the coastal monitoring programme, the Irish Coastal Mooring (53° 45'N, 06° 04'W) has a CTD and fluorometer deployed at 10m depth, together with water samplers for nutrient analysis and a thermistor string. The mooring is out of range of GSM networks and therefore data are downloaded directly at each mooring service carried out aboard the *RV Lough Foyle* at approximately six-week intervals.

Near real time data from the programme is available through an online publication at http://www.afsni.ac.uk/services/coastalmonitoring. Access to data in summary form is free to non-commercial (academic) users, with appropriate acknowledgement.

Another off-shore site is Station 38a (53° 47'N, 05° 39'W), with a thermistor string measuring three-hourly sea temperature data at 10 m depth intervals, CTDs at surface (15 m) and bottom (80 m) depth, a fluorometer at 15 m depth, an automatic water sampler taking daily samples which are analysed for dissolved phosphate and silica and a seasonally deployed larger volume water sampler analysed for phytoplankton species. In addition, temperature data are available from the records of temperature at the cooling water intake at Ballylumford Power Station (54° 50.8'N, 54° 7.3'W). Although the power station sits on Larne Lough, the intake is effectively drawing in North Channel water. At present, the data can be accessed on application to DARD(NI).

'Ellett' Line and Extended 'Ellett' Line

The 'Ellett' Line (Sound of Mull to Rockall) and the extended 'Ellett' Line (Rockall to Iceland). The former is maintained by the Dunstaffnage Marine Laboratory, the Scottish Executive Fisheries Research Services (FRS) and SOC. The latter has been occupied by SOC once per year from 1996 to 2001 (but the cruise in 2000 was severely hit by storms and was not able to be completed). Both lines are monitored to provide a long-time series of physical, chemical and biological properties of the ocean. Primary measurements are of temperature, salinity, directly-measured currents, nutrients and dissolved oxygen. Additional parameters (periodically since 1996) are chlorophyll-a, pH, alkalinity and chemical tracers (CFCs). See http://www.soc.soton.ac.uk/GDD/hydro/nph/ellett/index.php and http://www.soc.soton.ac.uk/GDD/hydro/nph/ellett/extended.php for further details. The main repository for the Ellett line data is the BODC.

Environment Agency Anglian Region Strategic Coastal Monitoring Programme

The Environment Agency Anglian Region Strategic Coastal Monitoring Programme covers a region between the Humber and the Thames and has been in operation since 1991. Beach profiles, beach surveys, bathymetric surveys, sediment samples and aerial photographs are taken each year, together with measurements of sea levels, waves and currents. A Shoreline Monitoring Data Catalogue is available (EA Anglian Region, 2002). All data are publicly available, subject to costs where the data request is particularly onerous or repeated. At present (winter 2003) there is no dedicated website but the EA website can be found at http://www.environment-agency.gov.uk/.

Environment Agency Annual Beach Monitoring Survey (ABMS)

The EA Annual Beach Monitoring Survey (ABMS) dates from 1973, when parts of Sussex were first surveyed. It now covers the whole of the coast of the EA Southern region and extends to the boundary of Hampshire and Dorset. The programme is managed by the EA, with annual contributions from many Local Authorities. The output from the survey programme comprises annual aerial photography of 440 km of coast, producing approximately 1300 aerial photographs; annual production of 2600 profiles, derived by photogrammetry; periodic overviews of the data set and annual dissemination of data and reports to contributing local authorities.

Channel Coastal Observatory

From 2002, the Channel Coastal Observatory (hosted by New Forest District Council, in partnership with the University of Southampton and the Southampton Oceanography Centre (SOC)) is the data management and regional coordination centre for the Southeast Regional Coastal Monitoring Programme (http://www.channelcoast.org). The Programme includes the ABMS and provides a consistent regional approach to coastal process monitoring, providing information for development of strategic shoreline management plans, coastal defence strategies and operational management of coastal protection and flood defence. Its purpose is to develop a region wide coastal monitoring and analysis programme over the approximately 1000 km of open coastline between Portland Bill and the Isle of Grain. The programme is funded by Defra, in partnership with Local Authority Coastal Groups and the EA. The survey programme includes measurement of beach surveys, beach profiles, aerial photography, LIDAR surveys of cliffs and salt marsh, bathymetric surveys, hydrographic surveys, waves, tides and winds. Real-time data are collected by Local Authorities and the EA at a number of sites within the area. All new data will be freely available via an extensive website that is being developed.

Faroe Shetland Channel (FRS)

Faroe Shetland Channel surveys are undertaken by the FRS along two standard sections, Nolso (Faroe) – Flugga (Scotland) and Fair Isle (Scotland) – Munken (Faroe), three times a year. In addition FRS and the Norwegian Institute for Marine Research regularly survey, up to five times a year, a section from Start Point on Orkney to the centre of the North Sea (known as the Joint North Sea Information System (JONSIS) line). Temperature and salinity data are available from FRS (http://www.marlab.ac.uk) and the original CTD data are banked with BODC and the International Council for the Exploration of the Sea (ICES).

FRS Coastal Long-term Monitoring programme

The FRS Coastal Long-term Monitoring programme was set up in 1999 to monitor water quality parameters at sites in Scottish coastal waters. (The regular collection of data from some sites predates 1999). The sampling sites are serviced by volunteer teams from a variety of Scottish institutes and facilities. Data are collected on water temperature, salinity, nutrients and phytoplankton. Full sample sites (temperature, salinity and nutrients) are at Loch Ewe, Loch Muldy (North Uist), Scapa Pier (Orkney), Scalloway (Shetland) and Stonehaven. Secondary sampling sites (temperature only) are at Mallaig (west coast) and Findon (east coast).

The data are freely available to anyone as long as they acknowledge the source and can be obtained by contacting FRS (http://www.marlab.ac.uk). All data are published annually in the Scottish Ocean Climate Status Report (e.g. FRS, 2003).

HumberNet

The HumberNet Tide Gauge Network accesses data from the Associated British Ports (ABP) tide gauge network. In addition, NorthSeaNet has installed on-line meteorological and oceanographic instrumentation systems at King George Dock, consisting of a meteorological station for weather data, a tide gauge, a wave recorder and water property sensors. Also, an Aanderaa RCM9 and ELE Cumulus automatic weather station was installed at the Spurn Head lifeboat jetty in late 2002 and redeployed in 2003 to the Hawke Light Ship within the mouth of the Humber. The former measures flow speed and direction, water depth, temperature, salinity, suspended particulate matter; and the latter measures wind speed and direction, air temperature, humidity, atmospheric pressure, rainfall and solar radiation. Monthly data reports are available from http://www.northseanet.co.uk/humber/digitaldisplay.htm . Other data are available via the website http://www.northseanet.co.uk, but presently restricted to the EA who are funding the work.

ICES International Bottom Trawl Survey (IBTS)

The ICES International Bottom Trawl Survey (IBTS) is conducted in the spring and autumn in the North Sea. (The ICES International Young Fish Survey (IYFS) in the North Sea was undertaken during January/February in each year since about 1970 and the January-February IYFS became the IBTS Quarter 1 survey in 1993.) The number of young fish (herring, sprat, mackerel, cod, haddock, whiting, saithe and Norway pout) near the seabed is recorded, together with temperature and salinity and sometimes nutrients. The UK contribution began in 1977 and is carried out over four to five weeks during August and September.

Contour maps of temperature and salinity (and nutrients if available) drawn from data collected since the start of these annual surveys and other surveys during January and February can be viewed by selecting IBTS at http://www.ices.dk/ocean/INDEX.HTM.

Liverpool Bay Coastal Observatory

The Liverpool Bay Coastal Observatory is coordinated by the Proudman Oceanographic Laboratory (POL). POL's Rig 857 Buoy measures currents, hydrography (including temperature and salinity), winds and waves. An HF Radar measures surface currents. Drifting Buoys are planned for deployment in 2004 and a second in-situ site in 2005. Other contributions are from the University of Wales (Bangor) observational programme (monthly surveys of basic physical, chemical and biological parameters along a transect and measurements at individual sites); the PEML line along 54°N and their Cypris & Bayrnagh stations; the DARD(NI) moorings; a CEFAS SmartBuoy; instrumented ferries; coastal images from a Compact Airborne Spectrographic Imager (CASI); satellite remote sensing infra-red (temperature) and visible data (suspended sediment, chlorophyll); and river discharge monitoring by the EA.

For access to the data, users need to register at http://cobs.pol.ac.uk but data plots and statistics can be viewed without the need to pre-register. For the latest satellite image of Irish Sea SST, from the PML Remote Sensing Group, access http://cobs.pol.ac.uk/cobs/sat . For near-real time coastal sea levels from the Irish Sea and Liverpool Bay, access http://cobs.pol.ac.uk/cobs/ctide .

The Marine Environmental Change Network (MECN)

The Marine Environmental Change Network is a collaboration between organisations in England, Scotland, Wales, Isle of Man and Northern Ireland collecting long-term time series information for marine waters. It is coordinated by the MBA and is funded by Defra. The goal of the network is to use long-term marine environmental data from around the British Isles and Ireland to separate natural fluctuations from global, regional and local anthropogenic impacts. See http://www.mba.ac.uk/research/MECN/about.htm.

The major aims of the network are:

- Establish a network to measure environmental change in marine waters by undertaking long-term research and monitoring
- Maintain and enhance existing long-term research programmes
- Restart important discontinued long-term research programmes
- Develop a quality-controlled database of long-term marine data series

- Deliver and interpret long-term and broad scale contextual information to inform water quality monitoring
- Demonstrate the benefits of preserving and networking long-term time series programmes.

Meteorological and Wave monitoring network (METNET)

The Meteorological and Wave monitoring network (METNET) is operated by Shell UK Exploration and Production Ltd. on installations in the northern North Sea (Dunlin A, Tern, North Cormorant, Brent B), central North Sea (Kittiwake, Awasuria Ocean, Gannet A, Fulmar A and Auk A) and southern North Sea (Clipper PT, Leman AD1, Sean PP). The majority of stations were installed in the late 1970s or early 1980s, and upgraded in the mid 1990s. Measurements include wind speed and direction, atmospheric pressure, air temperature, humidity, precipitation, cloud height and visibility and waves.

Real-time data are sent over a telecommunications network to Shell's headquarters in Aberdeen, for quality control and data management. Some data are sent from Aberdeen to other users, e.g. the Meteorological Office.

The Met Office's Hadley Centre for Climate Prediction and Research

The Met Office's Hadley Centre for Climate Prediction and Research monitors global sea surface temperature, night time marine air temperature and sea level pressure in a semi-operational way, producing monthly field of these variables in near-real time and updating the historical record that goes back to the mid-19th century (http://www.metoffice.com/research/hadleycentre/obsdata).

The near real time data are collected mostly from Voluntary Observing Ships and moored and drifting buoys via the GTS, although the latest version of the historical record is based upon the ICOADS (International Comprehensive Ocean-Atmosphere Data Set) database (http://dss.ucar.edu/pub/coads/). The temperature data are corrected for the effects of changing measurement methods/circumstances relative to a reference period to ensure a homogeneous record throughout.

Met Office Marine Automatic Weather Station (MAWS) Network

The Meteorological Office Marine Automatic Weather Station (MAWS) Network consists of automatic observational systems on islands, light vessels and buoys, some operated jointly with Meteo-France. There are four Island Stations (Muckle Holm, Sule Skerry, North Rona and Foula), four Light Vessels (Channel, Seven Stones, Sandettie and Greenwich) and 11 moored deep-ocean buoys (Gascogne, K1, K2, K4, RARH, K3, Brittany, Aberporth, Turbot Bank, K5, K7). The two North Sea moored buoys (K16 and K17) have recently been taken out of service and there are no plans, at present, to reinstate them.

Meteorological and oceanographic parameters (air temperature, dew point, pressure, wind speed and direction, maximum wind gust, visibility, sea temperature and wave height and period) are collected at hourly intervals and the data transmitted to a meteorological database. Hourly observations for the last 24 hours and a rolling 14-day archive of observations at 12-hourly intervals are available at http://www.metoffice.com/research/ocean/goos/maws.html

All MAWS data on the web site are freely available; other data are available without restrictions but at a marginal cost for extraction and provision.

Permanent Service for Mean Sea Level (PSMSL)

The Permanent Service for Mean Sea Level (PSMSL) is the global data bank for long-term sea level change information from tide gauges, including the UK National Tide Gauge Network. It contains over 49 000 station-years of monthly and annual mean values of sea level from over 1 800 tide gauge stations around the world.

The PSMSL provides a regular summary of the status of each of the 287 sites in the Global Core Network (GCN) of GLOSS, the international programme coordinated by the IOC for the establishment of high quality global and regional sea level networks for application to climate, oceanographic and coastal sea level research. The UK maintains three GLOSS sea level stations in the UK (Lerwick, Stornoway and Newlyn) and is responsible for 10 GLOSS stations overseas: Ascension, Bermuda (St. George's Is), Diego Garcia Is, Faraday (Antarctica), Gibraltar, St. Helena, Stanley (Falklands), Edinburgh (Tristan Da Cunha), Signy (South Orkney Is) and South Caicos (the latter three are not operational and are unlikely to become so in the near future).

Information on monthly and annual values of UK mean sea level held by the PSMSL is available from http://www.pol.ac.uk/psmsl/datainfo

Port Erin Marine Laboratory (PEML) programme
The Port Erin Marine Laboratory (PEML) programme measures salinity, temperature, chlorophyll and inorganic nutrients along a section at 54°N and at the Cypris & Bayrnagh stations off the Isle of Man. The data can be accessed via PEML; no charge is generally levied if data are supplied for non-commercial research or educational purposes, other organisations or parties are considered on an individual basis. At present (winter 2003), there is no dedicated website for the long-term databases but some of the information is presented in graphical form at http://www.liverpool.ac.uk/plankton.

Satellite Missions
Satellite missions provide long-term near-global data sets of MPC parameters: sea level and ocean topography (and hence currents and circulation), winds and waves from radar altimeters and scatterometers; and ocean colour, optical properties and sea surface temperature from radiometers.

After relatively inaccurate and imprecise (NASA's Skylab, 1973; Geodynamic Experimental Ocean Satellite (GEOS-3), 1975-1978) or short-lived (Seasat, 1978) missions, high accuracy and precision altimeters were flown on the USA Geodetic Satellite (GEOSAT, 1985-1990); USA/French TOPEX/Poseidon, launched 1992 and now followed up by Jason-1, launched 2001; and the European Space Agency's European Remote Sensing Satellites, ERS-1 (1991 – 2000) and ERS-2 (launched 1995) and followed up by the Environment Satellite EnviSAT, launched in 2002. Homogeneous, inter-calibrated and highly accurate long time series of sea level anomalies are being produced as part of the ENACT project from multi-mission altimeter data sets for 1986 –1989 (data from GEOSAT) and 1992-2004 (data from T/P, ERS-1/2, Jason-1 and EnviSAT). (http://www.cls.fr./html/oceano/projets/enact/project_en.html).

The first ocean colour measurements were made using the Coastal Zone Colour Scanner (CZCS) aboard Nimbus-7 (1978-1986) (http://daac.gsfc.nasa.gov/data/dataset/CZCS/). An Advanced Very High Resolution Radiometer (AVHRR) is carried on the NOAA/NASA polar-orbiting series of satellites (starting with NOAA-9 in 1985 and currently operating with NOAA-12, -14, -15 and –16) as part of the Pathfinder project. NASA's OrbView-2 (formerly SeaStar), launched in 1997, carries the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) instrument (data from http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/).

ERS-1/2 both carried an infrared radiometer, providing a near-continuous data set of SST over ten years and continuing with EnviSAT. Also ERS-1/2 both carried an active microwave instrument that combined the functions of a synthetic aperture radar and wind scatterometer for wave height and sea surface wind measurements.

The SOC Laboratory for Satellite Oceanography (LSO) has collected extensive datasets from many satellite missions, most of which are available to other users (http://www.soc.soton.ac.uk/lso/noindex/lso_data.php).

Severn Estuary Helicopter Surveys
Severn Estuary Helicopter Surveys along the Severn Estuary were undertaken on a quarterly basis from 1977 to 1997, to assess spatial and temporal trends in water quality, at a total of 43 sites along the length of the estuary. The survey was initially undertaken by the water authorities and later by the NRA and the EA. Temperature, salinity and dissolved oxygen were measured at all sites with water samples collected at 24 sites for subsequent analysis of nutrients, metals and biological determinands.

Data are now banked at the EA's National Centre for Environmental Data and Surveillance, in Bath. Access to the data is generally free of charge without restrictions but commercial usage requires a licence.

SOC Ferry-Box project
The Southampton Oceanography Centre Ferry-Box project uses a continuously recording instrument package to study the dynamics of phytoplankton blooms. SOC line 1 uses the Red Funnel *Red Falcon* to measure sea temperature, conductivity, chlorophyll-a and fluorescence on up to eight round trips per day from Southampton

to Cowes since 1999. SOC line 2 uses the P&O European Ferries *Pride of Bilbao* to measure the same parameters plus turbidity, nitrate and algae twice a week from Portsmouth to Bilbao since 2002 and once per week from Portsmouth to Cherbourg since 2002. The raw ten-minute data can be accessed via http://www.soc.soton.ac.uk/ops/ferrybox_index.php, with access free to public sector uses.

Tiree Passage Time Series

The Tiree Passage time series is the longest moored time series of flow and temperature on the NW European continental shelf, having been maintained for 22 years by the Scottish Association for Marine Science (SAMS) (http://www.sams.ac.uk/dml/projects/physics) [link not functioning]. The mooring sits on a bank in less than 50 m of water in the narrowest sector of the Passage, a SW-NE orientated strait between the Isle of Mull to the southeast and the Isles of Coll and Tiree to the northwest, on the western coast of Scotland.

Hourly current and temperature measurements using Aanderaa recording current meters started in June 1981 at the bottom (11 m above the bed) and on November 1987 nearer the surface (22 m above the bed), and ended in September 1997 at both depths. Hourly salinity measurements started in September 1993 at both depths using Aanderaa conductivity sensors. The mooring was re-deployed between June 1999 and February 2000, and in May 2002 until the present with the current meters at 20 m and 45 m. A Seabird Microcat salinity sensor was added at 20 m above bed in August 2002. A total of 57 deployments have been made, 44 of which have yielded good data.

UK National Marine Monitoring Programme (NMMP)

The UK National Marine Monitoring Programme (NMMP) ensures co-coordinated quality status monitoring between the UK Government Departments and agencies with environmental protection responsibilities. The strategy for the NMMP programme is described in the ‘Green Book’, available from the FRS web site (http://www.marlab.ac.uk).

Phase one of the NMMP was carried out in 1993-95 and 1996 -1998 by a spatial survey at monitoring stations in estuarine, intermediate and offshore locations. This included the National Coastal Baseline Survey operated by the EA and its forerunner, the National Rivers Authority (NRA).

Phase two of the programme (NMMP2) was started in 1999, concentrating on temporal trend monitoring and also introducing new biological effects studies. Based on over 100 locations, the programme monitors contaminants (trace metals, organic compounds) in water, sediment and biota (shellfish and fish); biological effects (mortality of organisms); nutrients in water; and temperature and salinity. A full description is given at http://www.defra.gov.uk/environment/marine/mpmmg/index.htm#1 .

A central computerized data base for contaminants was established in 1996 and is now located at the EA’s National Centre for Environmental Data and Surveillance, in Bath.

Access to the data is generally free of charge without restrictions, but this depends on the QA status and prior reporting to Defra, ICES and OSPAR. All commercial usage requires a licence.

U.K. National Tide Gauge Network

The U.K. National Tide Gauge Network is funded by Defra and comprises 44 sites. In addition to the sea level data collected by the tide gauges, measurement of vertical land movements using continuous GPS and absolute gravity are undertaken at key sites, to enable the separation of the absolute and relative sea level trends and the determination of their spatial variations.

The Tide Gauge Inspectorate at POL is responsible for the operation, maintenance and development of the tide gauge network. The BODC is responsible for the retrieval of quarter hourly sea level data, enabling daily checks to be kept on the performance of the gauges and thus allowing any problems arising at the remote sites to be quickly identified by the interrogating computer and appropriate action taken to minimise data loss. The data are downloaded weekly, routinely processed, quality controlled and banked by BODC. Further details of the Network can be found at http://www.pol.ac.uk/ntslf/tgi and information on accessing data from the Network is available at http://www.bodc.ac.uk/cgi-bin/ntslf_data.pl?polntslf . Access to near-real time data from UK gauges is available via http://www.actuelewaterdata.nl .

WaveNet
The strategic wave-monitoring network for England and Wales (WaveNet) is funded by Defra and integrates existing data from a series of buoys and platforms around the UK coast operated by the Met Office, Shell, the Irish Marine Institute and others. Defra have commissioned CEFAS to develop a wave buoy monitoring network and the Met Office to develop a coastal HF wave radar network. The former will provide a limited number of high quality point measurements with the latter giving spatial coverage at a lower accuracy.

The network includes measurements of Hsig, Tz, Tpeak, mean direction and spread at Gabbard (since 2002), Hastings (2002), Liverpool Bay (2002), Bristol Channel - Scarweather Bank (2003), Dowsing (2003), Outer Wash (2003) and Poole Bay (2003).

The data can be accessed via http://www.cefas.co.uk/wavenet together with wave data from past deployments of wave recorders and pressure sensors from previous deployments and experiments. Conditions of access are free but all commercial usage requires a licence.

REFERENCES

Defra (2001). United Kingdom report on systematic observations for climate for the Global Climate Observation System (GCOS) for The Third National Communication to the Conference of the Parties to the United Nations Framework Convention on Climate Change. Department for Environment, Food and Rural Affairs, London, 67pp. This document is also available on the DEFRA website: http://www.defra.gov.uk/environment/index.htm

Environment Agency Anglian Region (2002). Shoreline Monitoring data catalogue, July 2002 – Public Version. EA, Kingfisher House, Goldhay Way, Orton Goldhay, Peterborough PE2 5ZR.

FRS (2003). Scottish Ocean Climate Status Report 2000 - 2001. Fisheries Research Services Report 05/03, Marine Laboratory, Aberdeen, 20pp.

IACMST (2001). Climate of UK Waters at the Millennium – Status and Trends. Edited by Graham Alcock and Lesley Rickards. IACMST Information Document No. 9. (also available at http://www.oceannet.org/UKclimate-status).

3. Weather and climate

SUMMARY OF CHANGES AND TRENDS

- The annual mean Central England Temperature has increased by about 0.5°C during the 20th Century. The warmest years since records began in 1659 occurred in 1990 and 1999 and the 1990s was the warmest decade, with five of the six warmest years occurring then.

- The 30-year mean of annual mean temperature in Northern Ireland and Scotland increased by between 0.11°C to 0.39°C from 1873-1902 to 1961-1990.

- The average number of storms in October to March at UK stations has increased significantly over the past 50 years or so, with the largest increases in the south. However, the magnitude of storminess at the end of the 20th century was similar to that at the start.

- There is a tendency towards wetter winters in north-east England and drier summers in south-east England.

- The 24-month period ending in March 2001 was the wettest in England and Wales since records of the monthly total precipitation began in 1766. April 2000 to March 2001 was the wettest twelve months on record. There were no statistically significant trends in either annual precipitation or winter precipitation in Northern Ireland for the period from 1931-2000.

- The most extreme change in the NAO since the 1860s has occurred from about 1960 up to the present, with the Winter (December - March average) Index showing an upward trend. There are indications of several earlier years of comparable values over the past 500 years, but the systematic rise in values from the 1960s to the 1990s is unique.

3.1 INTRODUCTION

The three main weather parameters that drive ocean circulation are the wind speed and direction, air/sea heat exchange and evaporation/precipitation. Thus 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 will drive a greater influx of Atlantic water into UK waters and bring more rainfall and warmer air temperatures. Higher rainfall will result in lower salinities in coastal waters due to increased river runoff and this will enhance density driven coastal flows. Warmer air temperatures will warm the shallower areas of UK waters or at least slow their cooling.

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.

Descriptions of the monitoring networks that regularly measure marine weather data are given in Chapter 1, including details of how to access near real-time data.

Refer to the list of links to monitoring networks and data sets at the end of this chapter (section 8.).

3.2 GLOBAL ATMOSPHERIC FEATURES - ENSO AND THE NORTH ATLANTIC OSCILLATION

3.2.1 ENSO

‘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. During El Niño events, unusually high atmospheric sea level pressure develops in the western tropical Pacific and Indian Ocean regions, and unusually low sea level pressure develops in the southern tropical Pacific. This causes weaker than normal trade winds, allowing warm water to flow easterly across the equatorial Pacific from the Indonesian region. Consequently there is a warming of the upper layers of the sea in the eastern and central equatorial Pacific Ocean, a release of carbon dioxide from the sea and atmospheric warming through the greenhouse effect. During La Niña events, unusually low pressures to the west and unusually high pressures to the east of the International Date Line cause stronger than normal trade winds, inhibiting the easterly flow of warm water across the equatorial Pacific and hence causing anomalously cold sea temperatures, absorption of carbon dioxide from the atmosphere and atmospheric cooling.

The evidence for an influence of ENSO on the North Atlantic and European weather is weak and mostly limited to precipitation variability in parts of the Mediterranean (IPCC, 2001). However, there appears to be a correlation between the frequency of tropical Atlantic storms and ENSO activity, with El Niño and La Niña events inhibiting or enhancing the genesis of storms respectively. The number of hurricanes and tropical storms in the North Atlantic Basin was above average in 2001, a La Niña year, with 15 named storms, five more than the long-term average (WMO, 2001). 2002 started with near neutral ENSO conditions and then an El Niño event developed, and 12 named tropical storms were observed in the North Atlantic, above the average of around 10, but only four developed to hurricane strength – fewer than the average of five to six (WMO, 2002).

3.2.2 THE NORTH ATLANTIC OSCILLATION

3.2.2.1 Introduction

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 westerly winds over the North Atlantic.

During the winter season (December-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-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 minimums during the summer (June-August) season, when the centres of action are substantially north and east relative to winter. By autumn (September-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 presently no evidence of a causal connection between ENSO and the NAO, and both appear to respond quite independently of one another. However, the NAO is a regional expression of the seesaw 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), and therefore there may be teleconnections between it and the ENSO.

3.2.2.2 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). The Azores/Iceland data set produces an Index better representative of the strength of the Atlantic westerly winds during the whole year, but Hurrell (1995) concluded that the Lisbon/Iceland

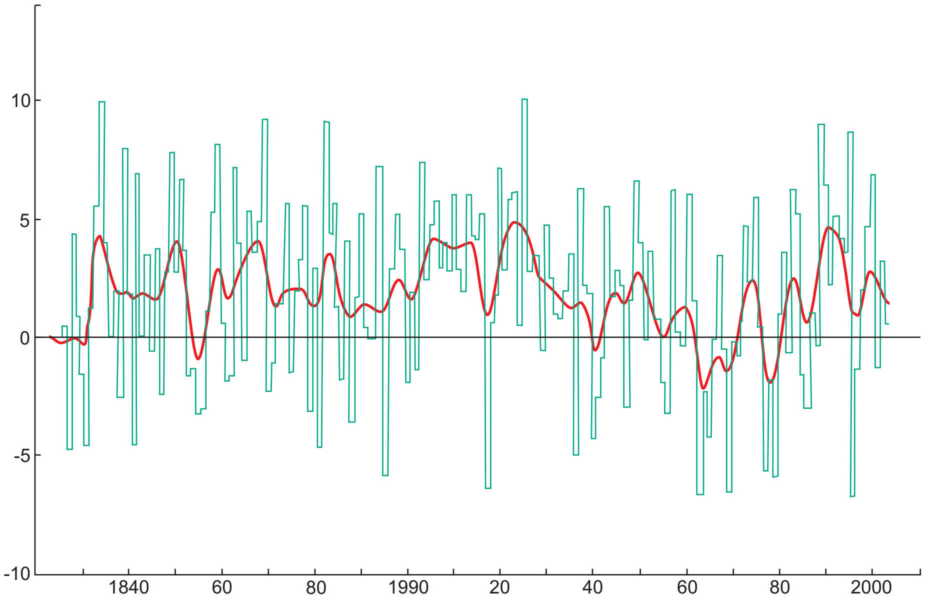


Figure 3.1. NAO Winter index. Based on the normalised pressure difference between Gibraltar and Reykjavik. Data series ends at December 2003. Courtesy of CRU, UEA

data set better captured NAO-related wintertime variability in sea level pressure over the North Atlantic sector and produced a time series back to 1864 (refer to Hurrell's web page at http://www.cgd.ucar.edu/~jhurrell/nao.stat.winter.html).

Jones *et al*. (1997) subsequently showed that an adequate Winter Index could be obtained using the even longer record from Gibraltar (to 1821). Jones *et al*. (2003) showed that all of these indices are highly correlated on interannual and longer time scales. Also, the choice of the Iceland station is not critical since the temporal variability over this region is much larger than the spatial variability; e.g. the December-March anomalies in SLP at Stykkisholmur and Akureyri correlate at 0.98 (Hurrell and van Loon, 1997). For continuity with the previous report (IACMST, 2001), we use Jones' NAO Winter Index. (This version of the Index has also been used in a recent study of wave climate in UK waters, refer to the work of Cotton *et al*. (1999) in the chapter on Waves).

For further information on the NAO Index compiled by the Climate Research Unit go to http://www.cru.uea.ac.uk/cru/data/nao.htm. The Met Office make predictions of the NAO Winter Index (http://www.metoffice.com/research/seasonal/regional/nao/index.html).

According to Hurrell *et al*. (2003), a disadvantage of station-based indices is that they are fixed in space, so given the movement of the NAO centres of action through the annual cycle, such indices can only adequately capture NAO variability for parts of the year. Moreover, individual station pressures are significantly affected by small-scale and transient meteorological phenomena not related to the NAO and thus contain noise. An alternative approach is to derive an Index from the principal component (PC) time series of sea level pressure anomalies over the Atlantic, although they can only be computed for parts of the 20th century, depending on the data source.

Visit http://www.cgd.ucar.edu/~jhurrell/nao.pc.winter.html for Hurrell's Winter (December – March) PC-based NAO Index from 1899 onwards.

Changes in the NAO index correspond to large-scale changes in the north-south pressure difference across the north-east Atlantic. A positive, or high, 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 winter 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 and unsettled and chilly summers in the UK. A negative, or low, Index indicates a weak subtropical high and a weak Icelandic low pressure. The reduced pressure gradient results in fewer and weaker westerly winds crossing the Atlantic on a more west-east path and more occurrences of easterly winds. Anticyclones can dominate and winters become colder than normal and summers warmer in the UK. High index years are associated with warming in the southern North Atlantic and northwest European shelf seas, and with cooling in the Labrador and Nordic Seas. Low index years generally show the reverse.

3.2.2.3 NAO trends

Over the full historical record of the NAO, the most extreme change since the 1860s has occurred from about 1960 up to the present, with the Winter (December to March average) Index showing a recent upward trend from the 1960s to the early 1990s, but with high year-to-year variability superimposed. The 1960s were generally low index years, with associated very weak westerly winds; whereas the 1980s and 1990s were generally high index years, with associated very strong westerly winds and relatively mild and wet winters over NW Europe. Long instrumental records and palaeoclimatic reconstructions of the NAO using ice cores and tree ring chronologies indicate several earlier periods of comparable values over the past 500 years. Thus strongly positive values for individual winters occurred during the early decades of the 20th century and for several earlier periods of one or two decades in earlier centuries; but the rise in values from the 1960s to the 1990s does appear unique in the long records (Jones, 2003; Mann and Jones, 2003).

The winter of 1994/95 had one of the most positive values on record, followed in winter 1995/96 by the lowest value on record (see wind data, above). This ‘flip’ was associated with radical changes in European weather: a reversal of the precipitation regime over Europe from more than 150 per cent of the average winter precipitation over most of northern Europe in the winter of 1994/95 to less than 60 per cent of the average in the winter of 1995/96 (ICES, 1999). The index subsequently rose from the extreme low of 1995/96 and the recovery continued during 1999/2000, again became negative during the winter of 2000/01 but positive in both winter 2001/02 and 2002/03. However, whilst the index for 2002/03 suggested weakly positive NAO conditions, the winter sea level pressure anomaly was not dominated by the NAO pattern and conditions in the west were more consistent with conditions associated with a negative NAO pattern (ICES, 2003a).

The recent trend in the NAO is fairly unusual but might nevertheless be part of a natural cycle, and it is uncertain if the dip in the index in the mid 1990s is only part of a decadal oscillation, or if the upward trend of the past few decades has ceased, or perhaps reversed. However, the NAO undergoes long-term cycles with varying periodicity, so any long-term trends are confused by variations on time scales from annual to multi-decadal. However, Gillet *et al*. (2003) showed that the observed trend in the Winter Index is outside the 95 per cent range of internal variability, indicating that the recent climate change is due in part to external forcing; perhaps from volcanic aerosols, anthropogenic influences on the atmospheric composition or variations in solar activity, all of which can modulate the strength of the winter polar vortex.

The upward trend in the NAO strength during the last several decades has been associated with a stratospheric trend toward much stronger westerly winds encircling the pole and anomalously cold polar temperatures (Thompson *et al*., 2003). Reductions in stratospheric ozone and increases in GHG concentrations also appear to enhance the meridional temperature gradient in the lower stratosphere, via radiative cooling of the wintertime polar regions. This change implies a stronger polar vortex. It is possible, therefore, that the upward trend 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 Index in response to increasing GHG levels, leading them to conclude that increasing GHG concentrations have contributed to a strengthening of the North Atlantic surface pressure gradient.

3.2.2.4 Effects of NAO on MPC parameters

(Some of these effects are considered in more detail in the relevant parameter chapters.)

Most studies of the NAO focus on the winter months, 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 (see section 6.5), is also greatest at this time of year. But Hurrell et al. (2003) 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, they state that vigorous wintertime NAO can interact with the slower components of the climate system (the ocean, in particular) to leave persistent surface anomalies into the ensuing parts of the year that may significantly influence the evolution of the climate system.

The NAO produces changes in the strength and direction of the westerly wind flow over the North Atlantic and such changes alter the seasonal mean heat and moisture transport between the Atlantic and the neighbouring continents, as well as the intensity and number of storms, their paths, and their weather. Significant changes in ocean surface temperature and heat content, ocean currents and their related heat transport, and sea ice cover in the North Atlantic are also induced by changes in the NAO. 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), (see section 3.2.2.5, below).

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 NAO and its time dependence appear central to changes in global temperature. Hurrell (1996) showed that much of the local cooling in the northwest 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 per cent 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 linearly for much, but not all, of the hemispheric warming through the mid-1990s. However, the warming of the most recent winters is beyond that which can be linearly explained by changes in the NAO. Over 1999-2002, for instance, record warmth was recorded while generally cold conditions prevailed in the tropical Pacific and NAO-related circulation anomalies were weak.

According to Pingree (2002), it is now established that winter NAO indices correlate with rainfall with the positive phase of NAO tending to lead to mild and wet winters over northern Europe.

The NAO controls or modifies three of the main parameters that drive ocean circulation (wind speed, air/sea heat exchange and evaporation/precipitation). Changes in NAO are also reflected in sea surface temperature, e.g. accounting for 40-50 per cent 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 (GSA) (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 upward trend toward more positive NAO index winters has been associated with increased wave heights over the northeast 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 Britain, but not to the east (Cotton *et al*., 1999; Woolf *et al*., 2002 and 2003).

3.2.2.5 Effects of NAO on non-MPC parameters

A brief description is given here; see other sector reports for more details.

Changes in the NAO have been associated with a wide range of effects on the marine ecosystem, including changes in the production of plankton and the distribution of different fish species. For example, the northward shift of phytoplankton and zooplankton in the Northeast Atlantic over the last 40 years, and recent visits in UK waters by warm-water fish such as sailfin dory, blue marlin and barracuda, 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, 2003b).

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 both direct and indirect pathways. Drinkwater *et al*. (2003) state that there are three possible pathways by which the NAO affects the marine ecosystem. The first is the effect of NAO-induced temperature changes on metabolic processes such as feeding and growth. Since 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 between the northeast and northwest Atlantic. More complex pathways may involve several physical and biological steps, e.g. 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. A third 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 (Heath et al., 1999).

3.3 GLOBAL TEMPERATURE

The Northern Hemisphere, Southern Hemisphere and Global average near-surface temperature annual anomalies from 1861 to 2003 can be accessed at http://www.metoffice.com/research/hadleycentre/CR_data/Monthly/HadCRUGNS_3plots.gif. These data are 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.

Global surface temperature has increased by about 0.6 ± 0.2°C since the late 19th Century (IPCC, 2001). The increase in temperature in the 20th Century is likely to have been the largest in any century during the last 1,000 years (WMO, 2003). Based on a reconstruction of the global climate from data derived from ice cores, trees' annual growth rings and other records, Mann and Jones (2003), consider that the Earth appears to have been warmer since 1980 than at any time in the last 18 centuries.

Including 2002, the 10 warmest years since records began in 1860 have all occurred since 1990, with the four warmest years being 1998, 2002, 2001 and 1997 (in descending order). The general increase in atmospheric gases like carbon dioxide, nitrous oxide, ozone etc. is considered to be the major contributor to this global warming, through the greenhouse effect; but one contributory warming factor over the last few decades has been the El Niño events of 1982-83, 1990-95 and 1997-98, with the latter the strongest of the 20th century and contributing to the warmest year, 1998. However, in some years global warming has been offset by cooling due to factors like 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 was a cooling factor in 2001, even though that year was the third warmest on record.

3.4 UK TEMPERATURE

The Central England Temperature (CET) record is the longest continuous record of measured surface air temperatures in the world and is representative of a triangular central area of the United Kingdom enclosed by Bristol, Manchester and London (Parker *et al*., 1992). It is compiled from records in a roughly triangular area enclosed by Bristol, Manchester and London; 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. During the twentieth century, the annual mean CET has warmed by about 0.5°C. The warmest years since 1659 occurred in 1990 and 1999 and the 1990s was the warmest decade in central England since records began, with five of the six warmest years occurring then. There is a high correlation between the CET record and the NAO; for example, the cold winter of 1995/96 was associated with the lowest value on record of the NAO index. A plot of the CET annual anomalies from 1772 to 2003 can be accessed at http://www.metoffice.com/research/hadleycentre/CR_data/Annual/cet.gif.

The Scottish and Northern Ireland Forum for Environmental Research (SNIFFER, 2000) has produced three regional terrestrial indices of temperature – a Northern Ireland Index (data from Armagh), a Scottish Mainland Index (data from Barmier, Dumfries, Edinburgh Royal Botanic Gardens, Paisley and Wick) and a Scottish Islands Index (data from Stornoway and Lerwick). A comparison of 30-year means of annual mean temperature between 1873-1902 and 1961-1990 demonstrated clearly that, although the amount of warming varied, the three indices showed warming of between 0.11°C and 0.39°C - similar to the CET record. Most of this warming was found to result from an increase in the mean minimum temperature, rather than any significant change in the mean maximum temperature.

Temperature records from Lerwick (Figure 3.2) also show a long-term warming, although values for 2000 and 2001 were lower than those seen in 1998 and 1999 (FRS, 2003).

Figures 3.3 to 3.8 show air temperature data for 2000 – 2002 from selected stations of the Met Office's Marine Automatic Weather Station Network (MAWS) Network. For an animation of air temperatures from the MAWS network (using STEMgis) refer to the active link on the web version of this report.

3.5 UK WIND

Recent work by the Hadley Centre (2003) has shown that the average number of storms in October to March (as detected by 3-hourly pressure changes) at UK stations has increased significantly over the past 50 years or so. (Pressure changes were used instead of winds because the results are less sensitive to site moves and instrumentation changes.) There is also some evidence that storm frequency has increased over the UK and decreased in the north (Iceland), which is consistent with a southerly movement of the Atlantic storm track. Regional analysis shows that the largest increases occur over the southern UK.

There is poor correlation between the storm rate calculated from the pressure measurement sites and the changes (an upward trend) in the NAO Index, implying that the severe storms over the UK are more related to strong local gradients of pressure than to the large-scale pressure differences over the Atlantic. However, it is likely that the local severe storms are modified by the long-term changes on the large-scale, which are seen in the NAO index (Hadley Centre, 2003).

However it is important to place these results in context. Evidence of storm frequency from daily

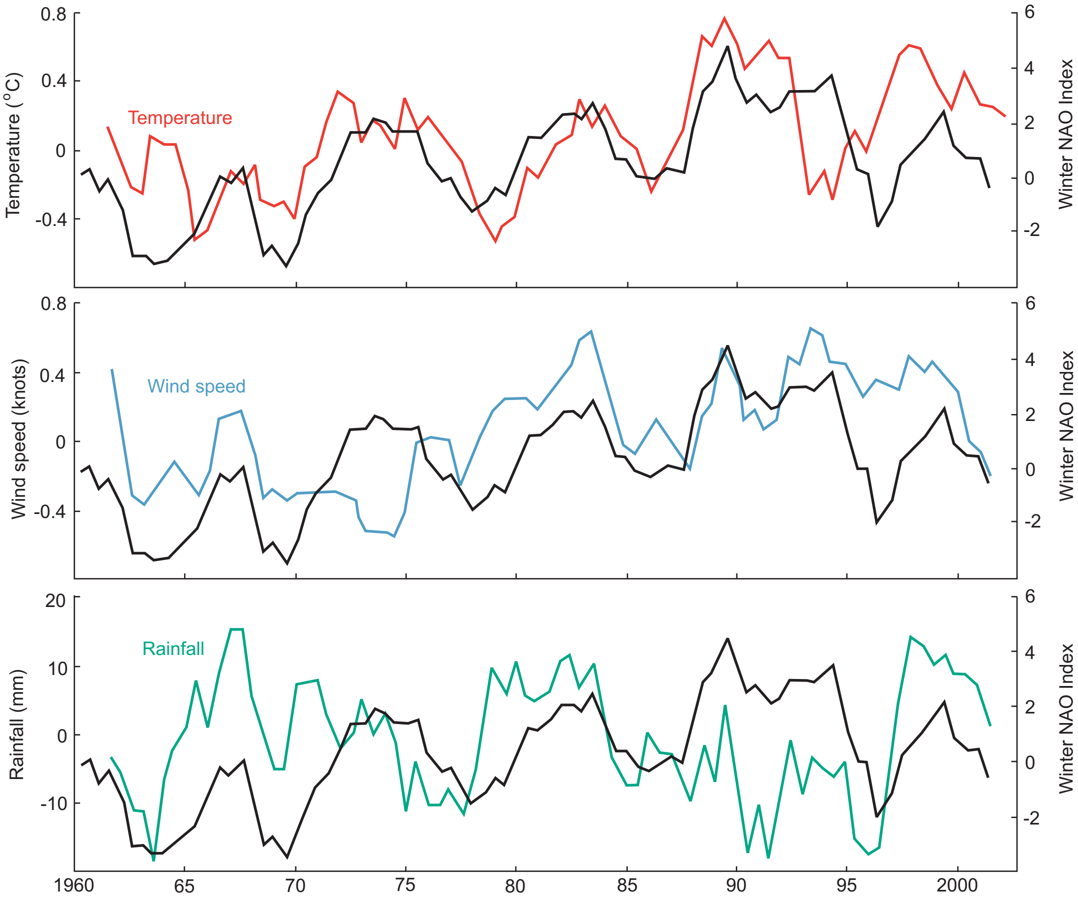


Figure 3.2. Long-term changes in the monthly average air temperature, wind speed and rainfall at Lerwick. Long term changes in the monthly average air temperature, wind speed and rainfall at Lerwick and changes in the NAO Winter Index. For temperature and wind, the large change through the year due to seasonal changes has been removed by subtracting the long-term (1961-1990) monthly averages, leaving the smaller change from year to year. Courtesy of FRS

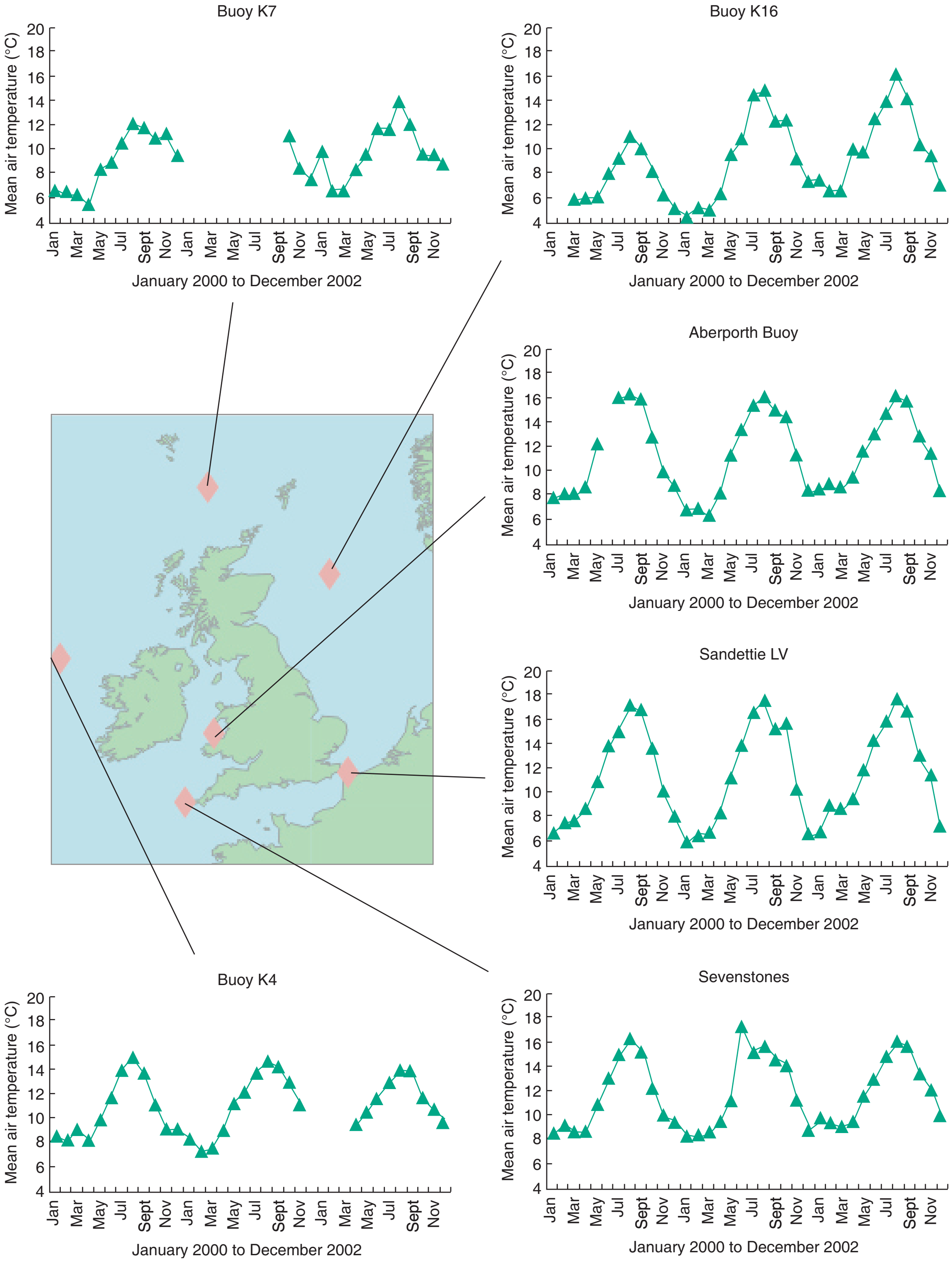
indices suggest that although it has increased in recent times, the magnitude of storminess at the end of the 20th Century was similar to that at the start. This could mean that natural variations in the magnitude of storminess on timescales of several decades or more are responsible for all or part of the trends seen in these new results and that data covering a longer period is needed in order to distinguish a climate change trend from the natural variability (Hadley Centre, 2003).

Figure 3.2 (above) shows that average wind speeds at Lerwick have been increasing by approximately half a knot every 10 years, but with a good deal of variability from year to year (FRS, 2003).

The change in wind regime over the UK due to the extreme differences in the NAO between winter 1994/95 and winter 1995/96 (see below) is illustrated in Figures 3.9, 3.10 and 3.11.

For an animation of annual winter wind rose data from Lerwick, Bidston, and Shoeburyness (using STEMgis) refer to the active link on the web version of this report.

Figures 3.12 to 3.17 show mean data for 2000 – 2002 from selected stations of the Met Office's Marine Automatic Weather Station Network (MAWS) Network. For an animation of wind data from the MAWS network (using STEMgis) refer to the active link on the web version of this report.



Figures 3.3-3.8. Mean air temperature data from MAWS Network. Courtesy of the Met Office

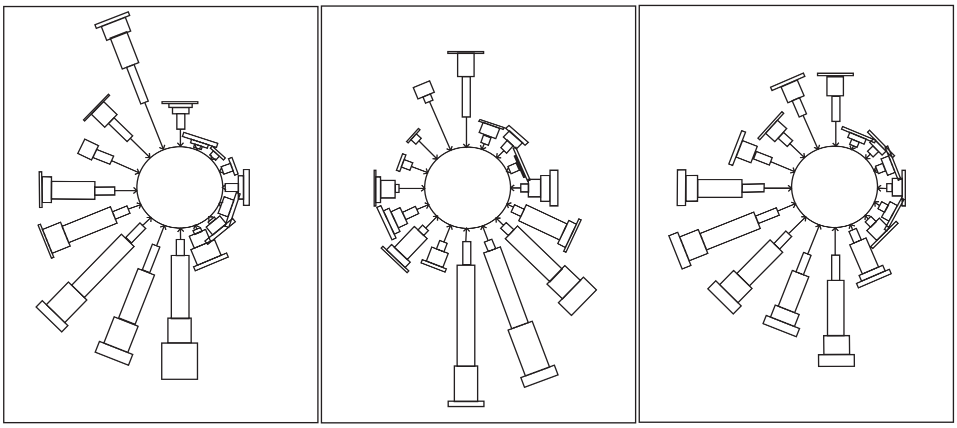


Figure 3.9. Lerwick wind roses for extreme NAO Index years and full data series. Frequency, force and direction of the wind at Lerwick, for winter (December to February). Left is winter 1994/5, centre is winter 1995/6, right is full data series, 1983-2000. Courtesy of FRS and Andy Tabor

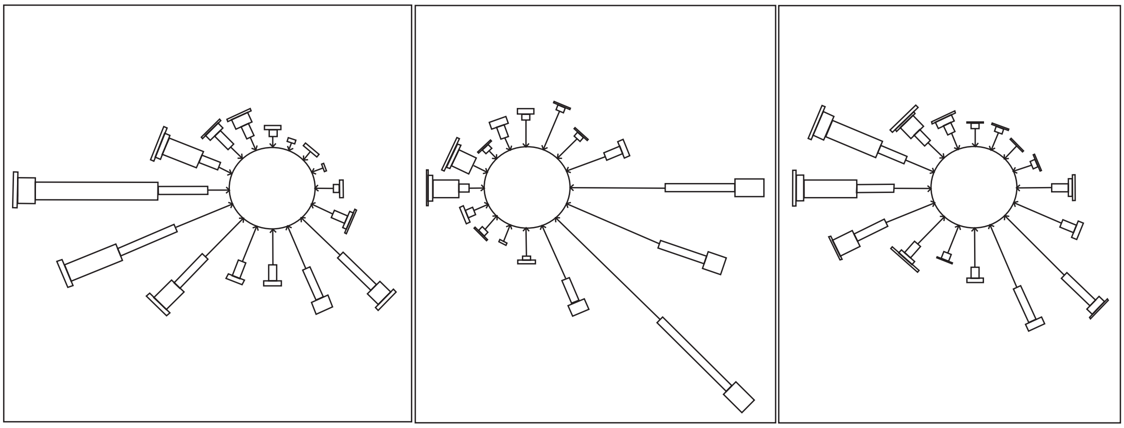
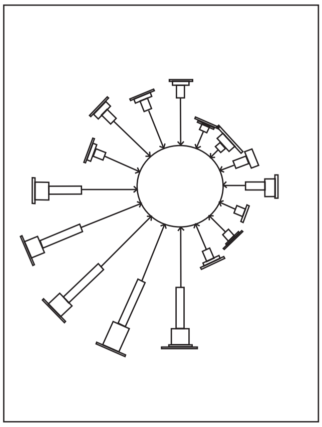


Figure 3.10. Bidston wind roses for extreme Index years and full data series. Frequency, force and direction of the wind at Bidston Observatory, Birkenhead, for winter (December to February). Left is winter 1994/5, centre is winter 1995/6, right is full data series, 1992-2003. Courtesy of POL and Andy Tabor



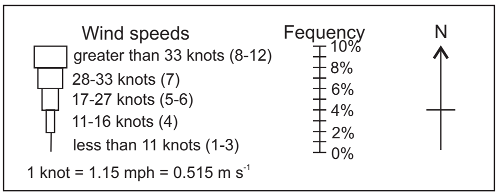
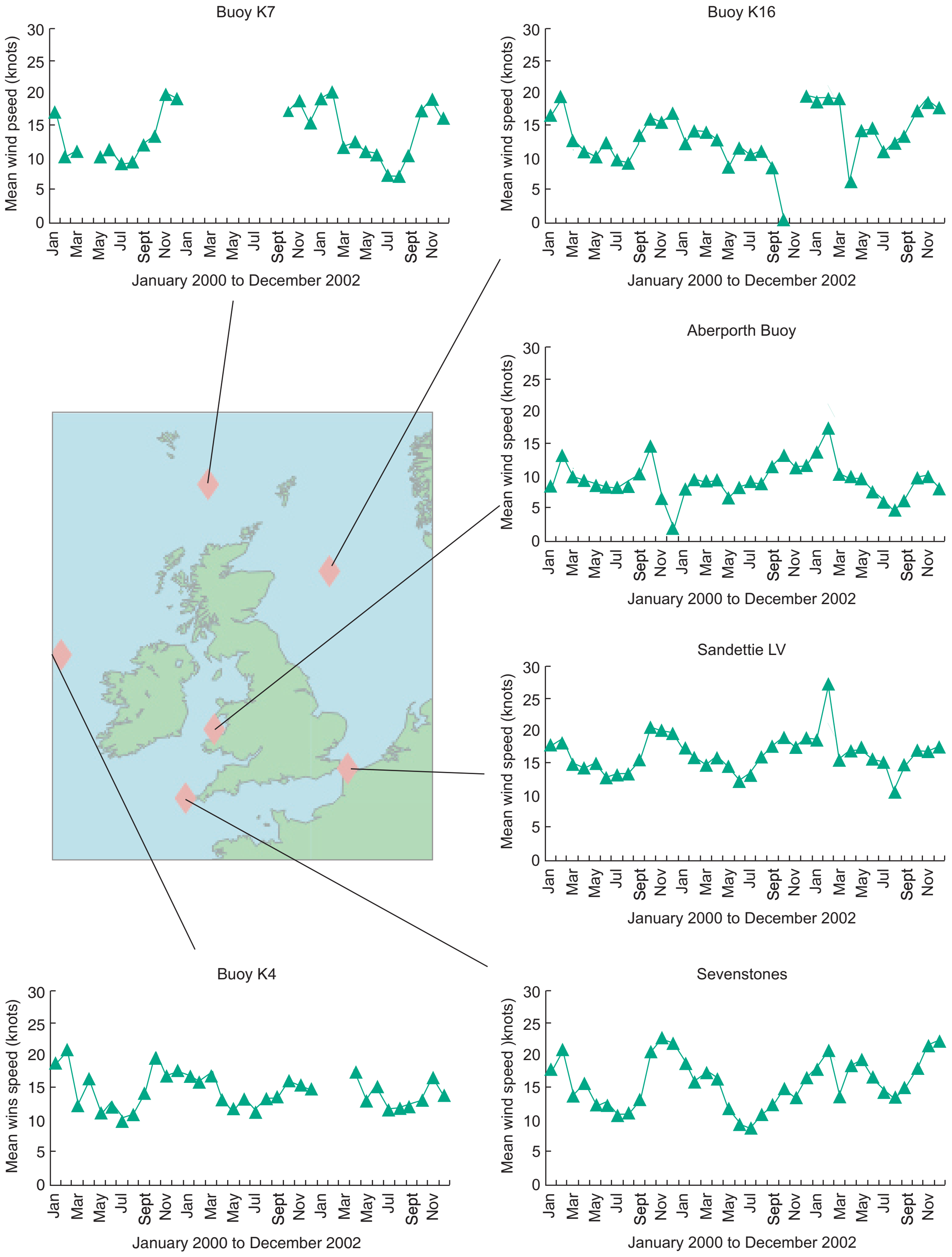


Figure 3.11. Wind roses for full data series for Shoeburyness. Frequency, force and direction of the wind at Shoeburyness, for winter (December to February, 1983-1993). Courtesy of BADC and Andy Tabor



Figures 3.12-3.17. Wind data from MAWS Network. Courtesy of the Met Office

3.6 UK PRECIPITATION

Compiled by the Met Office, the monthly time-series of England and Wales total precipitation 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 24-month period ending in March 2001 was the wettest in England and Wales since records began and April 2000 to March 2001 the wettest twelve months (WMO, 2001). There is a tendency towards wetter winters in north-east England and drier summers in south-east England (Alexander and Jones, 2001).

To see a plot of the England and Wales Precipitation Annual Totals from 1766 – 2003 visit the following website: http://www.metoffice.com/research/hadleycentre/CR_data/Annual/HadEWP_act_graph.gif

Figure 3.2 (above) shows that rainfall at Lerwick during 2000 and 2001 was lower than in 1998 and 1999, with the greatest amounts since 1961 in the late 1960s (FRS, 2003).

An analysis (SNIFFER, 2000) of area-averaged monthly rainfall records in Northern Ireland for the period from 1931-2000 concluded that there were no statistically significant trends in either annual precipitation or winter precipitation on its own. Summers in Northern Ireland have generally been drier during the past three decades than earlier in the 70-years record, with 1976, 1983 and 1995 being particularly dry years. This has led to an increasing trend in the balance between winter and summer precipitation, measured as proportions of the relatively unvarying (or trend-less) total annual precipitation, i.e. a trend in rainfall towards relatively drier summers and wetter winters.

3.7 REFERENCES

Alexander, L.V. and Jones, P.D. (2001). Updated precipitation for the UK and discussion of recent extremes. *Atmospheric Science Letters*, 1: doi:10.1006/asle.2001.0025

Ambaum, M.H.P., Hoskins, B.J. and Stephenson, D.B. (2001). Arctic Oscillation or North Atlantic Oscillation? *Journal of Climate*, 14: 3495-3507.

Bacon, S., and Carter, D.J.T. (1993). A connection between mean wave height and atmospheric pressure gradient in the North Atlantic. International *Journal of Climatology*, 13: 423–436.

Beaugrand, G., Reid, P.C., Ibañez, F., Lindley, J.A. and Edwards, M. (2002). Reorganization of North Atlantic Marine Copepod Biodiversity and Climate. *Science*, 296: 1692-1694.

Cotton, P.D., Carter, D.J.T., Allan, T.D., Challenor, P.G., Woolf, D., Wolf, J., Hargreaves, J.C.,, Flather, R.A., Li Bin, Holden, N. and Palmer, D. (1999). Joint Evaluation of Remote Sensing Information for Coastal And Harbour Organisations (JERICHO). Final Report to the British National Space Centre, project no: R3/003. 38pp. Retrieved 10th September 2003 from the World Wide Web: http://www.satobsys.co.uk/Jericho/webpages/jeripdf.html.

Curry, R. G., and McCartney, M. S. (2001). Ocean gyre circulation changes associated with the North Atlantic Oscillation. *Journal of Physical Oceanography*, 31: 3374–3400.

Dickson, R. R., Lazier, J., Meincke, J., Rhines, P. and Swift, J. (1996). Long-term co-ordinated changes in the convective activity of the North Atlantic. *Progress in Oceanography*, 38: 241–295, 1996.

Dickson, R.R., Meincke, J., Malmberg, S.A. and Lee, A.J. (1988). The 'Great Salinity Anomaly' in the northern North Atlantic 1968–1982. *Progress in Oceanography*, 20: 103–151.

Dickson, R.R., and Meincke, J. (2003). The North Atlantic Oscillation and the ocean's response in the 1990s. *ICES Marine Science Symposia*, 219: 15-24.

Drinkwater, K.F., Belgrano, A., Borja, A., Conversi, A., Edwards, M., Greene, C.H., Ottersen, G., Pershing, A. J. and Walker, H. (2003). The response of marine ecosystems to climate variability associated with the North Atlantic Oscillation, Pp 211 to 234 *In* The North Atlantic Oscillation: Climate Significance and Environmental Impact. (Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M. Editors, 2003) Geophysical Monograph Series, 134, 279pp.

Fromentin, J.M., and Planque, B. (1996). Calanus and environment in the eastern North Atlantic. II. Influence of the North Atlantic Oscillation on *C. finmarchicus* and *C. helgolandicus*. *Marine Ecology Progress Series*, 134: 111-118.

FRS (2003). Scottish Ocean Climate Status Report 2000 - 2001. Fisheries Research Services Report 05/03, Marine Laboratory, Aberdeen, 20pp.

Gillett, N. P., Graf, H. F. and Osborn, T. J. (2003). Climate change and the North Atlantic Oscillation, Pp 174 to 193 *In* The North Atlantic Oscillation: Climate Significance and Environmental Impact. (Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M. , Editors, 2003) Geophysical Monograph Series, 134, 279pp.

Hadley Centre (2003). Climate Change, Observations and Predictions. Recent research on climate change science from the Hadley Centre. Brochure available from http://www.metoffice.com/research/hadleycentre/pubs/brochures/2003/global.pdf

Heath, M.R., Backhaus, J.O., Richardson,K., McKenzie, E., Slagstad, D., Beare, D., Dunn, J., Gallego, A., Hay, S., Jónasdóttir, S., Hainbucher, D., Madden, H., Mardalijevic, J. and Schlacht, A. (1999), Climate fluctuations and the spring invasion of the North Sea by *Calanus finmarchicus*. *Fisheries Oceanography*, 8: 163–176.

Hurrell, J.W. (1995). Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. Science 269: 676-679. Hurrell, J.W. (1996). Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophysical Research Letters*, 23(6): 665-668.

Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M., Editors (2003). The North Atlantic Oscillation: Climate Significance and Environmental Impact. *Geophysical Monograph Series*, 134, 279pp.

Hurrell, J.W. and van Loon, H. (1997). Decadal variations in climate associated with the North Atlantic oscillation. *Climate Change,* 36: 301-326.

IACMST (2001). Climate of UK Waters at the Millennium: Status and Trends. Edited by Graham Alcock and Lesley Rickards. IACMST Information Document No. 9. (Also available at http://www.oceannet.org/UKclimate-status).

ICES (1999). The Annual ICES Ocean Climate Status Summary 1998/1999. Prepared by the Working Group on Oceanic Hydrography, ICES, Copenhagen, Denmark. (Edited by W. Turrell.) Retrieved 9th May 2003 from the World Wide Web: http://www.ices.dk/status/clim9899/.

ICES (2003a). The 2002/2003 ICES Annual Ocean Climate Status Summary. Prepared by the Working Group on Oceanic Hydrography, ICES, Copenhagen, Denmark. (Editors: Hughes, S.L. and Lavín, A.) Retrieved 4th October 2003 from the World Wide Web: http://www.ices.dk/status/clim0203/IAOCSS2002.PDF.

ICES (2003b). Environmental status of the European seas. Edited by Neil Fletcher. Retrieved 26th September 2003 from the World Wide Web: http://www.ices.dk/reports/germanqsr/23222_ICES_Report_samme.pdf.

Jones P.D., Jónsson, T. and Wheeler D. (1997). Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. International *Journal of Climatology*, 17: 1433-1450.

Jones, P.D., Osborn, T.J. and Briffa, K.R. (2003). Pressure-based measures of the North Atlantic Oscillation (NAO): A comparison and an assessment of changes in the strength of the NAO and in its influence on surface climate parameters. Pp 51 to 62 *In* The North Atlantic Oscillation: Climate Significance and Environmental Impact. (Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M., Editors, 2003) Geophysical Monograph Series, 134, 279pp.

Jones, P.D. (2003). The decade of the 1990s over the Atlantic in comparison with longer instrumental and palaeoclimatic records. *ICES Marine Science Symposia*, 219: 25-31.

Kushnir, Y., Cardone, V.J., Greenwood, J.G. and Cane, M. (1997). On the recent increase in North Atlantic wave heights. Journal of Climate, 10: 2107–2113. Loewe, P. (1996). Surface temperatures of the North Sea in 1996. Deutsche Hydrographisce Zeitschrift, 48, 175 – 184.

Mann, M.E. and Jones, P. D. (2003). Global surface temperature over the past two millennia. *Geophysical Research Letters*, 30 (15): 1820.

Parker D.E., Legg, T.P. and Folland, C.K. (1992). A new daily Central England Temperature series, 1772—1991. *International Journal of Climatology*, 12: 317-342.

Pingree, R. (2002). Ocean structure and climate (Eastern North Atlantic): in situ measurement and remote sensing (altimeter). *Journal of the Marine Biological Association of the United Kingdom*, 82: 681-705.

SNIFFER (2000). Development of Temperature Indices for Scotland and Northern Ireland. Report number SR(99)07F. SNIFFER, 11/13 Cumberland Street Edinburgh EH3 6RT.

Thompson, D. W. J., Lee, S. and Baldwin, M. P. (2003) Atmospheric processes governing the Northern Hemisphere Annular Mode/North Atlantic Oscillation. Pp 81 to 112 *In* The North Atlantic Oscillation: Climate Significance and Environmental Impact. (Hurrell, J.W. Kushnir, Y., Ottersen, G. and Visbeck, M., Editors, 2003) Geophysical Monograph Series, 134, 279pp.

Wakelin, S.L., Woodworth, P.L., Flather, R.A. and Williams, J.A. (2003). Sea-level dependence on the NAO over the NW European Continental Shelf. *Geophysical Research Letters*, 30(7): 1403, doi: 10.1029/2003GL017041.

WMO (2001). WMO statement on the status of the global climate in 2000. Publication No. 920, Geneva 12 pp. Retrieved 12th June 2003 from the World Wide Web: http://www.wmo.ch/web/wcp/wcdmp/statement/pdf/wmo920e.pdf

WMO (2002). WMO statement on the status of the global climate in 2001. Publication No. 940, Geneva, 12 pp. Retrieved 12th June 2003 from the World Wide Web: http://www.wmo.ch/web/wcp/wcdmp/statement/pdf/wmo940e.pdf

WMO (2003). WMO statement on the status of the global climate in 2002. Publication No. 949, Geneva, 12 pp. Retrieved 24th September 2003 from the World Wide Web: http://www.wmo.ch/web/wcp/wcdmp/statement/pdf/wmo949e.pdf .

Woolf, D.K., Challenor, P.G. and Cotton, P.D. (2002). The variability and predictability of North Atlantic wave climate. *Journal of Geophysical Research*, 107(C10), 3145.

Woolf, D.K., Cotton, P.D. and Challenor, P.G. (2003). Measurements of the offshore wave climate around the British Isles by satellite altimeter. Philosophical Transactions: *Mathematical, Physical & Engineering Sciences*, 361(1802), 27-31.

3.8 LIST OF LINKS TO MONITORING NETWORKS AND DATA SETS

Online search interfaces for catalogues and inventories maintained by the IACMST's Marine Environmental Data Network
http://www.oceannet.org

CEFAS Marine Environmental Real-time Observation System (MEROS)
http://www.cefas.co.uk/monitoring

HumberNet
http://www.northseanet.co.uk/humber/digitaldisplay.htm
and
http://www.northseanet.co.uk

Liverpool Bay Coastal Observatory
http://cobs.pol.ac.uk

Met Office's Hadley Centre for Climate Prediction and Research
http://www.metoffice.com/research/hadleycentre/obsdata

Met Office's Marine Automatic Weather Station (MAWS) Network
http://www.metoffice.com/research/ocean/goos/maws.html

Satellite missions
http://www.soc.soton.ac.uk/lso/noindex/lso_data.php

4. Sea temperature

SUMMARY OF CHANGES AND TRENDS

- Global sea surface temperature (SST) warmed from about 1910 to about 1940, remained steady and then began warming again during the 1970s. • There is no clear trend in summer SST in the eastern North Atlantic since the 1950s, but a warming in winter SST since the early 1990s is indicated.

- SST at the Continental Shelf Edge warmed between 0.12°C and 0.29°C over the past century.

- Annual SST averaged around the UK coastline has increased by about 0.5°C for the period 1871 to 2000, with most coastal sites showing a warming trend.

- Most of the waters around the UK have been warming since the 1980s, with the trend more pronounced in the southern North Sea and the Irish Sea (between 0.5°C and 1.0°C per decade) than elsewhere (between 0.0°C and 0.5°C per decade).

- There is a warming trend in winter and summer SST averaged over the northern North Sea since the early 1980s, with a warming of about 1°C and 0.5°C respectively.

- North Sea winter bottom temperatures increased by about 0.3°C and 0.6°C per decade since a cool period in the late 1970s.

- Irish Sea annual mean SST increased by about 0.7°C over the last 100 years. Winter SST from 1950 to 2002 shows a clear warming since the 1980s. An apparent cooling in summer SST since the 1980s may be due to sparse data.

- The Faroe Shetland Channel has become warmer over the last 40 years, with temperatures rising at a rate of approximately 0.3°C per decade from the late 1960s minimum.

- Temperatures in the Rockall Trough were relatively low in the early 1990s but then increased. The highest temperatures reached in the 1990s were similar to those in the 1960s.

4.1 INTRODUCTION

The role of the world’s oceans is critical in the global climate system because the high density and specific heat of water means that it can store and transport large amounts of heat. A meridional (tropics to poles) transport of energy is required for the Earth system to be in global radiative balance, with some 30-50% of the energy carried by ocean currents at mid latitudes and a higher proportion at lower latitudes (Bryden & Imawaki, 2001). The oceancirculation is determined primarily by the forcing due to momentum, heat and water fluxes to and from the atmosphere, and by the distributions of temperature (and salinity) in the ocean that set its density structure, and hence density currents. In particular, the density structure affects the ‘meso-scale’ dynamics of fronts and eddies, which are the most energetic motions.

Changes in sea temperature cause sea level changes, e.g. a warming causes sea level rise through thermal expansion.

Changes in sea temperature induce shifts in the geographic distribution of marine biota and changes in biodiversity, with direct effects on the species composition, breeding and population plankton and fish. Edwards *et al.* (2001) showed that there has been a steady increase in phytoplankton biomass in the North Sea Since the mid 1980s, with a peak in 1989 corresponded with anomalous warm sea surface temperatures. Beaugrand *et al.* (2002) found that the northward extension of more than 10° of latitude of warm-water copepod is related to the increasing trend in sea temperature. Hughes *et al.* (2003) suggest that there was a correlation between winter temperatures and catches of young cod in the North Sea during the 1990s. A strongly positive

NAO Index is associated with higher surface and bottom water temperature (and vice versa for a negative NAO) around the British Isles. Changes in the NAO contribute up to half the variability in sea surface temperature, in winter in the southern North Sea (Loewe, 1996).

Descriptions of the monitoring networks that regularly measure sea temperature data are given in Chapter 1, including details of how to access near real-time data.

Also refer to the list of links to monitoring networks and data sets at the end of this chapter (section 5.).

4.2 GLOBAL AND NORTH ATLANTIC SEA TEMPERATURE

The global ocean heat content has increased significantly since the late 1950s, with all oceans, including the Atlantic, undergoing a net warming (Levitus *et al.*, 2000). 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). Global SST for the past 100 years shows two distinct warming periods, the first from about 1910 to 1940 and the second starting during the 1970s (IPCC, 2001). Figures 4.1 and 4.2 show winter and summer SST data respectively in the eastern North Atlantic (55-60°N, 25-15°W). There appears to be no clear trend in summer SST since the 1950s, but a warming in winter SST since the early 1990s is indicated (Dooley, 2003). In 2001, except for southern areas of the Newfoundland and the northern Scotian shelves, North Atlantic sea temperatures were above normal, (ICES, 2002); and in most areas of the North Atlantic during 2002 temperature was higher than the long-term average (ICES, 2003a).

Figure 4.3 shows that most areas of the eastern North Atlantic have experienced a warming trend of between 0.2°C and 1°C per decade since the 1980s.

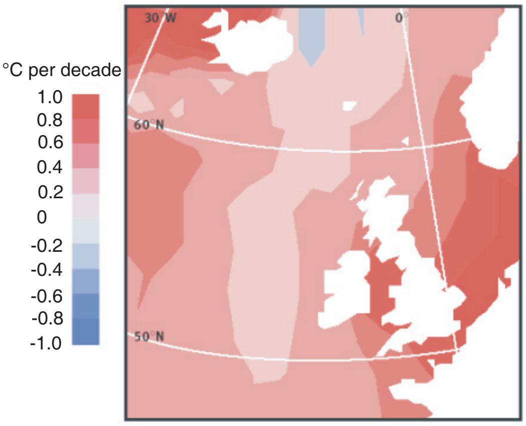


Figure 4.3. SST trend for 1981-2000. Red shading indicates warming (a positive trend in temperature) and blue shading indicates cooling (a negative trend in temperature). Trend values are °C per decade. Courtesy of FRS, taken from Reynolds Optimally Interpolated Sea-Surface Temperature dataset provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/

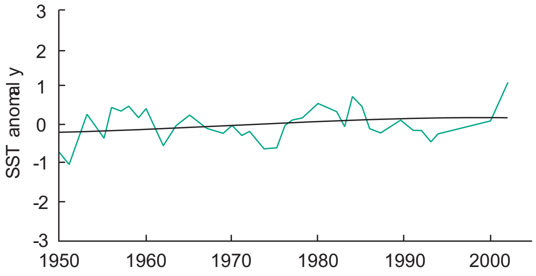


Figure 4.1. Winter (January to March) SST Anomaly, 1950-2002, eastern North Atlantic (55-60°N, 25-15°W). Time series produced by averaging the winter data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

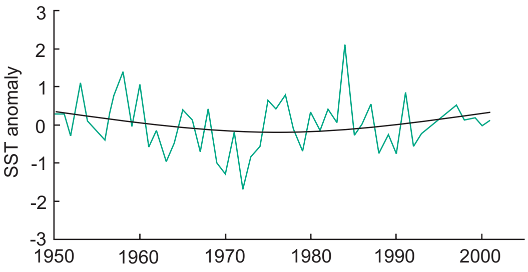


Figure 4.2. Summer (July to September) SST Anomaly, 1950-2002, eastern North Atlantic (55-60°N, 25-15°W). Time series produced by averaging the summer data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

4.3 UK WATERS SEA TEMPERATURE

For a figure of annual sea surface temperature averaged around the UK coastline for the period 1871 to 2000, see Figure 15 of the UKCIP report (at the following website: http://www.ukcip.org.uk/scenarios/pdfs/UKCIP02TechRep/UKCIP02_Ch2.pdf or refer to the web version of this report). Sea-surface temperature has increased by about 0.5°C during this period, with a substantial increase over the last 20 years (Hulme *et al.*, 2002). Figure 4.4 shows the annual sea surface temperature (with best fit line) from coastal stations in the UK.

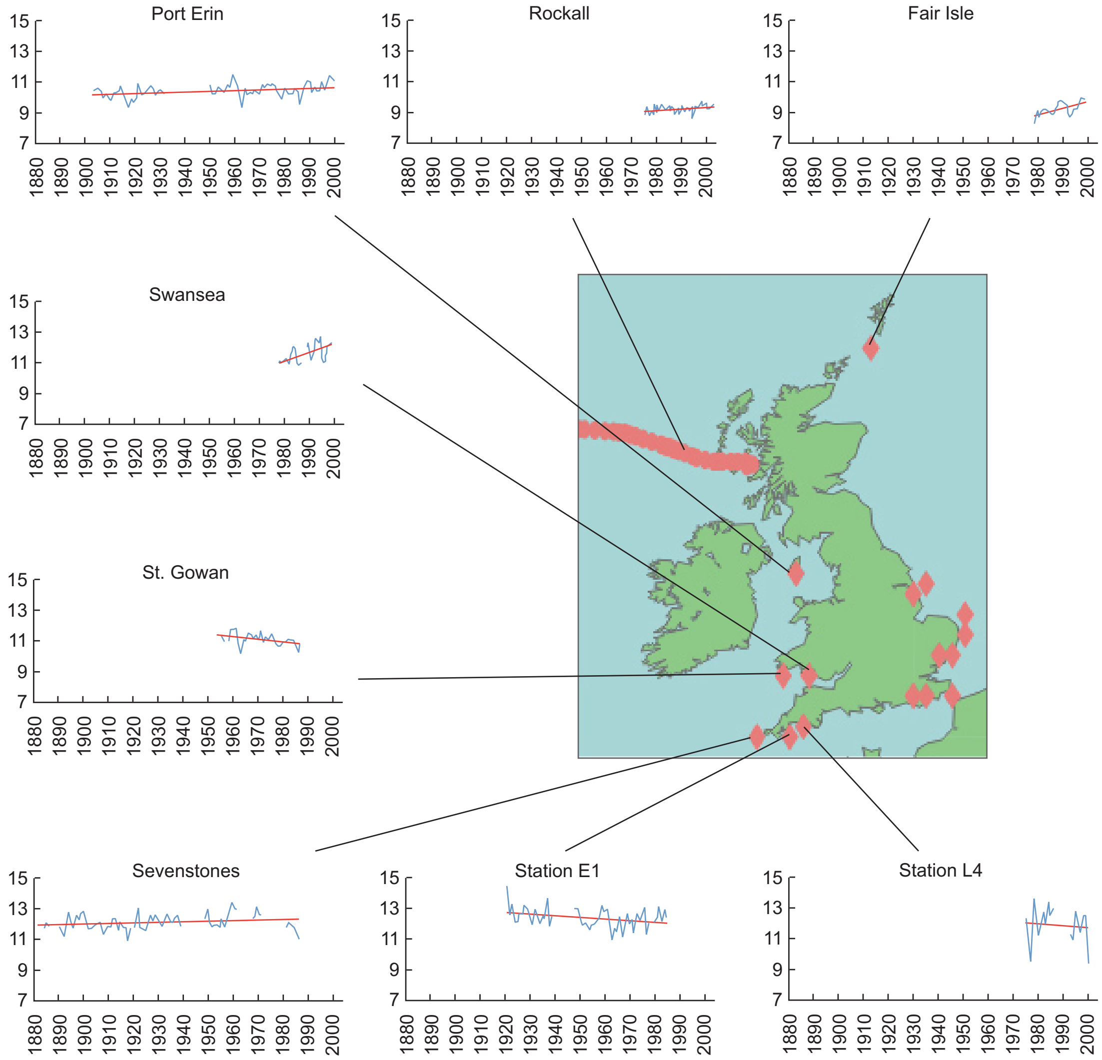


Figure 4.4. Annual sea surface temperature (°C) from coastal stations in the North Sea and English Channel (with best fit line). Courtesy of various suppliers

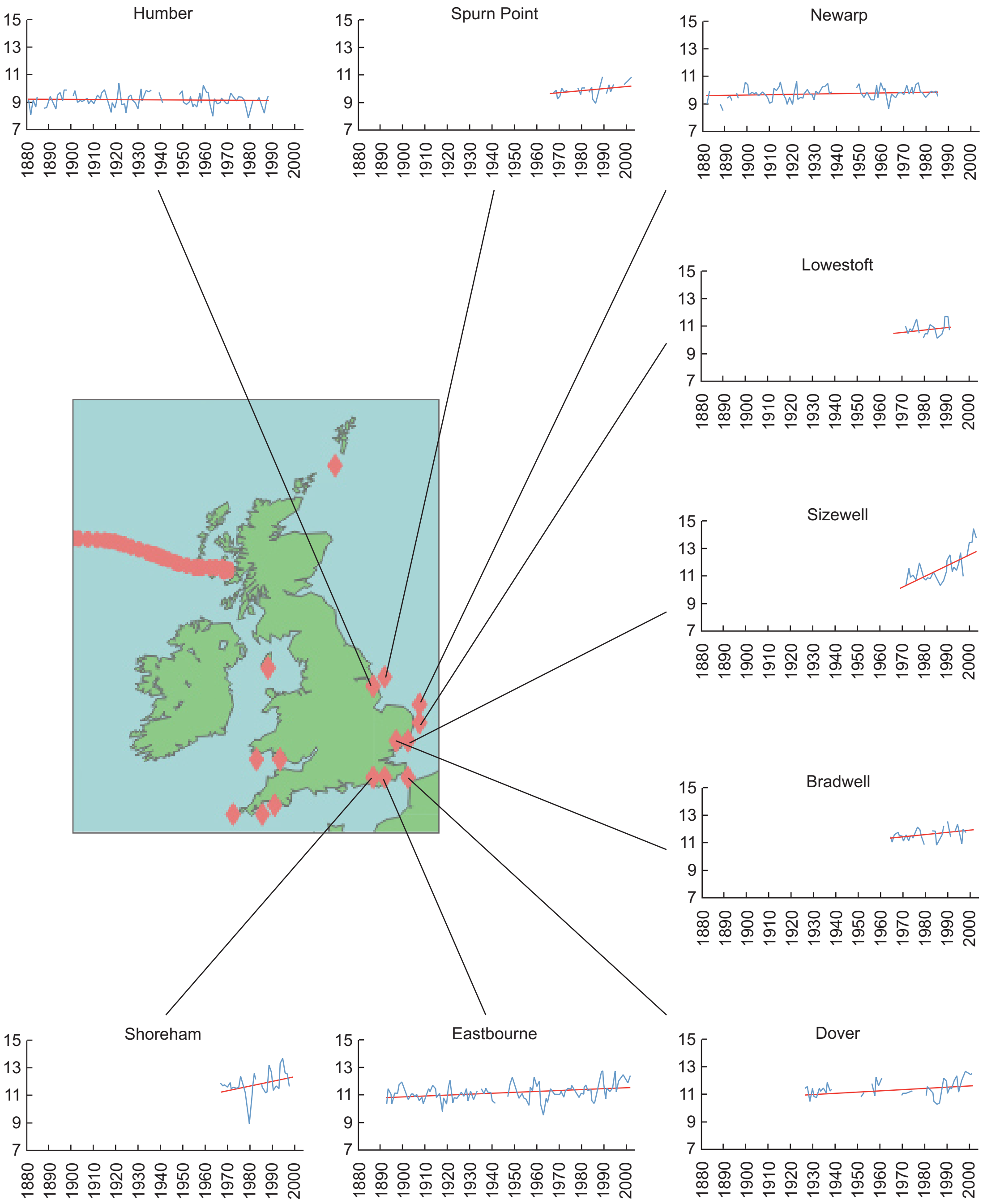


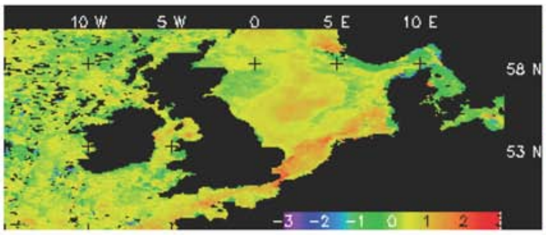
Figure 4.4. continued: Annual sea surface temperature (°C) from coastal stations in the North Sea and English Channel (with best fit line). Courtesy of various suppliers

Table 4.1. Trends in sea surface temperature from stations in UK waters

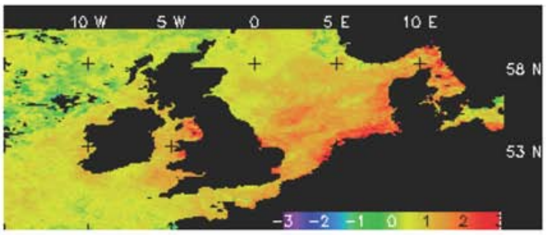
	Nominal position	Data Span	Trend (°C/decade)
North Sea SST			
Spurn Point	53.5°N 00.0°E	1966-2002	+ 0.17
Humber LV	53.5°N 00.0°E	1880-1989	+ 0.01
Newarp LV	53.0°N 02.0°E	1880-1986	+ 0.02
Lowestoft	52.5°N 02.0°E	1966-1991	+ 0.16
Sizewell	52.0°N 01.5°E	1967-2002	+ 0.77
Bradwell	52.0°N 01.0°E	1964-2001	+ 0.15
English Channel, Celtic Sea and Bristol Channel SST			
Dover	51.0°N 01.5°E	1926-2001	+ 0.09
Eastbourne	51.0°N 00.0°E	1892-2002	+ 0.06
Shoreham	51.0°N 00.0°E	1966-1997	+ 0.31
E1	50.0°N 04.5°W	1921-1987	- 0.13
Sevenstones LV	50.0°N 06.0°W	1881-1986	+ 0.04
St Gowan LV	51.5°N 05.0°W	1953-1987	- 0.17
Swansea	51.5°N 04.0°W	1976-1997	+ 0.58
Irish Sea SST			
Port Erin, Isle of Man	54.0°N 04.5°W	1904-2003	+ 0.07

The longest continuing records in UK waters (Dover, Eastbourne and Port Erin) show an increase in sea surface temperature of about 0.6°C over the last 75 to 110 years (Table 4.1). The long records from the Newarp, Humber and Seven Stones Light Vessels, discontinued in the 1980s, also show a warming trend since the late 19th Century, but the latter has a cooling of about 1.5°C from the early 1970s to 1986 (which invites further investigation). Shorter records, of between about 25 and 40 years, generally show a warming in annual SST of about 0.2°C per decade since the mid 1960s/1970s, but there is considerable inter-annual variability. Greater rates of warming are at Sizewell (+0.8°C per decade from 1967 to 2002), Shoreham (+0.3°C per decade from 1966 to 1997) and at Swansea (+0.6°C per decade from 1976 to 1997). The measurements at the St. Gowan Light Vessel and E1 show a cooling of about 0.2°C per decade from 1953 to 1987 and about 0.1°C per decade from 1921 to 1987 respectively. Since the 1980s, Figure 4.3 (above) shows that most of the waters around the UK have been warming, with the trend more pronounced in the southern North Sea and the Irish Sea (between 0.5°C and 1.0°C per decade) than elsewhere (between 0.0°C and 0.5°C per decade) (FRS, 2003).

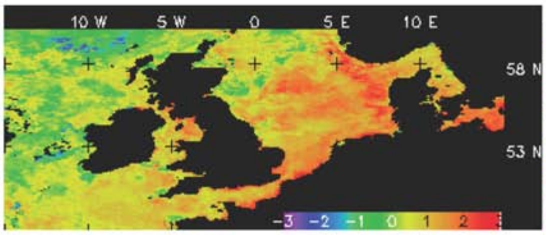
The following sequence of satellite images show sea surface temperature anomalies in UK waters during 1999 to 2002 (Courtesy of Plymouth Marine Laboratory and NASA's Pathfinder project). Refer to the web version of this report for an animation of this satellite sequence.



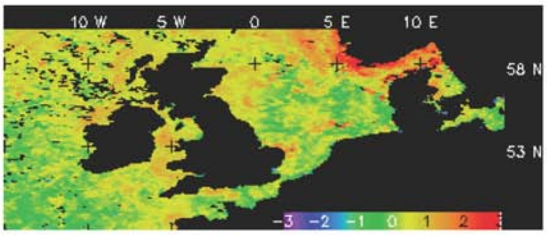
January 1999



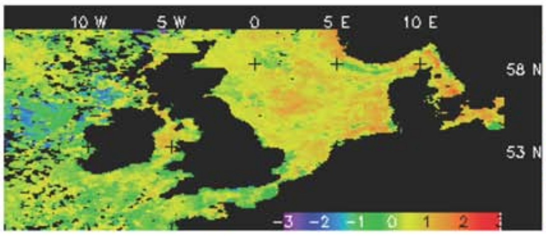
April 1999



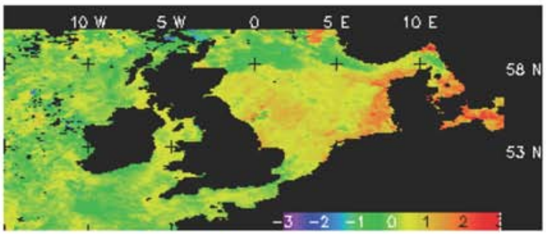
July 1999



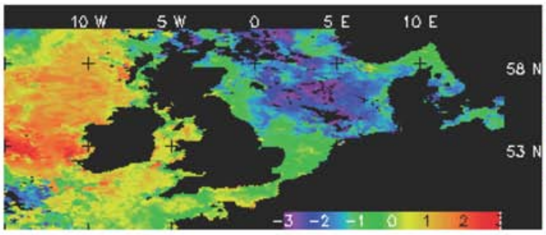
October 1999



January 2000



April 2000



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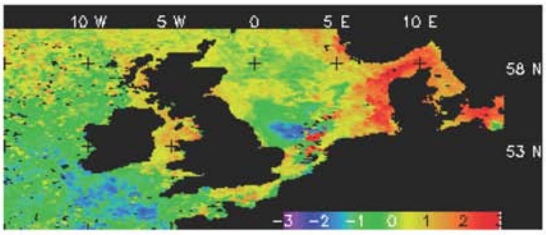

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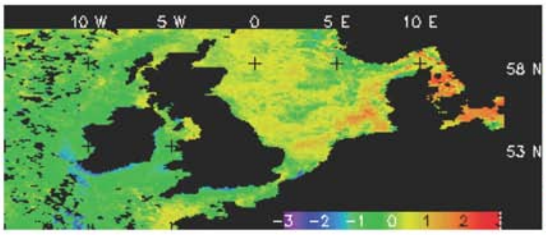
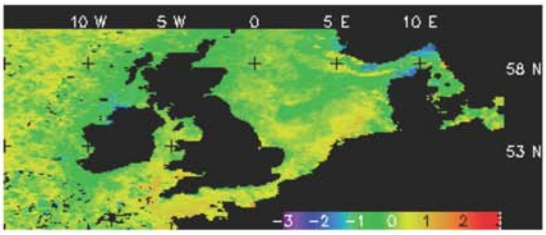
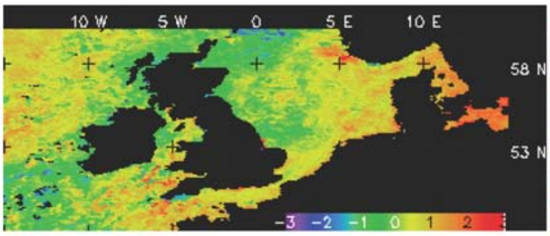


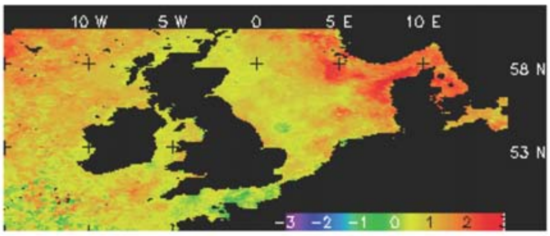
January 2001



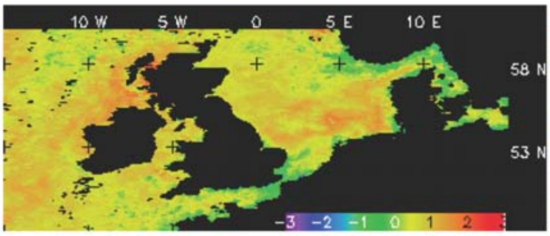
April 2001



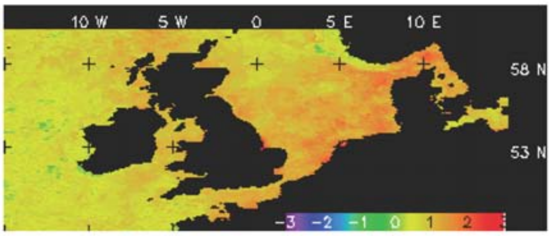
July 2001



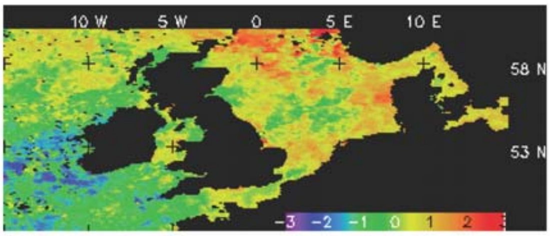
October 2001



January 2002



April 2002



July 2002

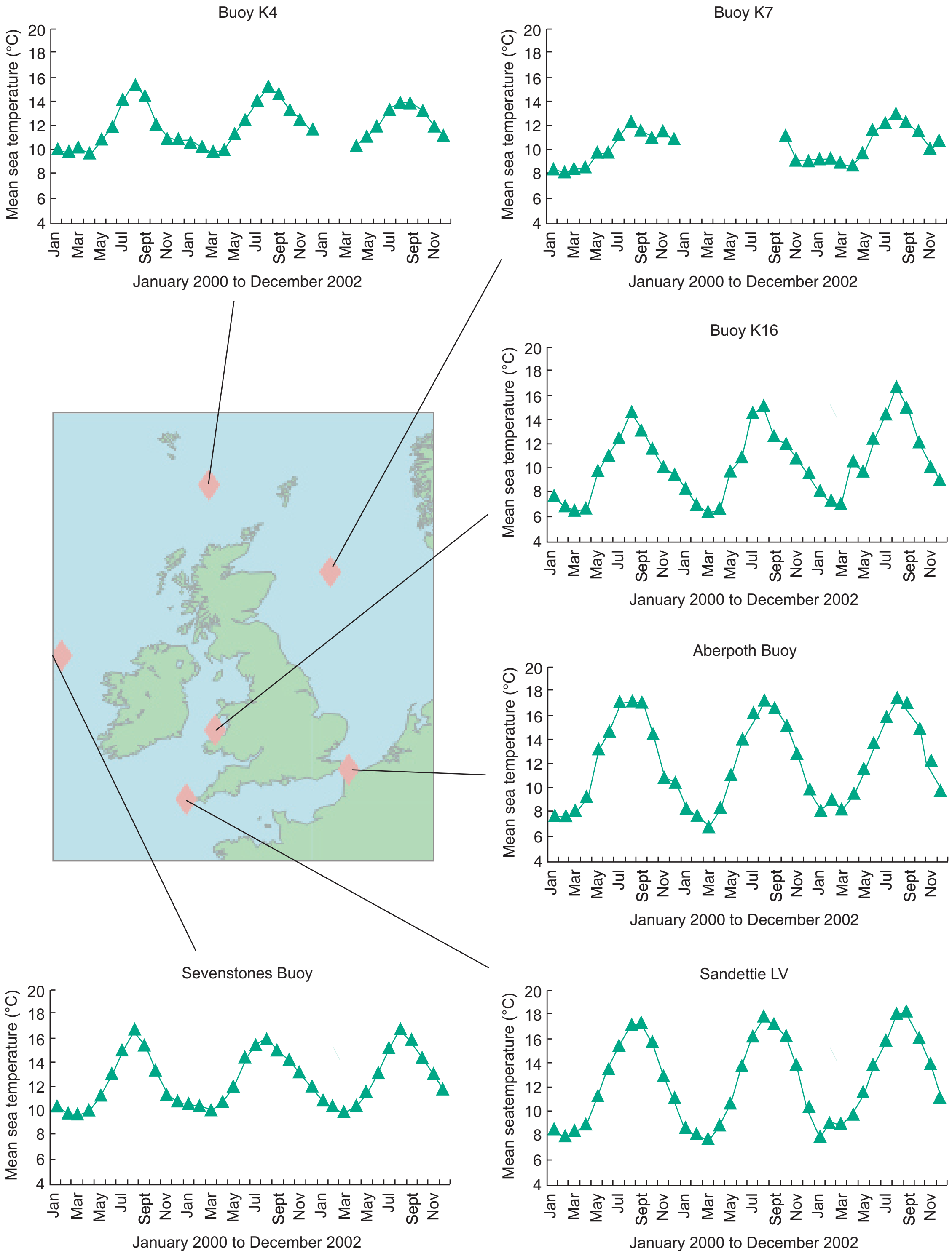
Refer to the web version of this report to see satellite images of temperature overlain with point data (using STEMgis).

Also link to the STEMgis ‘map’ (using Scalable Vector Graphics) of all coastal sea temperature data.

Refer to the web version of this report to see a map of temperature and salinity data in UK waters (using STEMgis)

Figures 4.5 to 4.10 show mean sea temperature data for 2000 – 2002 from selected stations of the Met Office’s Marine Automatic Weather Station Network (MAWS) Network.

For an animation of mean sea temperature data from the MAWS network (using STEMgis) refer to the web version of this report.



Figures 4.5-4.10. Mean sea temperature data from MAWS network. Data from Buoy K16 (North Sea), Light Vessel Sandettie (English Channel), Light Vessel Seven Stones (Celtic Sea), Buoy Aberporth (Bristol Channel), Buoy K4 (NE Atlantic), Buoy K7 (N Scotland). Courtesy of the Met Office

4.3.1 NORTH SEA

The SST of the North Sea is mainly controlled by local and regional weather conditions, i.e. local solar heating and heat exchange with the atmosphere. However, temperature changes also can reflect the influence of the NAO on the movement of Atlantic water into the North Sea and the meteorological forcing of the ocean-atmosphere heat exchange, with a positive Index usually corresponding with warmer temperatures. In particular, changes in winter temperatures are closely linked with changes in the NAO Winter Index - Loewe (1996) states that the NAO accounts for 40-50 per cent of the winter sea surface temperature variability in the southern North Sea.

Figure 4.11 shows that in the Fair Isle Current, temperature increased during 2002 to reach the highest values since the data set began in 1972. A cyclical variability is evident since 1977 (ICES, 2003a).

Figures 4.12 and 4.13 show winter and summer SST data respectively from 1950 to 2002, averaged over the northern North Sea (55-60°N, 5W-5°E). There is a clear warming trend in winter SST since the early 1980s, with a significant warming of about 1°C in the 1980s. This coincides with the persistence of westerly-type weather conditions over the area during this period, advecting warm water into the area and reducing the cooling effect of easterly winds. However summer SST seems to be more stable, showing an increase of about 0.5°C since the early 1980s (Dooley, 2003).

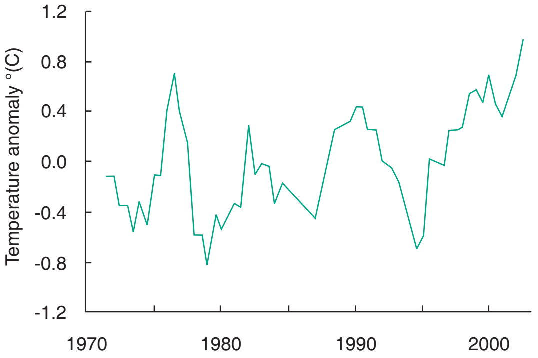


Figure 4.11. Fair Isle Current Water temperature anomalies. Nominal position: 59° 17'N, 2° 10'W. Courtesy of FRS

Figures 4.14 to 4.20 indicate that winter bottom temperatures at all North Sea fishing grounds show a long-term warming trend since a cool period in the late 1970s (Dooley, 2003; FRS, 2003). The low temperature seen in 1979 at a number of central North Sea locations arose from the northwestward spread of water from the southern North Sea due to very persistent and strong southeasterly winds (Dooley, 2003).

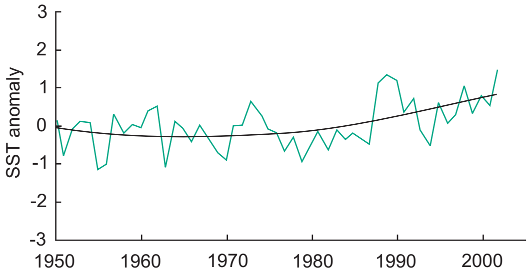


Figure 4.12. Winter (January to March) SST Anomaly, 1950-2002, northern North Sea (55-60°N, 5°W-5°E). Time series produced by averaging the winter data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

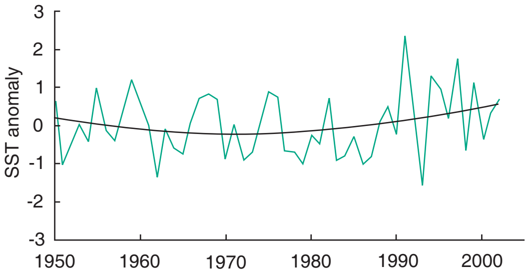
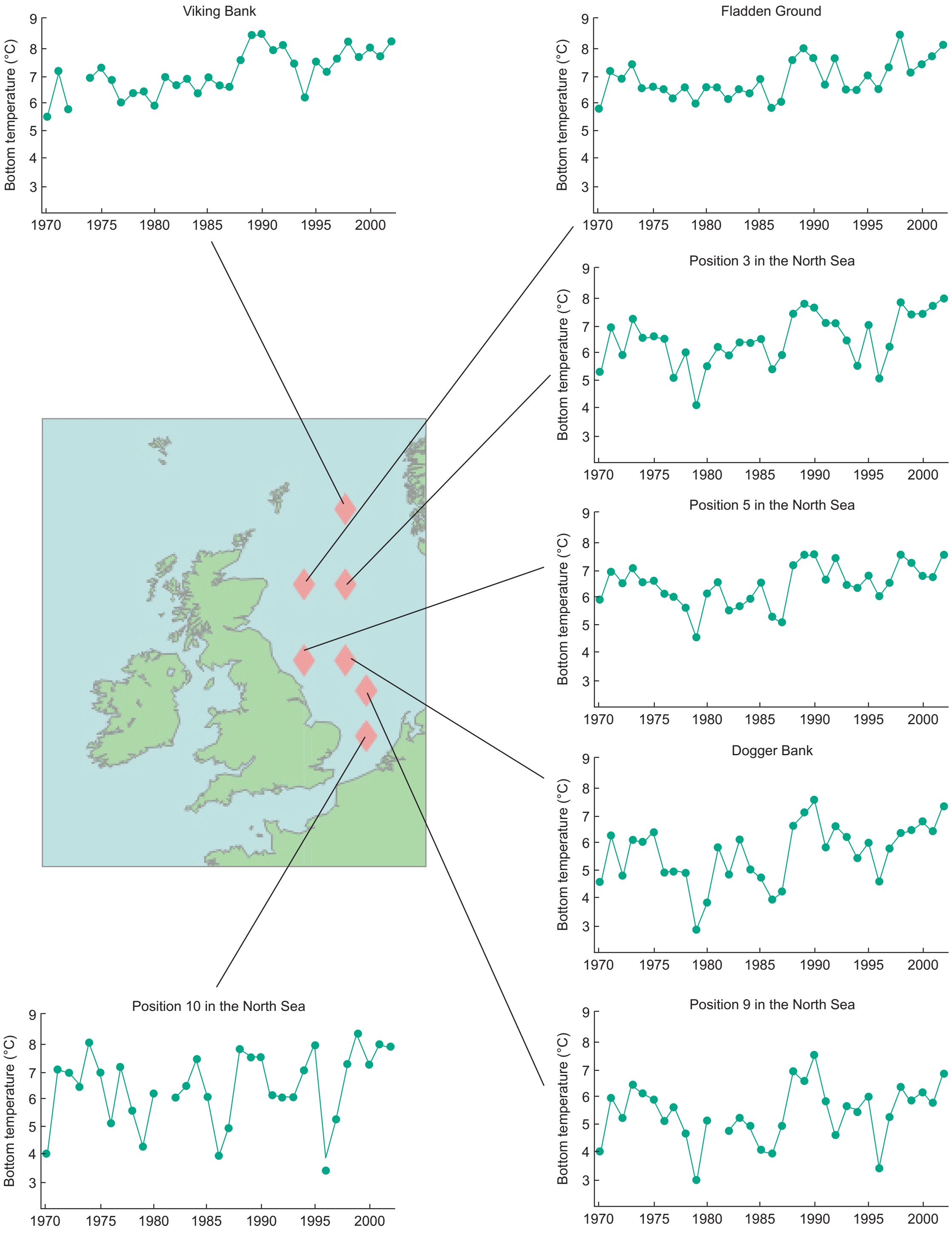


Figure 4.13. Summer (July to September) SST Anomaly, 1950-2002, northern North Sea (55-60°N, 5°W-5°E). Time series produced by averaging the summer data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre



Figures 4.14-4.20. Bottom Temperature time series in the North Sea, 1970-2002. Time series based on IBTS data and produced by averaging the data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

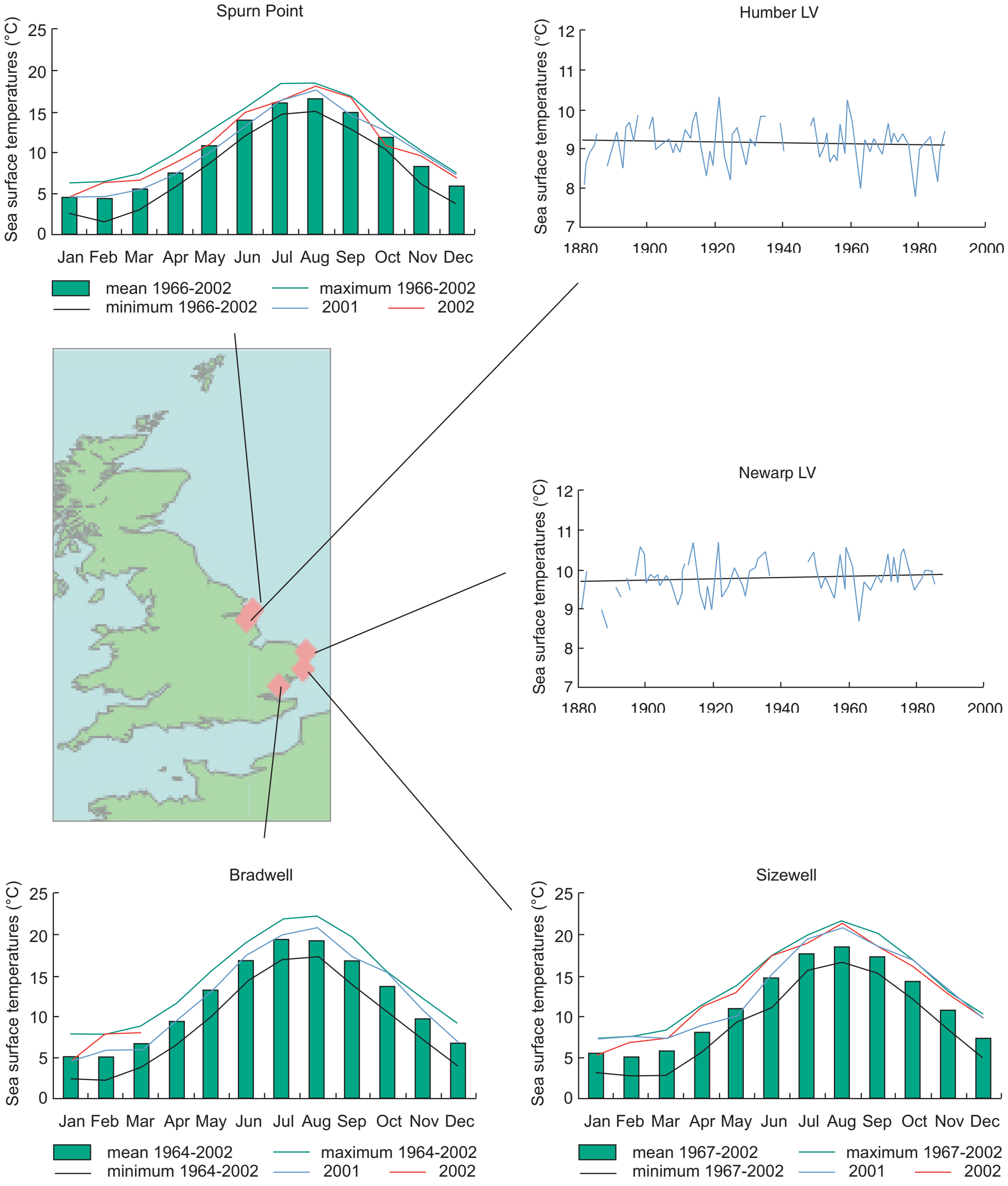
Table 4.2. Trends in near-bed temperature in the North Sea

	Nominal position	Data Span	Trend (°C/decade)
North Sea (Winter) Near-bed Temperature			
Viking Bank	60.0°N 02.0°E	1970-2002	+ 0.58
Fladden Ground	57.5°N 00.0°E	1970-2002	+ 0.37
Position 3	57.5°N 02.0°E	1970-2002	+ 0.44
Position 5	55.0°N 00.0°E	1970-2002	+ 0.29
Dogger Bank	55.0°N 02.0°E	1970-2002	+ 0.48
Position 9	54.0°N 03.0°E	1970-2002	+ 0.24
Position 10	52.5°N 03.0°E	1970-2002	+ 0.33

Table 4.2 indicates that the rate of warming since 1970 is between about 0.3°C and 0.6°C per decade since a cool period in the late 1970s.

In 2001, the area-averaged mean SST of the North Sea in 2001 was 10.4°C (the same as in 2000), making it the sixth warmest year in records dating from 1971 (ICES, 2002). This was surpassed in 2002, when the area-averaged annual mean SST was 11.0°C (ICES 2003a). Overall, the integrated water column temperature in the North Sea is warmer now than in the 1960s (Brown, personal communication).

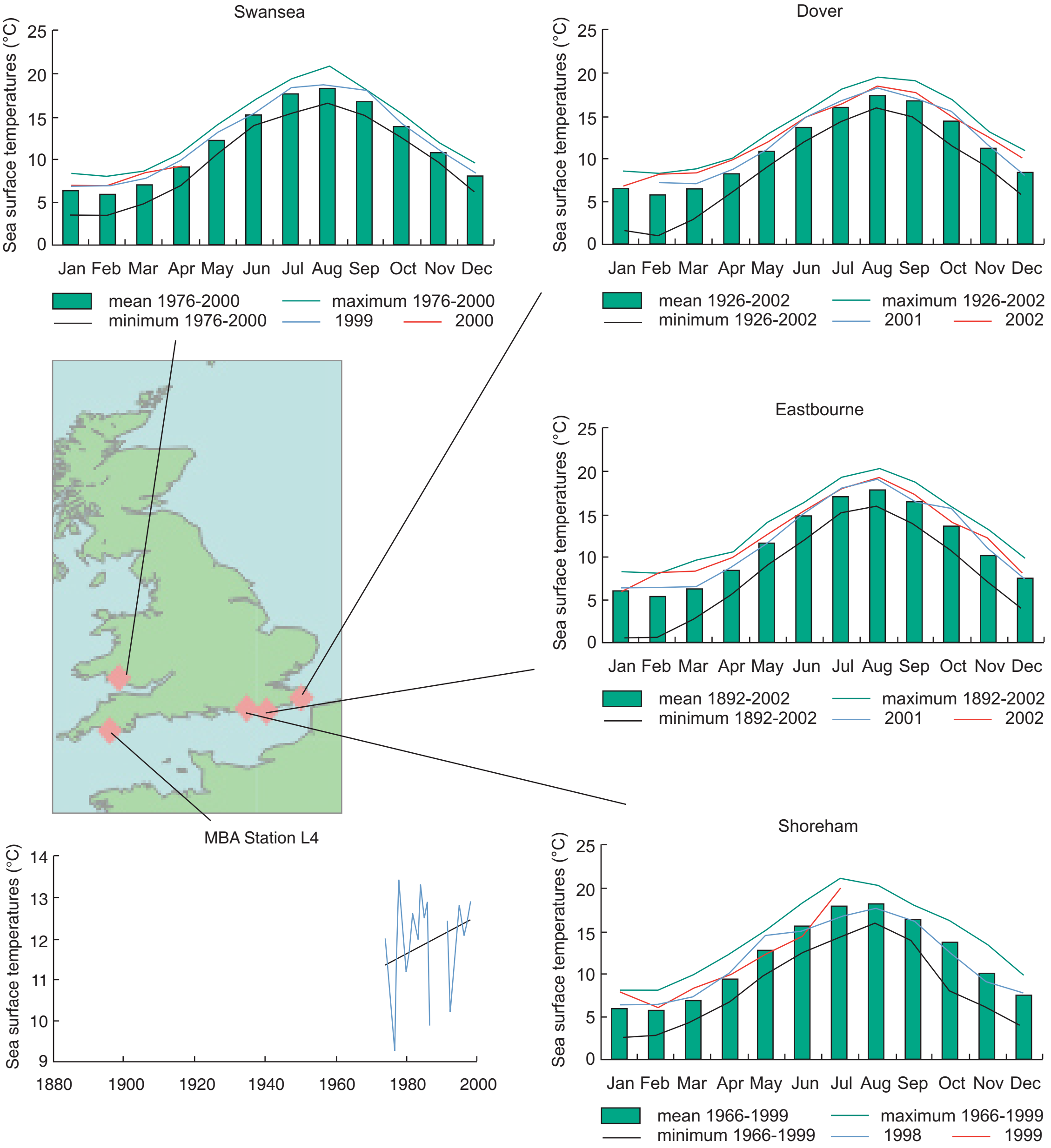
For coastal locations in the region, Figures 4.21 to 4.25 display an analysis of the monthly means of SST for the years 2001 and 2002, with long-term minima, maxima and monthly means. Mean temperatures for 2001 and 2002 were above the long-term averages at most stations.



Figures 4.21-4.25. Monthly mean temperatures at UK coastal sites: Humber, Spurn Point, Newarp, Sizewell, Bradwell. Courtesy of CEFAS. Data was supplied to CEFAS by the Met Office (Humber, Newarp), MAFF (now Defra, Spurn Point), British Energy Generation BNFL & CEGB (Sizewell), BNFL & CEGB (Bradwell)

4.3.2 ENGLISH CHANNEL AND CELTIC SEA, INCLUDING BRISTOL CHANNEL

For coastal locations in the region, Figures 4.26 to 4.30 show an analysis of the monthly means of SST for the years 2001 and 2002, with long-term minima, maxima and monthly means. Mean temperatures for 2001 and 2002 were above the long-term averages at most stations.



Figures 4.26-4.30. Monthly mean temperatures at UK coastal sites: Dover, Eastbourne, Shoreham-by-sea, Swansea. Dover (2001 & 2002) and Eastbourne (2001 & 2002) data are courtesy of CEFAS. Dover historical data is courtesy of Dover District Council. Eastbourne historical data is courtesy of Eastbourne Borough Council. Data for Shoreham and Swansea are courtesy of MAFF (now DEFRA).

4.3.3 IRISH SEA

For a 3D animation of changes in temperature structure in the Irish Sea during 1995 refer to the web version of this report [AVI animation, 6.6MB]. Courtesy of Alex Souza, POL.

Figures 4.31 and 4.32 show winter and summer SST anomalies in the Irish Sea from 1950 to 2002, averaged over the area 53°-55°N and 6°-4°W. The dominance of the warming that has occurred since the 1980s over all UK waters is clear in the winter record. However, the observation coverage in the Irish Sea decreased significantly from the early 1980s onwards, which may explain the significant increase in variability in the mean since then and the apparent downturn in summer SST since the 1980s (Dooley, 2003).

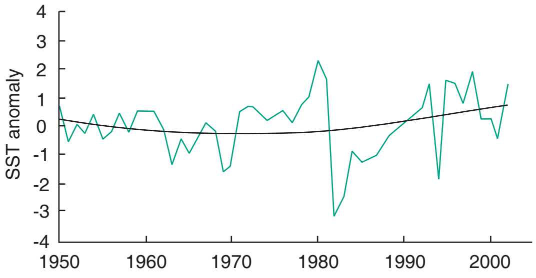


Figure 4.31. Winter (January to March) SST Anomaly, 1950-2002, Irish Sea (53-55°N, 6-4°W) Time series produced by averaging the winter data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

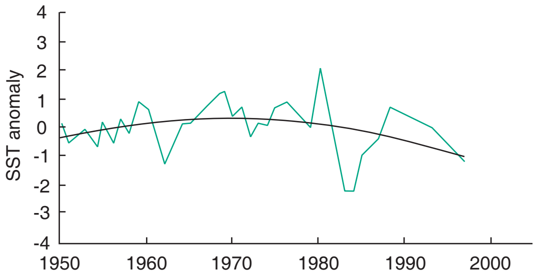


Figure 4.32. Summer (July to September) SST Anomaly, 1950-2002, Irish Sea (53-55°N, 6-4°W) Time series produced by averaging the summer data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

Figure 4.3 (above) indicates that, together with the North Sea, the Irish Sea has experienced the most pronounced warming trend in UK waters, of between 0.5°C and 1.0°C per decade (FRS, 2003); albeit rising from the minimum values in the early 1980s.

For coastal locations in the region, Figures 4.33 to 4.34 show an analysis of the monthly means of SST for the years 2001 and 2002, with long-term minima, maxima and monthly means. Mean temperatures for 2001 and 2002 were above the long-term averages at most stations.

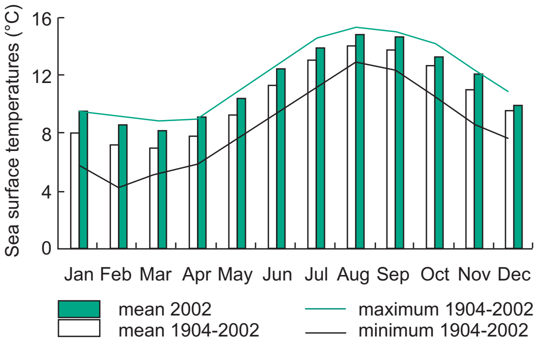


Figure 4.33. Monthly mean temperature at Port Erin (Isle of Man). Courtesy of Theresa Shammon, Port Erin Marine Laboratory

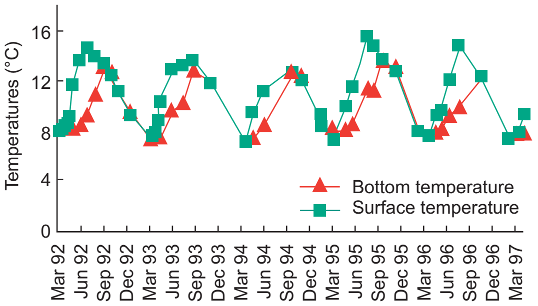


Figure 4.34a. Monthly mean temperature at Station 38 in the Irish Sea (53°50'N, 5°34'W). Courtesy of DARD(NI)

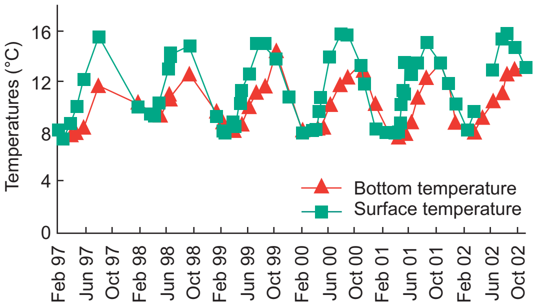


Figure 4.34b. Monthly mean temperature at Station 38a in the Irish Sea (53°47'N, 5°38'W). Courtesy of DARD(NI)

4.3.4 MINCHES, WEST SCOTLAND, SCOTTISH CONTINENTAL SHELF AND FAROE SHETLAND CHANNEL

The Scottish and Northern Ireland Forum for Environmental Research (SNIFFER, 2000) produced three regional sea temperature indices, a West Coast Index, a Shelf Edge Index and a North Sea Index, using both data measured in-situ along ocean transects at multiple depths (except for the West Coast Index) and through use of a global 1° resolution long-term sea surface temperature data set. The Shelf Edge Index (the only long-term index) showed warming of between 0.12°C and 0.29°C over the past century (depending on the use of in-situ measurements or the global sea-surface temperature data set).

Figure 4.35 shows that the trend in monthly mean sea temperature has been increasing since 1953 at Millport, Fair Isle and Peterhead.

Figure 4.36 shows monthly temperature anomalies from 1981 to 1998 in the Tiree Passage, a SW-NE orientated strait between the Isle of Mull to the southeast and the Isles of Coll and Tiree to the northwest, on the western coast of Scotland.

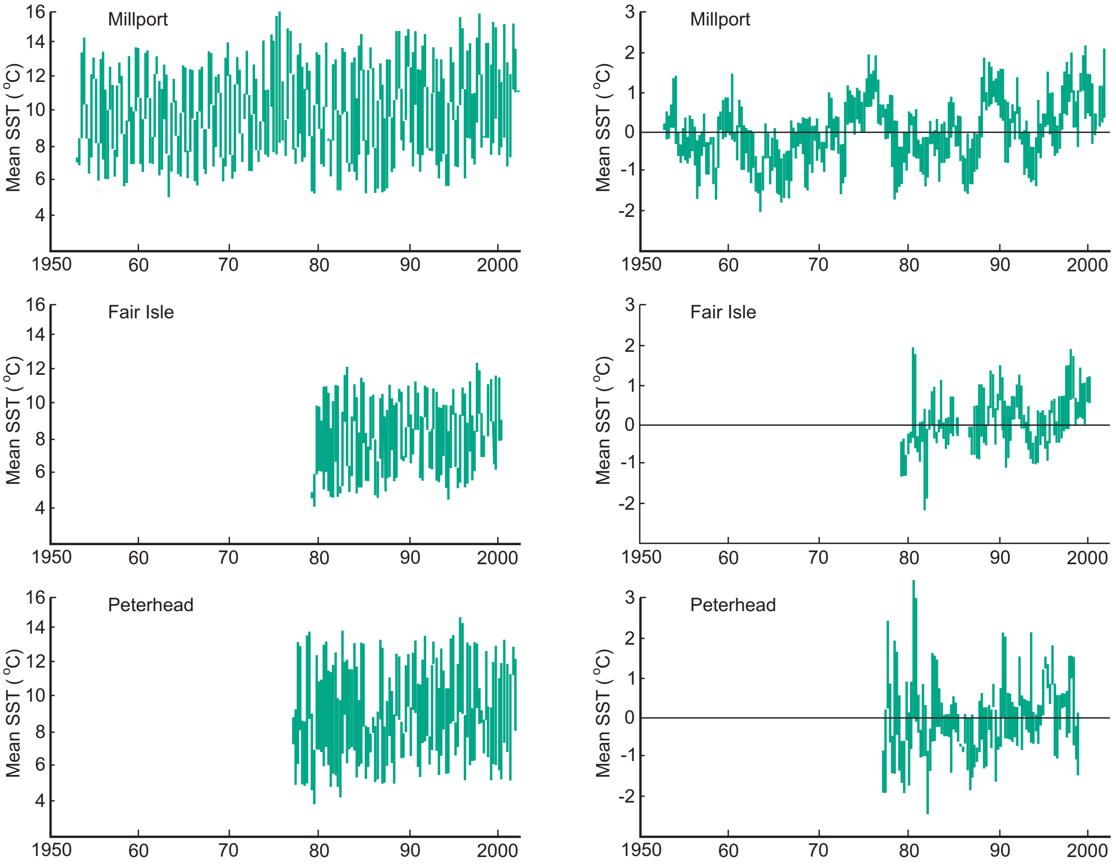


Figure 4.35. Monthly mean SST at Millport, Fair Isle and Peterhead. The large change during the year due to seasonal changes has been removed by subtracting the long-term monthly averages.
Courtesy of FRS (Source of data: Millport Marine Biological Station, Fair Isle Marine Environment & Tourism Initiative, Scottish and Southern Energy plc)

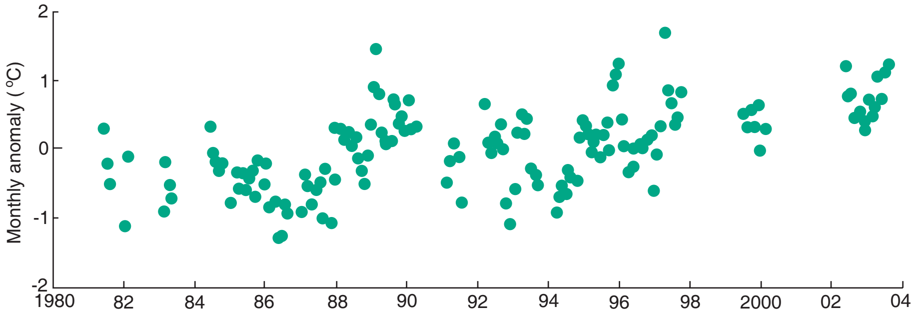


Figure 4.36. Monthly temperature anomalies in the Tiree Passage. Courtesy of Colin Griffiths, DML

With the exception of occasional episodes the water column at the mooring site is well mixed or weakly stratified throughout the year. The mean water temperature was 10.1°C over the 22 years and the dominant mode of variance in the temperature record is the seasonal cycle, with amplitude of 3.2°C. Whilst the dominant modes of variability are as expected for a shelf location the seasonally adjusted temperature anomalies exhibit patterns similar to those reported in the NE Atlantic by Holliday (2003). This serves to emphasise the important role of Atlantic water in the Scottish Coastal Current. Comparing the monthly temperature anomalies with the NE Atlantic upper layer heat content anomalies shows that both time series had highs in the late 1980s and 1990s and lows in the early 1980s and mid 1990s (Inall and Griffiths, 2003).

Over the last four decades, Atlantic waters in the Faroe Shetland Channel have become warmer with temperatures rising from a minimum in the late 1960s at a rate of approximately 0.3°C/decade (see Figure 4.37). The temperature decreased slightly in 2001 but the trend reversed during 2002 and values increased again (ICES, 2002 and ICES, 2003a).

4.3.5 ROCKALL TROUGH AND BANK AND ATLANTIC NORTH WEST APPROACHES

Figure 4.38 shows de-seasoned upper ocean (0-800 m) temperature anomalies from the Rockall Trough, from 1975 onwards.

The early part of the 1990s was characterised by relatively low temperatures, reaching a low in May 1994. In contrast, the 1990s were characterised by increasing temperature with the maximum temperature anomaly occurring in 2002; probably caused by an influx of unusually warm water into the region (Holliday, 2003; ICES, 2003a). Holliday (2003) refers to sea surface observations made from 1948 onwards (Ellett and Jones, 1994), showing that the decade is not perhaps as unusual as indicated by the more recent time-series; the highest temperatures reached in the 1990s were similar to the peak reached in the1960s following a decade of increasing values.

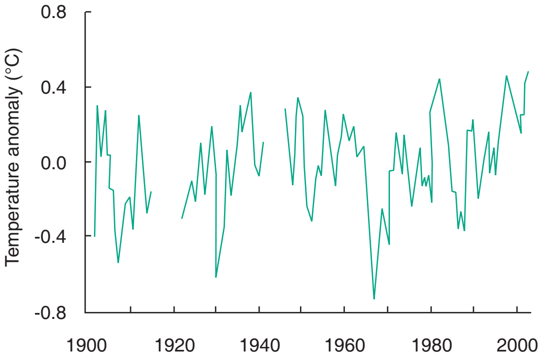


Figure 4.37. Temperature anomalies in the Faroe Shetland Channel. Temperature anomaly (°C) in the North Atlantic Water (NAW) in the Slope Current. Courtesy of Sarah Hughes, FRS. From ICES (2003a), see http://www.ices.dk/status/clim0203/IAOCSS2002.PDF

During 2001, the Rockall Trough began to show signs of cooling (and freshening), following a peak in temperature (and salinity) in 1998–2000. However, the temperature (and salinity) remained high compared to the long-term mean,

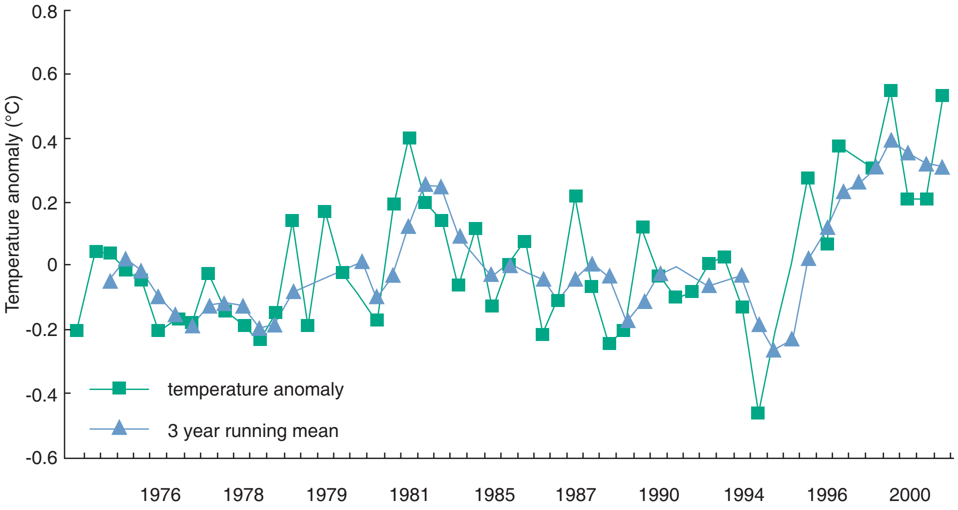


Figure 4.38. Temperature anomalies from the Rockall Trough. Data has been averaged across the section, the seasonal cycle removed and a three-point running mean included. Nominal Position: 60° 30'N, 3° 00'W. Courtesy of Penny Holliday, SOC

with values similar to previous peaks in the early 1980s (ICES, 2002).

Holliday (2003) points out that the late nineties have seen a warming phase similar to the one observed in the late fifties but that the significance of the present warming episode is unclear. She states that the NAO Winter Index shows no statistically significant correlation with the time-series of subsurface temperature (or salinity); the Rockall Trough lying in a region of low to zero correlation, between the high positive correlation to the south and east and high negative correlation to the west (Rodwell *et al*., 1999). Therefore she concludes that the conditions in the Rockall Trough do not appear to be directly related to atmospheric conditions, as indicated by the NAO Index; or to variations in local net atmospheric heat fluxes. Instead, she considers that the variations in temperature are caused by varying inputs of the water masses to the south of the region - central North Atlantic Water, Mediterranean outflow Water, Western North Atlantic Water and SubArctic Intermediate water.

4.4 REFERENCES

Beaugrand, G., Reid, P.C., Ibañez, F., Lindley, J.A. and Edwards, M. (2002). Reorganization of North Atlantic Marine Copepod Biodiversity and Climate. *Science*, 296: 1692-1694.

Bryden, H.L. and Imawaki, S. (2001). Ocean heat transport in: Siedler, G., Church, J. and Gould, J., Editors. Ocean Circulation and Climate: Observing and Modelling the Global Ocean, San Diego CA, Academic Press, 2001, 455-474.

Dooley, H. (2003). Formal communication from Hydrographer of the International Council

Edwards, M., Reid, P.C., and Planque, B. 2001. Long-term and regional variability of phytoplankton biomass in the Northeast Atlantic (1960-1995). *ICES Journal of Marine Science*, 58: 39-49.

Ellett, D.J. and Jones, S.R. (1994). Surface temperature and salinity time-series from the Rockall Channel. MAFF Directorate of Fisheries Research, Lowestoft. 24pp.

FRS (2003). Scottish Ocean Climate Status Report 2000 - 2001. Fisheries Research Services Report 05/03, Marine Laboratory, Aberdeen, 20pp.

Holliday, N.P. (2003). Extremes of temperature and salinity during the 1990s in the northern Rockall Trough: results from the 'Ellett line'. *ICES Marine Science Symposia*, 219: 95-101.

Hughes, S.L., Turrell, W.R. and Newton, A. (2003). Hydrobiological variability on the northwest European continental shelf during the 1990s and its relation to changes in fish stocks. ICES *Marine Science Symposia*, 219: 421-425.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. and Hill, S. (2002). Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK. 120pp.

ICES (2001). The Annual ICES Ocean Climate Status Summary 2000/2001. Prepared by the Working Group on Oceanic Hydrography, ICES, Copenhagen, Denmark. (Eds. Turrell, W. and Penny Holliday, N.) Retrieved 20th May 2003 from the World Wide Web: http://www.ices.dk/status/clim0001/iaocss2000.pdf

ICES (2002). The Annual ICES Ocean Climate Status Summary 2001/2002. Prepared by the Working Group on Oceanic Hydrography, ICES, Copenhagen, Denmark. (Eds. Turrell, W. and Penny Holliday, N.) Retrieved 20th May 2003 from the World Wide Web: http://www.ices.dk/status/clim0102/IOACSS01.PDF

ICES (2003a). The 2002/2003 ICES Annual Ocean Climate Status Summary. Prepared by the Working Group on Oceanic Hydrography, ICES, Copenhagen, Denmark. (Editors: Hughes, S.L. and Lavín, A.) Retrieved 4th October 2003 from the World Wide Web: http://www.ices.dk/status/clim0203/IAOCSS2002.PDF

Inall, M. and Griffiths, C. (2003). The Tiree Passage Time Series: 1981 - 2003. SAMS Internal Report No. 238.

IPCC (2001a). Climate Change 2001, the scientific basis. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M , van der Linden, P.J. and Xiaosu, D. Editors, Cambridge Univ. Press., Cambridge, 994pp.

Levitus, S., Antonov, J.I., Boyer, T.P. and Stephens, S. (2000). *Warming of the World Ocean. Science*, 287: 2225-2229.

Loewe, P. (1996). Surface temperatures of the North Sea in 1996. *Deutsche Hydrographisce Zeitschrift*, 48: 175–184.

Rodwell, M.J., Rowell, D.P. and Folland, C.K. (1999) Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. *Nature*, 398: 320-323.

SNIFFER (2000). Development of Temperature Indices for Scotland and Northern Ireland. Report number SR(99)07F. SNIFFER, 11/13 Cumberland Street Edinburgh EH3 6RT.

4.5 LIST OF LINKS TO MONITORING NETWORKS AND DATA SETS

Online search interfaces for catalogues and inventories maintained by the IACMST's Marine Environmental Data Network
http://www.oceannet.org

Argo project
http://www.metoffice.com/research/ocean/argo

CEFAS Coastal Temperature Network
http://www.cefas.co.uk/publications/catalogue.htm

CEFAS Marine Environmental Real-time Observation System (MEROS)
http://www.cefas.co.uk/monitoring

Continuous Plankton Recorder (CPR) programme
http://www.sahfos.org/standard_areas.htm

DARD(NI) Coastal Monitoring Programme http://www.afsni.ac.uk/services/coastalmonitoring

'Ellett' Line (Sound of Mull to Rockall) and the extended 'Ellett' Line (Rockall to Iceland).
http://www.soc.soton.ac.uk/GDD/hydro/nph/ellett/index.php
and
http://www.soc.soton.ac.uk/GDD/hydro/nph/ellett/extended.php
Faroe Shetland Channel surveys
http://www.marlab.ac.uk

FRS Coastal Long-term Monitoring programme
http://www.marlab.ac.uk

HumberNet
http://www.northseanet.co.uk/humber/digitaldisplay.htm
and
http://www.northseanet.co.uk

ICES International Bottom Trawl Survey (IBTS)
http://www.ices.dk/ocean/INDEX.HTM

Liverpool Bay Coastal Observatory
http://cobs.pol.ac.uk

Met Office's Hadley Centre for Climate Prediction and Research
http://www.metoffice.com/research/hadleycentre/obsdata

Met Office's Marine Automatic Weather Station (MAWS) Network
http://www.metoffice.com/research/ocean/goos/maws.html

Port Erin Marine Laboratory (PEML) programme
http://www.liverpool.ac.uk/plankton

Satellite missions
http://daac.gsfc.nasa.gov/data/dataset/CZCS/
http://daac.gsfc.nasa.gov/data/datset/SEAWIFS/
http://www.soc.soton.ac.uk/lso/noindex/lso_data.php

SOC Ferry-Box project
http://www.soc.soton.ac.uk/ops/ferrybox_index.php

Tiree Passage time series
http://www.sams.ac.uk/dml/projects/physics

UK National Marine Monitoring Programme (NMMP and NMMP2)
http://www.marlab.ac.uk
and
http://www.defra.gov.uk/environment/marine/mpmmg/index.htm#1

5. Salinity

SUMMARY OF CHANGES AND TRENDS

- Atlantic waters and adjacent shelf areas had low winter and summer sea surface salinity (SSS) in the mid-late 1970s (associated with the passage of the Great Salinity Anomaly (GSA)), followed by three decades of large inter-annual variability.
- Salinity records from the Faroe Shetland Channel and the Ellett line indicate a recent trend to high salinity.
- SSS averaged over the northern North Sea from 1950 to 2002 shows decreasing salinity since the 1970s and is reflected by observations at fixed locations in the Fair Isle Current and the North Sea fishing grounds.
- There is no discernible trend in mean SSS in the English Channel from 1900 to the early 1980s.
- SSS averaged over the Irish Sea from 1950 to 2002 shows a decrease in both winter and summer.

5.1 INTRODUCTION

The ocean circulation is determined primarily by the forcing due to momentum, heat and water fluxes to and from the atmosphere, and by the distributions of salinity (and temperature) in the ocean that determine its density structure. Changes in salinity cause changes in density and hence in density currents, thus affecting large scale thermo-haline circulation and local dynamics in coastal and estuarine locations. In particular, the density structure affects the 'meso-scale' dynamics of fronts and eddies, which are the most energetic motions in the ocean.

Salinity plays an important role in marine ecosystems. For example, nitrogen is a key element limiting primary production and its release from estuarine sediments alters in response to changes in overlying water salinity. An increase in salinity causes a decrease in the rate of denitrification and hence a nitrogen loss, thus determining the year-to-year variation in primary productivity, particularly in beginning and maintaining summer phytoplankton blooms. Also, many organisms are adapted to certain salinity conditions, especially in saline pool, lagoon and estuarine locations. The egg and larval stages of some fish species also depend on salinity tolerance. Descriptions of the monitoring networks that regularly measure salinity are given in Chapter 1, including details of how to access near real-time data. Also refer to the list of links to monitoring networks and data sets at the end of this chapter (section 5.).

5.2 NORTH ATLANTIC

Figures 5.1 and 5.2 show winter and summer sea surface salinity (SSS) data respectively, averaged over the eastern North Atlantic (55-6°N, 25-15°W). (The averaging of salinity should normally be done over small regions within a water mass, but this area lies in an area of weak salinity gradients, particularly in winter when deep convection produces a 600 m deep homogeneous water column (Dooley, 2003)). The low values observed in both winter and summer during the 1970s are associated with the Great Salinity Anomaly (GSA). This is believed to have been caused by the arrival of 'fresher' water that was created in the Arctic in the 1960s and then had drifted across the Atlantic in the prevailing current, arriving in UK waters in the mid-1970s (Dickson *et al.*, 1988). The GSA 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 in the past, 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.

The somewhat higher interannual variability observed during the late 1980s is probably a manifestation of the very low number of

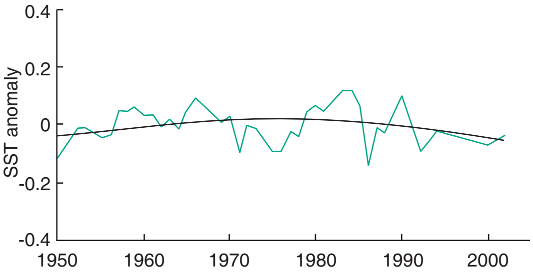


Figure 5.1. Winter (January to March) SSS Anomaly, 1950-2002, eastern North Atlantic (55-60°N, 25-15°W). Time series produced by averaging the winter data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

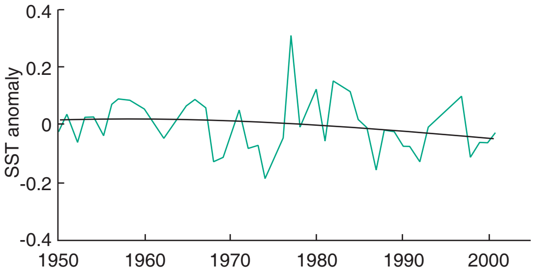


Figure 5.2. Summer (July to September) SSS Anomaly, 1950-2002, eastern North Atlantic (55-60°N, 25-15°W). Time series produced by averaging the summer data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend basedon a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

observations at this time, rather than a reflection of actual conditions (Dooley, 2003). During 2002 salinity was higher than the long-term average in most areas of the North Atlantic and increased to the highest levels observed in over a decade (ICES 2003a).

5.3 UK WATERS

Only a few long-term time series exist for UK waters and these do not indicate any overall long-term trend. Records from the Atlantic waters around the UK (Rockall and the Faroe Shetland Channel) and the areas on the shelf which are most influenced directly by in-flowing oceanic waters (Fair Isle, E1) reveal a general pattern of low salinity in the mid-late 1970s. This period was influenced by the passage of the GSA (see section 2 above) as it circulated around the Atlantic and Nordic Seas, and was then followed by three decades of quite large inter-annual variability probably closely associated with changes in the NAO. In the shallower areas of the North Sea and Irish Sea, the salinity is much more dependent on local runoff from land and local evaporation/precipitation changes, and hence is much more variable.

Refer to the web version of this report to see an interactive map of salinity and temperature data in UK waters using STEMgis.

5.3.1 NORTH SEA

The salinity characteristics of the North Sea are strongly influenced by freshwater exchange via the atmosphere and rivers, and also by water inflow from the North Atlantic. The North Atlantic Current brings oceanic water of high salinity into the northern North Sea in two branches: an inflow through the Fair Isle channel off the north of Scotland and a more significant inflow along the western slope of the Norwegian Trench. The Norwegian Coastal Current forms a contrasting outflow along the eastern side of the Trench, carrying less saline surface water from fjords and rivers northward. In addition to the oceanic inflow to the northern North Sea, the saline water of Atlantic origin also penetrates into the southern North Sea through the Dover Straits (ICES, 2003b). The main input of fresh water into the North Sea is from rivers discharging along its southern coast, so the southern North Sea is less salty than the northern North Sea. The salinity of the North Sea reflects the influence of the NAO on the movement of Atlantic water into the North Sea and the meteorological forcing of the ocean-atmosphere heat exchange and resulting precipitation (ICES, 2003a). Strongly positive values of the NAO Index are linked to low surface summer salinity and strongly negative values to high surface summer salinity.

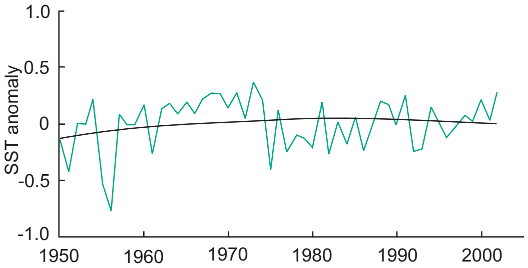


Figure 5.3. Winter (January to March) SSS Anomaly, 1950-2002, northern North Sea (55-60°N, 5°W-5°E). Time series produced by averaging the winter data sets by year. Anomalies produced by subtracting the mean calculated for the whole period.Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

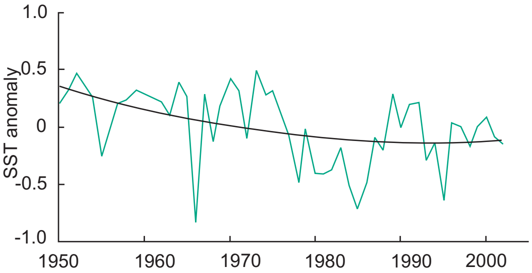


Figure 5.4. Summer (July to September) SSS Anomaly, 1950-2002, northern North Sea (55-60°N, 5°W-5°E). Time series produced by averaging the summer data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

Only a few really long salinity time series exist for the North Sea but none in UK waters. A salinity series measured at Helgoland in the German Bight since 1873 shows no significant trend over the 120 years of observations. Relatively high salinities were observed in the 1920s, at the end of the 1960s, and from 1989-95. In the late 1970s, and for most of the 1980s, the salinity was relatively low (OSPAR, 2000).

Figures 5.3 and 5.4 show time series of SSS anomalies averaged over the northern North Sea from 1950 to 2002. The salinity is higher in winter, reflecting changes in atmospheric forcing; in particular, the precipitation-evaporation balance of these seasons, with evaporation over the sea much higher in winter than summer (Dooley, 2003). The averaging of salinity should be done over small regions within a water mass and this area is one of significant spatial salinity gradients, both in winter and summer. However, the apparent freshening (i.e. decreasing salinity) since the 1970s, shown especially in the summer time series, is reflected at observations at fixed locations - see figure 5.5 (Fair Isle Current) and figures 5.6 to 5.12 (North Sea fishing grounds).

North Sea salinities returned to the long-term average values in 2002 following the low values observed in 2001, which were probably due to stronger than normal run-off from the continental rivers (ICES, 2002; ICES, 2003a).

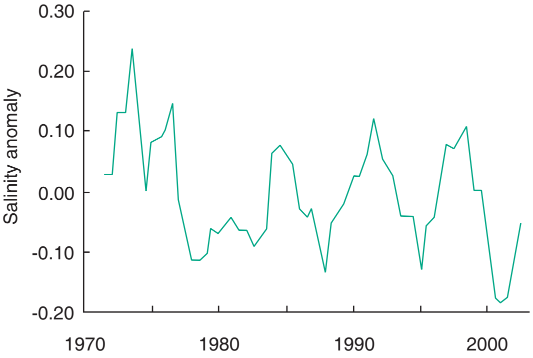
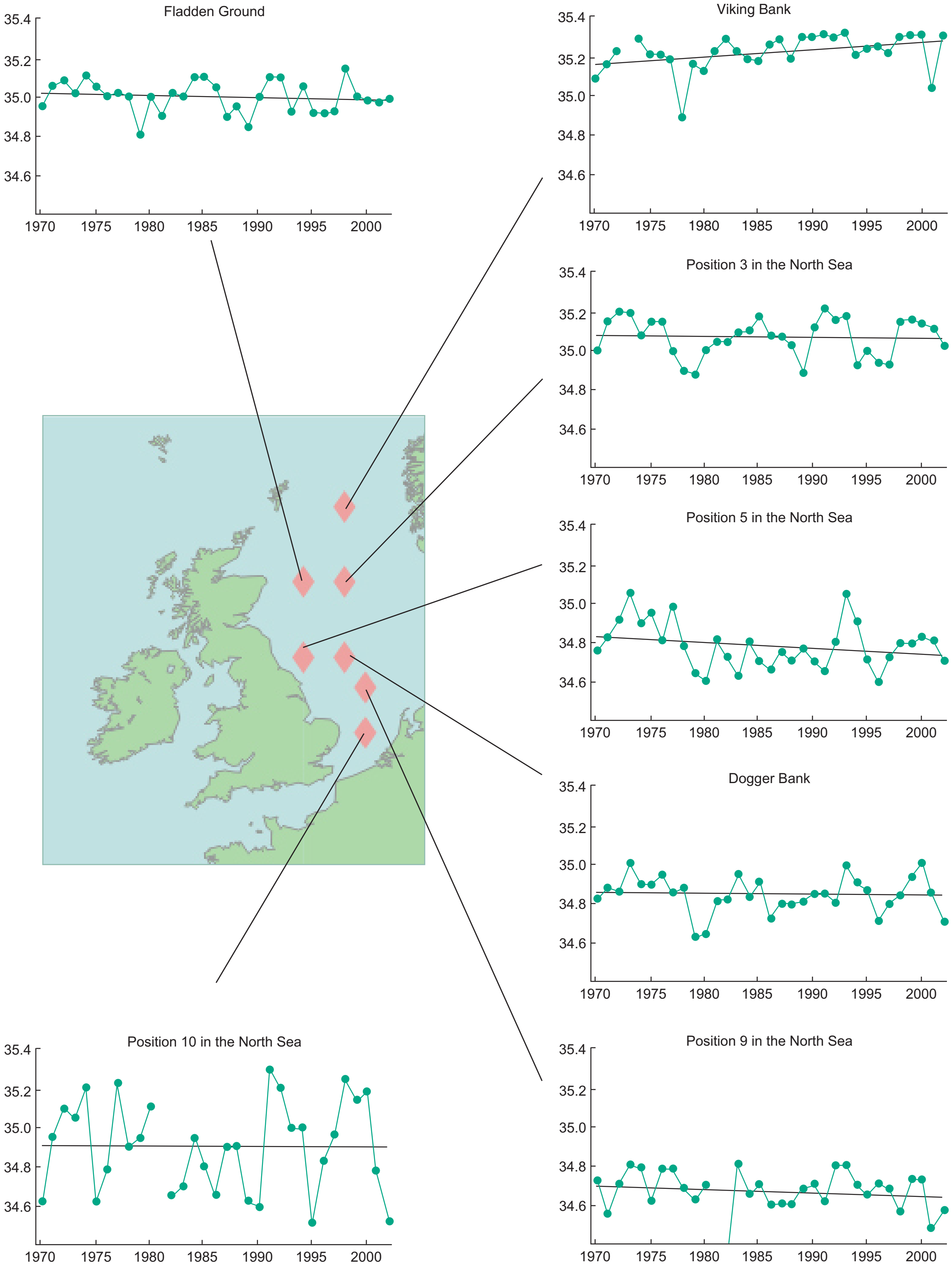


Figure 5.5. Fair Isle Current Water salinity anomalies Nominal position: 59° 17'N, 2° 10'W. Courtesy of FRS

Figure 5.5 indicates that the Fair Isle current appears to be freshening. The salinity demonstrated an almost cyclical variability since the end of the GSA in the 1970s. During 2001 the salinity was the lowest observed since the measurements began, but values increased during 2002 back towards the long-term average (ICES, 2003a).

In the North Sea fishing grounds, data collected as part of the International Bottom Trawl Survey (IBTS) shows a trend of decreasing salinity in the winter (see figures 5.6 to 5.12).



Figures 5.6-5.12. Bottom salinity time series in the North Sea, 1970-2002. Time series based on IBTS data and produced by averaging the data sets by year. Courtesy of the ICES Oceanographic Data Centre

5.3.2 ENGLISH CHANNEL AND CELTIC SEA, INCLUDING THE BRISTOL CHANNEL

Figure 5.13 shows that there is no discernible trend in mean sea surface salinity at MBA station E1 from 1900 to the early 1980s.

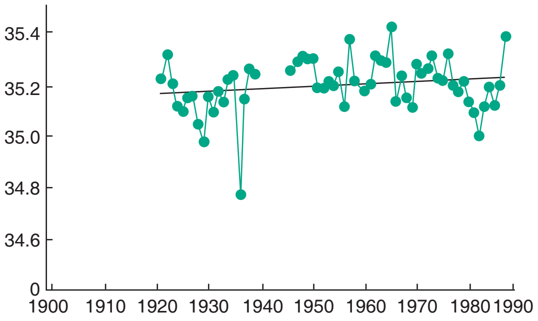


Figure 5.13. Mean sea surface salinity at MBA station E1, English Channel. Courtesy of the MBA

5.3.3 IRISH SEA

Figures 5.14 and 5.15 show winter and summer SSS anomalies averaged over the Irish Sea (53-55N, 6-4W) from 1950 to 2002. There is an indication of freshening (i.e. decreasing salinity), especially in the summer time series, but the observation coverage decreased significantly from the early 1980s onwards – for example, the very low value of the mean in 1991 is based on only one value (Dooley, 2003). Figure 5.16 shows the annual mean SSS since 1966 at the Port Erin site on the Isle of Man and Figure 5.17 shows an analysis of the monthly means of SSS for the years 2001 and 2002, with long-term minima, maxima and monthly means. Surface salinity data from CTD casts further west, at station 38a, is shown in Figure 5.18. There is a positive correlation between lower salinity at the Cypris station and the positive phase of the NAO (Gaynor Evans, personal communication, 2004).

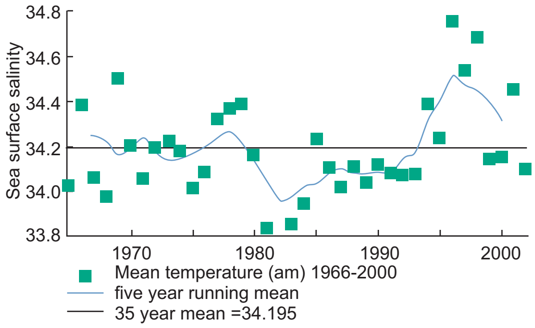


Figure 5.16. Annual mean sea surface salinity at Port Erin since 1966. Courtesy of Port Erin Marine Laboratory

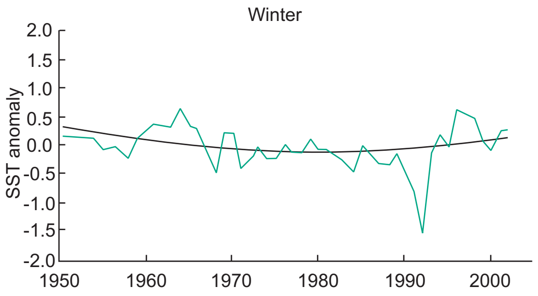


Figure 5.14. Winter (January to March) SSS Anomaly, 1950-2002, Irish Sea (53-55°N, 6-4°W) Time series produced by averaging the winter data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

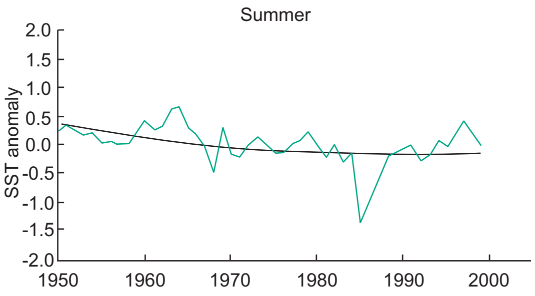


Figure 5.15. Summer (July to September) SSS Anomaly, 1950-2002, Irish Sea (53-55°N, 6-4°W) Time series produced by averaging the summer data sets by year. Anomalies produced by subtracting the mean calculated for the whole period. Long-term trend based on a second order polynomial. Courtesy of the ICES Oceanographic Data Centre

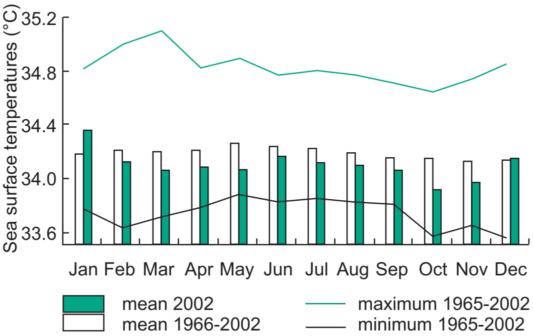


Figure 5.17. Monthly means for years 2001 and 2002, with long term minima, maxima and monthly means 1966 to 2002

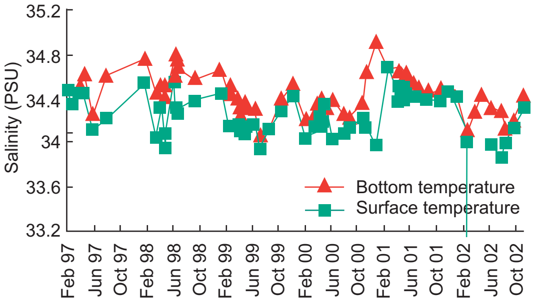


Figure 5.18. Surface salinity at Station 38a in the Irish Sea. Nominal position: 53° 05'N, 5° 38'W. Courtesy of DARD(NI)

5.3.4 MINCHES, WEST SCOTLAND, SCOTTISH CONTINENTAL SHELF AND FAROE SHETLAND CHANNEL

Figure 5.19 shows that there has been an overall increasing trend in salinity in the Faroe Shetland Channel since the low values caused by the passage of the GSA in the late 1970s. During 2001 there was a downward turn but a return to higher values in 2002 (ICES, 2003a).

5.3.5 ROCKALL TROUGH AND BANK AND ATLANTIC NORTH WEST APPROACHES

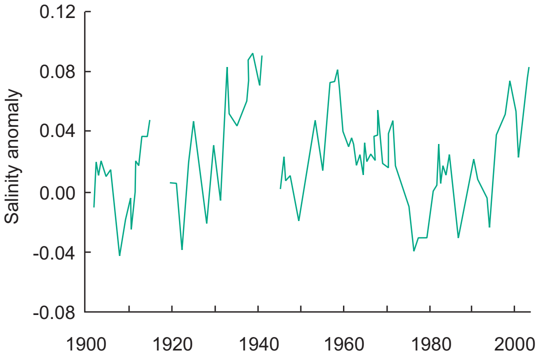


Figure 5.19. Salinity anomalies in the Faroe Shetland Channel. Courtesy of FRS

Figure 5.20 shows de-seasoned upper ocean (0-800m) salinity anomalies from the Rockall Trough, from 1975. The maximum salinity anomaly of the time series occurred at the end of the 1990s, in May 1998 (Holliday, 2003). In contrast the early part of the 1990s was characterised by relatively low salinity, although it remained higher than the low values caused by the passage of the GSA in the late 1970s. In 2001 the Rockall Trough began to show signs of freshening (and cooling), following a peak in salinity (and temperature) in 1998–2000. However salinity (and temperature) remained high compared to the long-term mean, with values similar to previous peaks in the early 1980s (ICES, 2002).

Holliday (2003) states that the NAO Winter Index shows no statistically significant correlation with the time-series of subsurface salinity (or temperature); the Rockall Trough lying in a region of low to zero correlation, between the high positive correlation to the south and east and high negative correlation to the west (Rodwell *et al*., 1999). Therefore she considers that the conditions in the Rockall Trough do not appear to be directly related to atmospheric conditions, as indicated by the NAO Index; or to variations in local net freshwater fluxes; but instead are caused by varying inputs of the water masses to the south of the region - central North Atlantic Water (ENAW), Mediterranean outflow Water (MEDW), Western North Atlantic Water (WNAW) and SubArctic Intermediate water (SAIW).

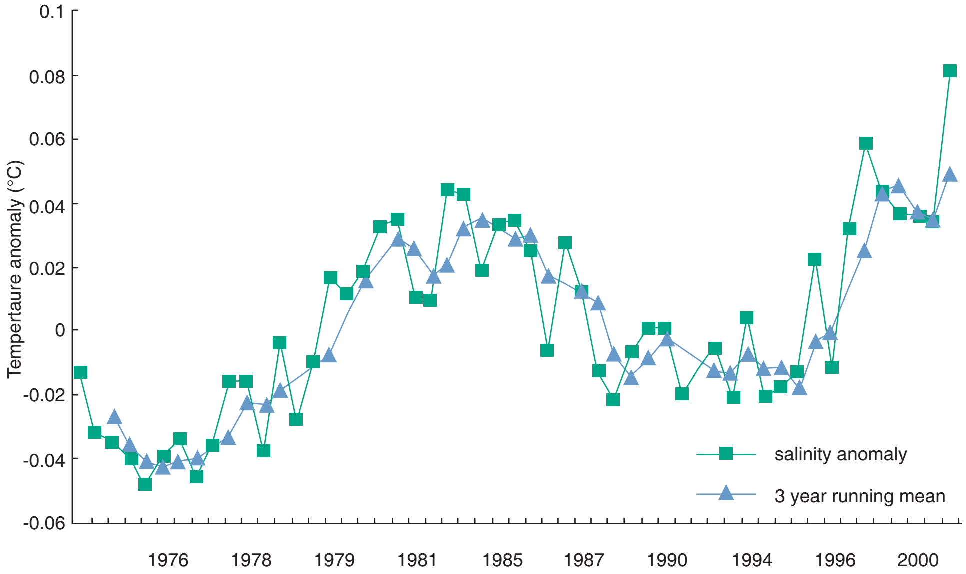


Figure 5.20. Salinity anomalies from the Rockall Trough from 1975 onwards. Data has been averaged across the section, the seasonal cycle removed and a three-point running mean included. Nominal Position: 60° 30'N, 3° 00'W. Courtesy of Penny Holliday, SOC

5.4 REFERENCES

Dickson, R.R., Meincke, J., Malmberg, S.A. and Lee, A. J. (1988). The 'Great Salinity Anomaly' in the northern North Atlantic 1968–1982. *Progress in Oceanography*, 20: 103–151.

Dooley, H. (2003). Personal communication. ICES, Denmark, Copenhagen. Holliday, N.P. (2003). Extremes of temperature and salinity during the 1990s in the northern Rockall Trough: results from the 'Ellett line'. *ICES Marine Science Symposia*, 219: 95-101.

ICES (2002). The Annual ICES Ocean Climate Status Summary 2001/2002. Prepared by the Working Group on Oceanic Hydrography, ICES, Copenhagen, Denmark. (Editors: Bill Turrell and N. Penny Holliday.) Retrieved 20th May 2003 from the World Wide Web: http://www.ices.dk/status/clim0102/IOACSS01.PDF

ICES (2003a). The 2002/2003 ICES Annual Ocean Climate Status Summary. Prepared by the Working Group on Oceanic Hydrography, ICES, Copenhagen, Denmark. (Editors: Hughes, S.L. and Lavín, A.) Retrieved 4th October 2003 from the World Wide Web: http://www.ices.dk/status/clim0203/IAOCSS2002.PDF

ICES (2003b). Environmental status of the European seas. Edited by Fletcher, N. Retrieved 26th September 2003 from the World Wide Web: http://www.ices.dk/reports/germanqsr/23222_ICES_Report_samme.pdf

OSPAR (2000). Quality Status Report 2000 for the North-East Atlantic. OSPAR (Oslo-Paris) Commission, London, 108pp.

5.5 LIST OF LINKS TO MONITORING NETWORKS AND DATA SETS

Online search interfaces for catalogues and inventories maintained by the IACMST's
Marine Environmental Data Network
http://www.oceannet.org

Argo project
http://www.metoffice.com/research/ocean/argo

DARD(NI) Coastal Monitoring Programme
http://www.afsni.ac.uk/services/coastalmonitoring

'Ellett' Line (Sound of Mull to Rockall) and the extended 'Ellett' Line (Rockall to Iceland).
http://www.soc.soton.ac.uk/GDD/hydro/nph/ellett/index.php
and
http://www.soc.soton.ac.uk/GDD/hydro/nph/ellett/extended.php

Faroe Shetland Channel surveys
http://www.marlab.ac.uk

FRS Coastal Long-term Monitoring programme
http://www.marlab.ac.uk
HumberNet
http://www.northseanet.co.uk/humber/digitaldisplay.htm
and
http://www.northseanet.co.uk

ICES International Bottom Trawl Survey (IBTS)
http://www.ices.dk/ocean/INDEX.HTM

Liverpool Bay Coastal Observatory
http://cobs.pol.ac.uk

Met Office's Marine Automatic Weather Station (MAWS) Network
http://www.metoffice.com/research/ocean/goos/maws.html

Port Erin Marine Laboratory (PEML) programme
http://www.liverpool.ac.uk/plankton

SOC Ferry-Box project
http://www.soc.soton.ac.uk/ops/ferrybox_index.php

Tiree Passage time series http://www.sams.ac.uk/dml/projects/physics

UK National Marine Monitoring Programme (NMMP and NMMP2)
http://www.marlab.ac.uk
and
http://www.defra.gov.uk/environment/marine/mpmmg/index.htm#1

6. Sea level

SUMMARY OF CHANGES AND TRENDS

- Sea level records from Liverpool, Newlyn, Portsmouth and Dover show local short-term variations in amplitude and phase of tidal constituents but no long-term trends.

- There is no evidence of a trend in sea level surges at Liverpool since 1768, Newlyn since the 1920s, or Portsmouth and Dover since the 1960s.

- Global mean sea level (MSL) has risen by about 120 metres since the last ice age around 20,000 years ago and by 1.0 to 2.0 mm per year during the 20th twentieth century.

- After adjusting for land movements, 'absolute' sea level around the UK coast has increased by about 1 mm per year during the 20th Century.

- 'Relative' MSL, due to the combined effect of absolute MSL changes and land movements, is increasing around most of the UK coast but remains constant or is even decreasing along some northern coasts.

- UK MSL shows an increase in the rate of rise towards the second half of the 19th Century. However, sea level is now rising on average less fast than over a base period of 1921-1990; i.e. there has been a decrease in the rate of rise in the 20th Century.

- Trends in UK extreme sea levels match MSL trends closely.

6.1 INTRODUCTION

Sea levels are a combination of tidal level, surge level, mean sea level and waves and their interaction. 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 or decrease in tidal levels. 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 at the UK coast 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 flooding along a coastline, especially if a rise in mean-sea level provides a higher 'base-line' for them. Also, rising sea level will reduce beach width and increase coastal erosion, particularly through the effect of increasing wave energy.

A rise in sea level can cause the loss of salt marsh and mudflats, thus having an effect on ecosystems, particularly on intertidal habitats. Also, the impact of sea level rise on a changing wave climate, and hence on water turbidity, will have an impact in the near shore leading to biological effects.

6.1.1 TIDAL LEVELS

These 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 the semi-diurnal (two tides a day) component of the tide and particularly strong responses occur in the Irish Sea and the Bristol Channel.

Semidiurnal lunar tides increase and decrease in range over an 18.6 year period because of changes in the lunar declination cycle. When the declinations are small the semidiurnal tides are bigger. The most recent maximum in semidiurnal

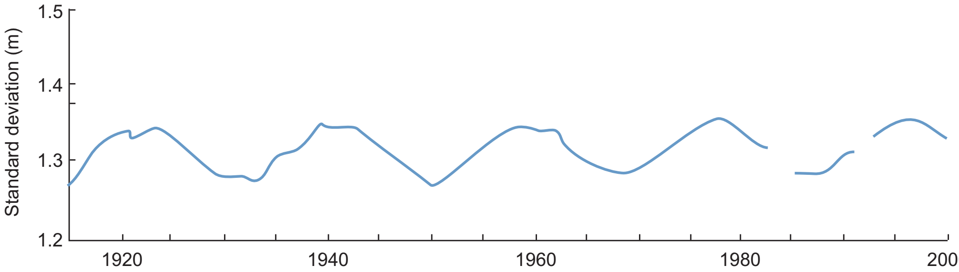


Figure 6.1. Standard deviation in the observed sea level variations at Newlyn, showing the 18.6 year modulations. Courtesy of David Pugh, from Pugh (2004)

tides was in 1997, with a subsequent fall to 2006. The theoretical modulations are 3.7 per cent about the mean, but in practice because of shallow water effects, around the UK the modulations vary locally around 2 per cent. Figure 6.1 shows the long-term cycles in the range of tidal sea level variations at Newlyn.

Refer to the web version of this report to see a figure of the tidal level characteristics at UK coastal sites using STEMgis.

6.1.2 SURGE LEVELS

These are caused by changes in atmospheric pressure and associated wind stress, and can result in water levels above ('positive surge') or below ('negative surge') those of the normal tide. The wind-stress effect depends upon water depth and increases in importance as the depth decreases whereas the pressure effect is independent of depth. "Storm surges" are generated by major meteorological disturbances, and can result in

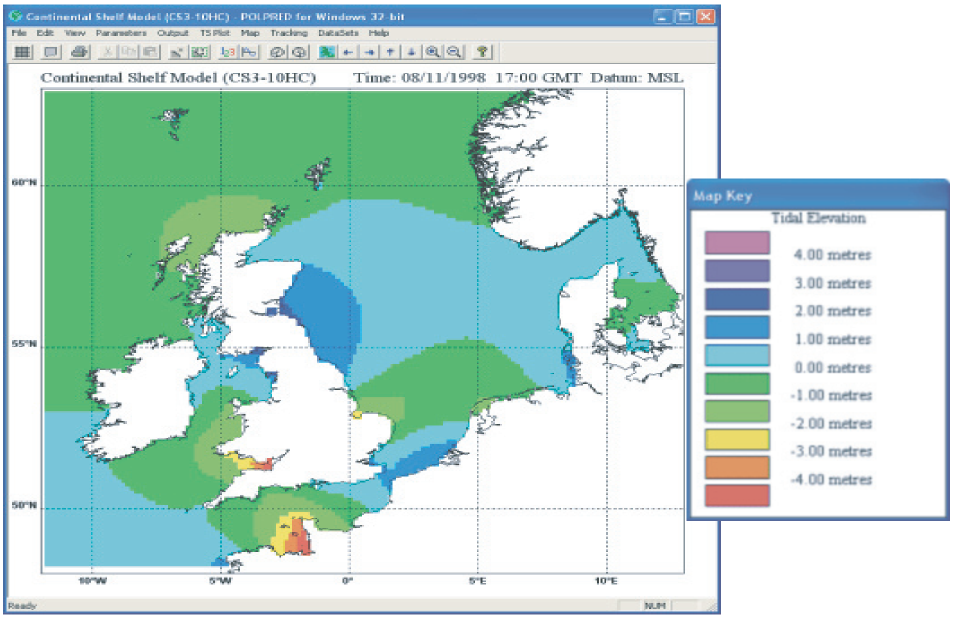


Figure 6.2. Go to theactive website to see an animation of tidal levels propagating around the UK coast during a specific 'storm surge' event, from 5pm on 8th -4am on 11th November 1998 [GIF animation, 453KB.]. The interactive website report will also show the same animation in AVI [2.0MB].Courtesy of Colin Bell, POL

sea level changes of up to several metres lasting a few hours to days, depending upon the storm duration, water depth and the extent of the storm. To see an animation of surge levels propagating around the UK coast during a specific storm surge event go to http://www.pol.ac.uk/home/insight/anim_surge_02.html (Courtesy of POL).

6.1.3 MEAN SEA LEVEL (MSL)

This is defined as the height of the sea averaged over a period of time, such as a month or year, long enough that fluctuations caused by waves and tides are largely removed. Daily, monthly, seasonal and annual variations of 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 about 10 cm seasonally, and a maximum in late summer. MSL changes 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 (e.g. sediment compaction or ground water extraction) or regional land movements (e.g. as a result of post-glacial 'isostatic' adjustment). Thus 'absolute' sea level has had any land movements removed from the 'relative' MSL signal. Long term, 'secular', changes in absolute MSL are mainly caused by changes in water volume, e.g. an increase caused by the melting of grounded ice or the thermal expansion of seawater due to heating.

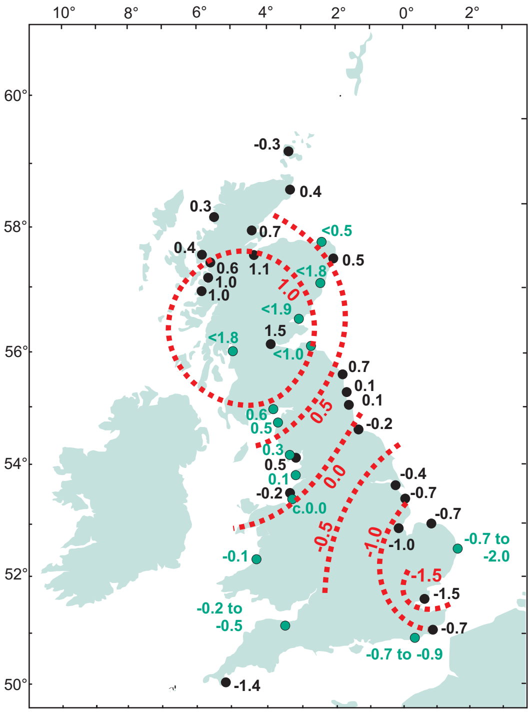


Figure 6.3. Land uplift (positive values) or subsidence (mm per year) in Great Britain, from the radiocarbon dating of microfossils contained in sedimentary deposits. Green and black circles indicate data collected before and after 1989 respectively. Red dotted line indicates approximate contour lines. Courtesy of Ian Shennan, Durham University.

Although small in global terms, the ice sheet that covered much of the British Isles was large enough for post-glacial isostatic adjustment processes to produce contrasting relative MSL changes at different locations. Maximum relative land uplift, approximately 1.6 mm/yr, occurs in central and western Scotland and maximum subsidence, approximately 1.2 mm/yr, in southwest England. 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 approximately 0.2 mm/yr land subsidence, but more in parts of southeast England, approximately 0.5 – 1.1 mm/yr (Shennan and Horton, 2002). The following figure shows a map of land uplift or subsidence in Great Britain, from the radiocarbon dating of microfossils contained in sedimentary deposits.

6.1.4 MEASURING AND MONITORING SEA LEVEL

Descriptions of the monitoring networks that regularly measure sea level are given in Chapter 1, including details of how to access near real-time data. Go to section 6 at the end of this chapter for a list of monitoring networks and data sets.

6.2 TRENDS IN TIDES AND SURGES

Sea level records from Newlyn, Portsmouth and Dover show local short-term variations in amplitude and phase of tidal constituents but no long-term trends (Araújo *et al.*, 2002). Tidal elevation records in the lower estuary of the River Mersey show almost no changes to the predominant tidal constituents over a sixty-three year period (Lane, 2004). Araújo *et al.*, (2002) 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. Analysis of surge statistics from the Liverpool tide gauge data has shown that there were no long term changes over the period 1768 to 1999 (Woodworth and Blackman, 2002).

6.3 TRENDS IN MSL

6.3.1 GLOBAL MSL TRENDS

Since the last ice age around 20,000 years ago, MSL has risen worldwide by about 120 metres. Based on tide gauge data, global MSL has increased by 1.0 to 2.0 mm per year during the 20th twentieth century, with a central value of 1.5 mm per year (IPCC, 2001). Analysis of satellite altimeter data for the 1990s suggest slightly larger rates, of about 3 mm/year, but it is uncertain whether this represents a real acceleration or not because of the short data length (Woodworth, personal communication). The main contributions to an increase in the ocean volume, and hence sea level rise, in the 20th century, have been a reduction in density due to ocean warming (i.e. a thermal expansion) and an increase in the ocean mass due to the melting of glaciers, ice caps and ice sheets. It is considered that these changes in mean sea level are a consequence of increases in global temperature arising from human-induced increases in greenhouse gases (IPCC, 2001).

6.3.2 UK MSL TRENDS

Refer to the web version of this report to see a map displaying sea level data from the UK National Tide Gauge Network using STEMgis.

Visit http://www.pol.ac.uk/ntslf/trends.php to see sea level trends from the UK National Tide Gauge Network.

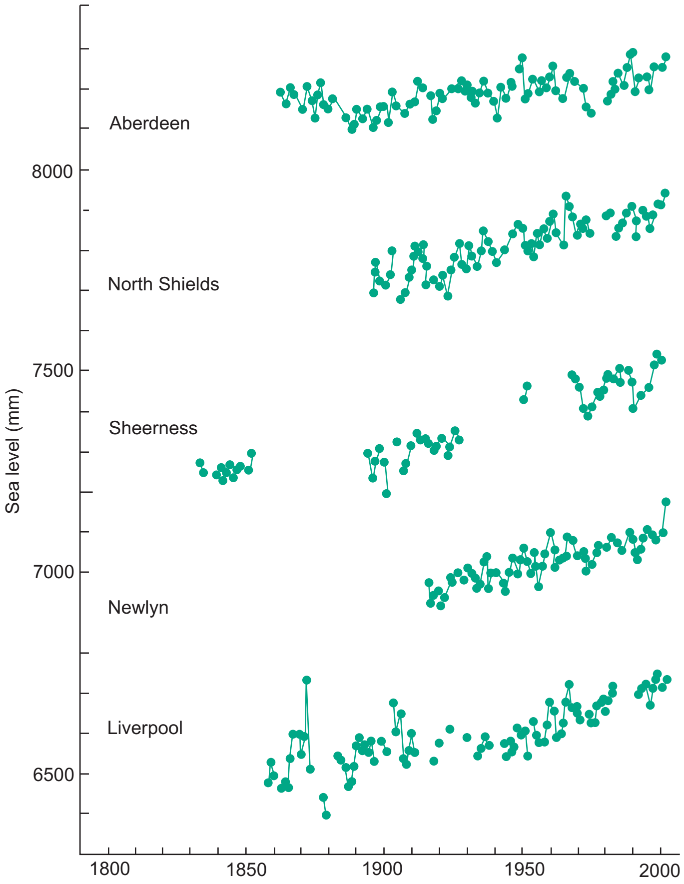


Figure 6.4. MSL at Aberdeen, North Shields, Sheerness, Newlyn and Liverpool. Courtesy of PSMSL

Figure 6.4 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 Permanent Service for Mean Sea Level (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*., 1999).

Various shortcomings in tide gauge data have meant that there is as yet no consistent estimate of the rate of change of MSL for Northern Ireland (OST, 2004b). These shortcomings include physical changes that have occurred to the Belfast harbour gauge such as relocation and harbour development and the shortness of the records of the recently installed gauges at Portrush and Bangor. Therefore the record of MSL at Malin Head (Republic of Ireland) is used by the Ordnance Survey as their geodetic gauge for Northern Ireland. Observations suggest there has been an almost zero change in relative sea level since records were started in 1958, but a large recent dip in the record is almost certainly instrumental (Woodworth *et al*., 1999).

Due to post-glacial recovery, the land in Scotland and northern England is uplifting but in southeast England it is submerging. After adjusting for these natural land movements, 'absolute' sea level around the UK coast has increased by about 1 mm per year, or 10 cm for the 20th Century. This trend is consistent with, but at the lower end of, the range of uncertainty of 10-20 cm of the estimates of global change by the IPCC (IPCC, 2001). The combined effect of absolute MSL changes and land movements mean that relative MSL in the UK is mainly increasing but remains constant or even decreases along some northern coasts. In UK waters, sea level changes show a small 'sea level acceleration' component, which is consistent with being the result of an acceleration towards the second half of the 19th Century (Woodworth, 1999), as well as considerable inter-annual and inter-decadal variability.

There is coherent variability in sea level changes around the British Isles (BI) (Woodworth *et al*., 1999). Therefore their 'BI sea level index' can be used as a guide to the 'average state' of MSL in UK waters, see Figure 6.5. The index is computed from the five longest UK MSL records at Aberdeen, North Shields, Sheerness, Newlyn and Liverpool. Each record has been detrended using the trend computed over a base period of 1921-1990; thereby, in principle, removing low-frequency geological and climate-change contributions. Therefore the index shows averaged interannual variability after long term trends have been removed.

The inter-annual changes in the index (Figure 6.5) are related to changes in local meteorological forcing (storm surges) and to oceanographic changes in shelf and nearby deep ocean circulation. The index shows a dip in the early 1990s that is as deep as the 'mid-1970s dip' that exists in all UK records. There are also dips around 1920, 1940 and 1962. The generally negative values in the latter part of the index indicate that sea level is now rising on average less fast than over a base period of 1921-1990; i.e. that there has been an overall deceleration, rather than an acceleration, in twentieth century MSL in UK waters. The inter-decadal variability in the index is reminiscent of that of other oceanographic and meteorological parameters in the North Atlantic, such as surface temperature, salinity, wind stress and storms (Woodworth *et al*., 1999).

6.3.3 TRENDS IN EXTREME LEVELS

The POL has carried out 'Peak over threshold' (POT) analyses for sea levels at Newlyn (1915 - 2001), Dover (1961-2001) and Lowestoft (1964-2001) (Law *et al*., 2003). All sea level values were extracted that were greater than a defined threshold value. The threshold was chosen to ensure that the lowest level expected to be exceeded on average five times a year in any 20 year subset was greater than the threshold. They were then analysed to give the sea level thresholds exceeded by, on average, 1 to 5 events per year - POT1 to POT5. Figure 6.6 shows that there is a clear upward trend in the 20 year running averages of all the POT1 to POT5 levels at Newlyn. At Dover, there are apparent trends in the 20-year mean POT2 to POT5 levels but POT1 has a step around 1985, probably due to missing data for five years (David Blackman, personal communication). Trends at Lowestoft are less clear but the record is shorter than those for other sites.

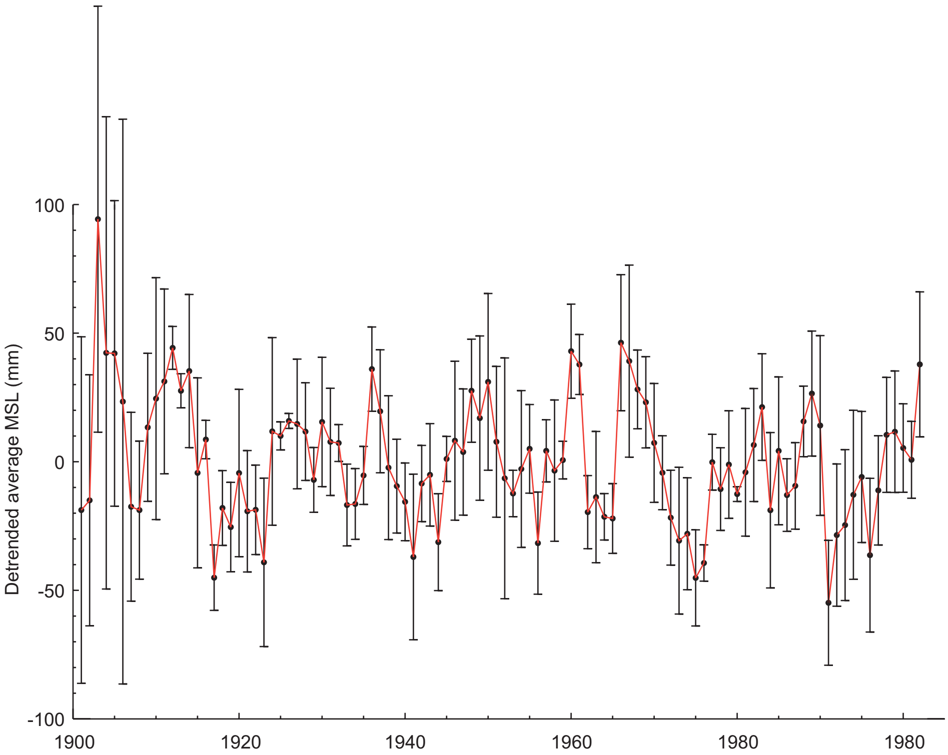


Figure 6.5. British Isles sea level index. Each record has been de-trended over the period 1921- 1990 and the de-trended values averaged. The figure also shows standard deviations of de-trended values about the average. Visit http://www.pol.ac.uk/ntslf/products.html to see the BI MSL indices. Courtesy of PSMSL

Trends in UK extreme sea levels have been found to be nearly uniform, ~ 1.1 mm/y; so matching MSL trends closely (Dixon and Tawn, 1992). Woodworth (1999) found no significant increase in extreme high waters at Liverpool from 1968-93, other than what can be explained in terms of changes in local tidal amplitudes, MSL and vertical land movement.

6.4 MEAN SEA LEVEL AND THE NORTH ATLANTIC OSCILLATION

Wakelin *et al*. (2003) have shown that winter (December to March)-mean values of monthly MSL and the NAO Index (Jones *et al*., 1997) are significantly correlated over much of the northwest European shelf. There is a clear spatial pattern in the correlation, with strongly positive (> 0.8) values in the northeast and strongly negative (<-0.7) in the south. 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 correlation >0.3, while 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, with sea level for 1909 – 1954 showing a lower correlation with the NAO compared with 1955 – 2000. Also, 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.

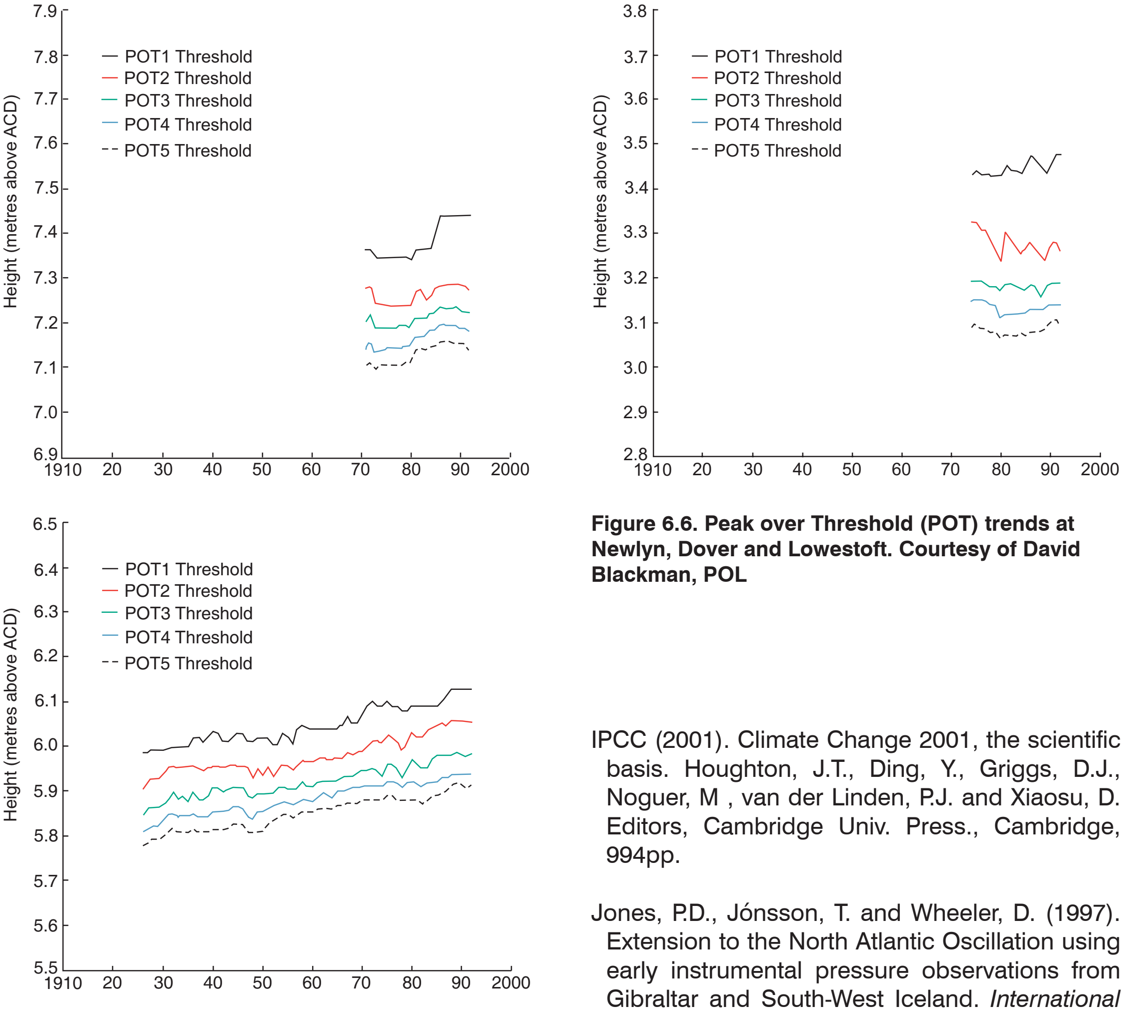


Figure 6.6. Peak over Threshold (POT) trends at Newlyn, Dover and Lowestoft. Courtesy of David Blackman, POL

6.5 REFERENCES

Araújo, I., Pugh, D.T. and Collins, M. (2002). Trends in components of Sea Level around the English Channel. Proceedings of Littoral 2000, Porto, Portugal, September 2002, 1-8.

Dixon, M.J. and Tawn, J.A. (1992). Trends in UK extreme sea-levels: a spatial approach. *Geophysical Journal International*, 111: 607-616.

Hilmer, M. and Jung, T. (2000). Evidence for a recent change in the link between the North Atlantic Oscillation and Artic sea ice export. *Geophysical Research Letters*, 27(7): 989–992.

IPCC (2001). Climate Change 2001, the scientific basis. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M , van der Linden, P.J. and Xiaosu, D. Editors, Cambridge Univ. Press., Cambridge, 994pp.

Jones, P.D., Jónsson, T. and Wheeler, D. (1997). Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *International Journal of Climatology*, 17: 1433-1450.

Lane, A. (2004) Bathymetric evolution of the Mersey Estuary, UK, 1906-1997: causes and effects. *Estuarine, Coastal and Shelf Science*, in Press.

Law, F.M., Farquharson, F., Brampton, A., Dale, M. and Flather, R.A. (2003). Environmental change indicators (including those related to climate change) relevant to flood management and coastal defence. Defra/EA R & D technical report FD2311-TR.

OST (2004b). Aspects of the Foresight project specific to Northern Ireland.. Prepared by Stuart Suter and John Chatterton. Foresight Flood and Coastal Defence Project - Phase 2 Overview Report, Chapter 2, Appendix I.

Pugh, D.T. (2004). Changing Sea Levels. Effects of tides, weather and climate. Cambridge Shennan, I. and Horton, B. (2002). Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science*, 17: 511-526. doi: 10.1002/jqs.710.

Wakelin, S.L., Woodworth, P.L., Flather, R.A. and Williams, J.A. (2003). Sea-level dependence on the NAO over the NW European Continental Shelf. *Geophysical Research Letters*, 30(7): 1403, doi: 10.1029/2003GL017041.

Woodworth, P.L., Tsimplis, M.N., Flather, R.A. and Shennan, I. (1999). A review of the trends observed in British Isles mean sea level data measured by tide gauges. *Geophysical Journal International*, 136: 651-670.

Woodworth, P.L. and Blackman, D.L. (2002). Changes in extreme high waters at Liverpool since 1768. *International Journal of Climatology*, 22: 697-714.

Woodworth, P.L. (1999). A study of changes in high levels and tides at Liverpool during the last two hundred and thirty years with some historical background. Proudman Oceanographic Laboratory Report No. 56, 62pp.

6.6 LIST OF LINKS TO MONITORING NETWORKS AND DATA SETS

Online search interfaces for catalogues and inventories maintained by the IACMST's Marine Environmental Data Network
http://www.oceannet.org

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.

HumberNet
http://www.northseanet.co.uk/humber/digitaldisplay.htm
and
http://www.northseanet.co.uk

Liverpool Bay Coastal Observatory
http://cobs.pol.ac.uk

Permanent Service for Mean Sea Level (PSMSL)
http://www.pol.ac.uk/psmsl/datainfo

Satellite missions

http://www.cls.fr./html/oceano/projets/enact/project_en.html
http://www.soc.soton.ac.uk/lso/noindex/lso_data.php

Southeast Regional Coastal Monitoring Programme
http://www.channelcoast.org

U.K. National Tide Gauge Network
http://www.pol.ac.uk/ntslf/tgi
and
http://www.bodc.ac.uk/cgi-bin/ntslf_data.pl?polntslf

7. Waves

SUMMARY OF CHANGES AND TRENDS

- Wave data from ships and buoys indicate that the mean winter wave height in the northeast Atlantic increased significantly between the 1960s and 1980s. Satellite data confirm that this increase continued into the early 1990s.

- In the northern North Sea, there was an upward trend of about 5-10 per cent (0.2-0.3m) in mean significant wave height (Hs) for January–March for the period 1973-1995, but a decrease thereafter.

- In the central North Sea, the trend for January–March was upwards until 1993/94, with a decrease thereafter. The October–December Hs peaked around 1982/83 and 1983/84, with a similar high value in 1999/2000.

- In the southern North Sea, there is no discernible trend in Hs for January–March and only a slight indication of a downward trend in Hs for October–December from 1980/81.

- At Sevenstones LV, off land's End, the acceptable value is an increase of 0.02 m/yr in mean wave height over a period of about 25 years. This trend seems to have persisted into the early 1990s at least, although recent winters have suggested a levelling off.

7.1 INTRODUCTION

The wave climate can be considered as consisting of three parts: the long term mean climate, the annual or seasonal cycle and non-seasonal variability on both the short term (within year) and long term (year to year, or interannual). In UK waters, wave climate is strongly seasonal with mean wave heights peaking around January, but with a high risk of both high monthly mean wave heights and extreme wave heights throughout autumn and winter (October to March). There is also high inter-annual variability in monthly mean wave heights, particularly in an 'extended winter period' from December to March and these months are those primarily associated with the North Atlantic Oscillation. (The NAO index is a measure of the mean atmospheric pressure difference across the North Atlantic, from north to south; see for example Jones *et al*., 1997.)

The height of offshore waves depends on the strength of the wind and the distance and length of time over which the wind has acted on the ocean surface. Waves approaching the UK coastline could have been generated not only locally and in the north-east Atlantic Ocean, but also from the north-west Atlantic and even from the south Atlantic. Coastal waves are influenced by local water depth and by the nature of the seabed.

High waves can cause risk to platforms and pipelines and disruption to routine marine operations. Estimates of likely extreme waves are essential for the design of ships and offshore structures such as oilrigs. At the coastline, waves can affect coastal development - larger waves can damage seawalls, cause coastal flooding 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 waves.

Visit http://www.oceannet.org/restricted/MCP_report/ch_waves/MCPreport_waves_pbell_anim.htm to see an animation of waves approaching a beach, derived from X-band radar images [animated GIF, 2.9MB]. Courtesy of Paul Bell, POL.

7.2 WAVE MEASUREMENTS

The measurement of waves is a relatively recent development, with only very crude instruments available prior to about 1955. In the 1960s and 1970s, the National Institute of Oceanography equipped a number of lightships around the coastline with ship-borne 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 1-2 years, the main exception being at Sevenstones LV, which eventually provided one of the longest wave records from UK waters. Wave-following buoys using accelerometers replaced pressure-type wave recorders and by the late 1970s most wave recording was being carried out using these instruments. A wide range of instruments for measuring waves has been developed in recent years, including directional wave buoys, downward looking lasers and HF radar; the satellite altimeter has proved particularly successful for climate studies, providing global coverage. See Tucker and Pitt (2001) for a description of wave-measuring instruments.

Descriptions of the monitoring networks that regularly measure waves are given in Chapter 2, including details of details of how to access near real-time data.

Also refer to the list of links to monitoring networks and data sets at the end of this chapter (section 7.).

The longest periods of wave measurements, at a consistent location around the UK coastline, are believed to be as follows (Law *et al*., 2003):

Coastal wave data
- Off the North Kent coast (1979-1998 off Whitstable, 1996 to present off Herne Bay)
- Tees Bay (1988-present)
- Perranporth (1975 – 1986)

Offshore wave data
- Sevenstones Light Vessel (1962-1988)
- Forties Field (1974-present)
- Frigg QP (1979-present)
- Ekofisk Field (1980-present)

Figures 7.1 to 7.7 show wave data for 2000 – 2002 at selected stations of the Met Office's Marine Automatic Weather Station (MAWS) Network.

Refer to the web version of this report for an animation of wave data from the MAWS network using STEMgis.

7.3 LONG-TERM MEAN WAVE CLIMATE AND ANNUAL SEASONAL CYCLE

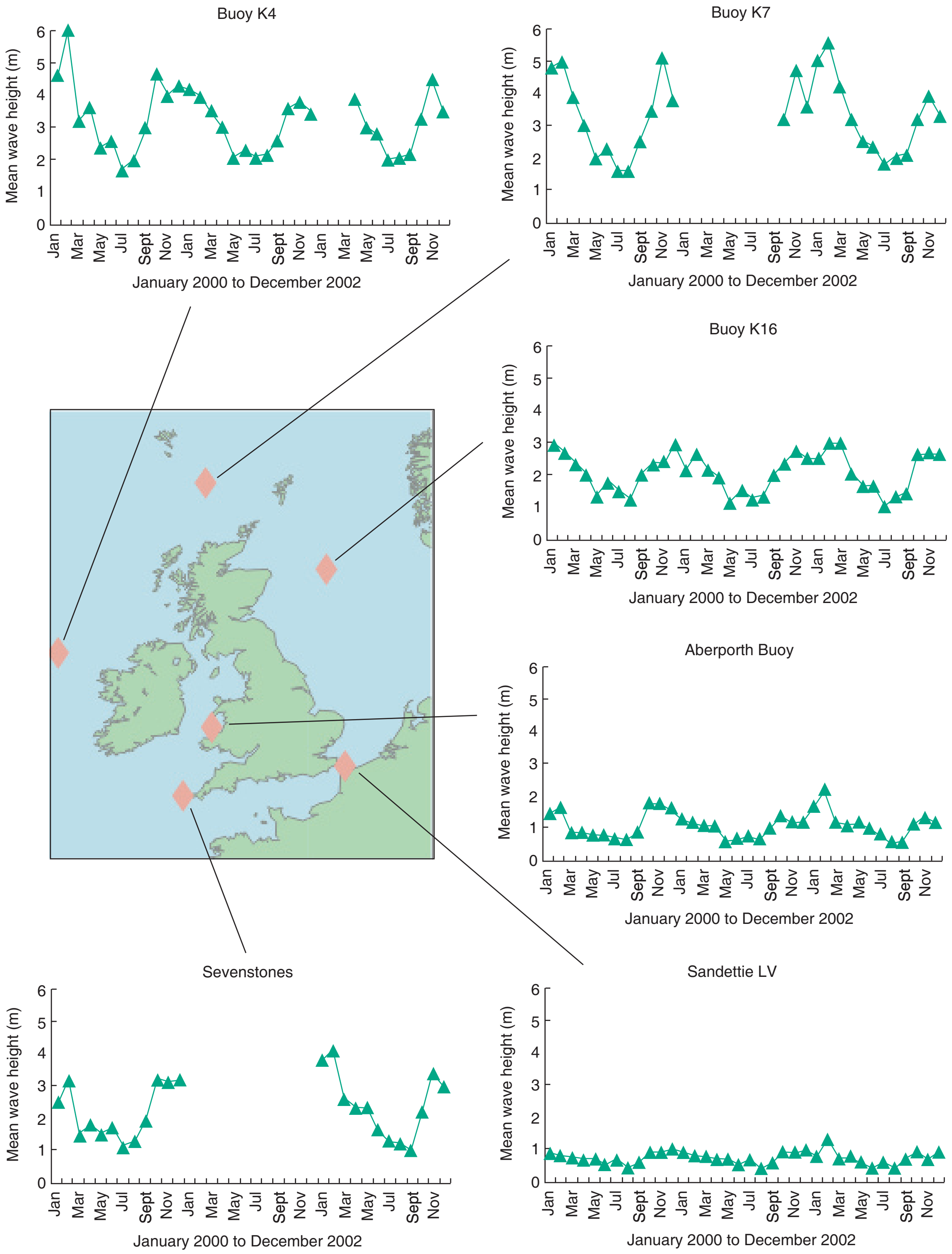
Figure 7.8 shows monthly means of significant wave heights (and wind speed at 10 m above the sea surface) derived using data from altimeters in the satellites Geosat, ERS-1, ERS-2, TOPEX-Poseidon and Jason from 1985 onwards. These fitted sine curves indicate a maximum ranging from late December in the southeast to mid-January at the northwest location where the February mean was 4.9 m compared to 4.5m in January; but the maximum individual, recorded wave height of 11.8 m and the maximum individual monthly mean of 7.3 m were both in January 1993 (Carter, personal communication).

In British waters, the west coast of Ireland and the Outer Hebrides experience the highest wave heights (long term mean significant wave height (Hs) of 3.0 m. Off the English and Welsh coastline, southwest Wales and western Cornwall experience the highest mean significant wave heights (2.0 - 2.5 m), whilst the English Channel and Eastern English coastline are the most sheltered, with a long term mean Hs of 1.5 m or less (Cotton *et al*., 1999).

The annual range in Hs (i.e. the difference between winter and summer) follows a similar pattern to the long-term mean. The winter to summer range is greatest in the north and west and lowest in the south and east. It decreases eastwards into the English Channel and southwards into the North Sea, from >3 m at 20°W, to 1 m or less at the southeast tip of Kent (Cotton *et al*., 1999).

7.4 SHORT- AND LONG-TERM NON-SEASONAL VARIABILITY

The seasonal cycle explains most of the variability in the monthly data of the northeast Atlantic (~70 per cent at 15-20°N), but less than half (30-50 per cent) of the variance in the North Sea and English Channel (Cotton *et al*., 1999). Therefore, inter-annual variability is also important, with some winters much stormier than others.



Figures 7.1-7.7. Wave data from MAWS Network. Courtesy of the Met Office

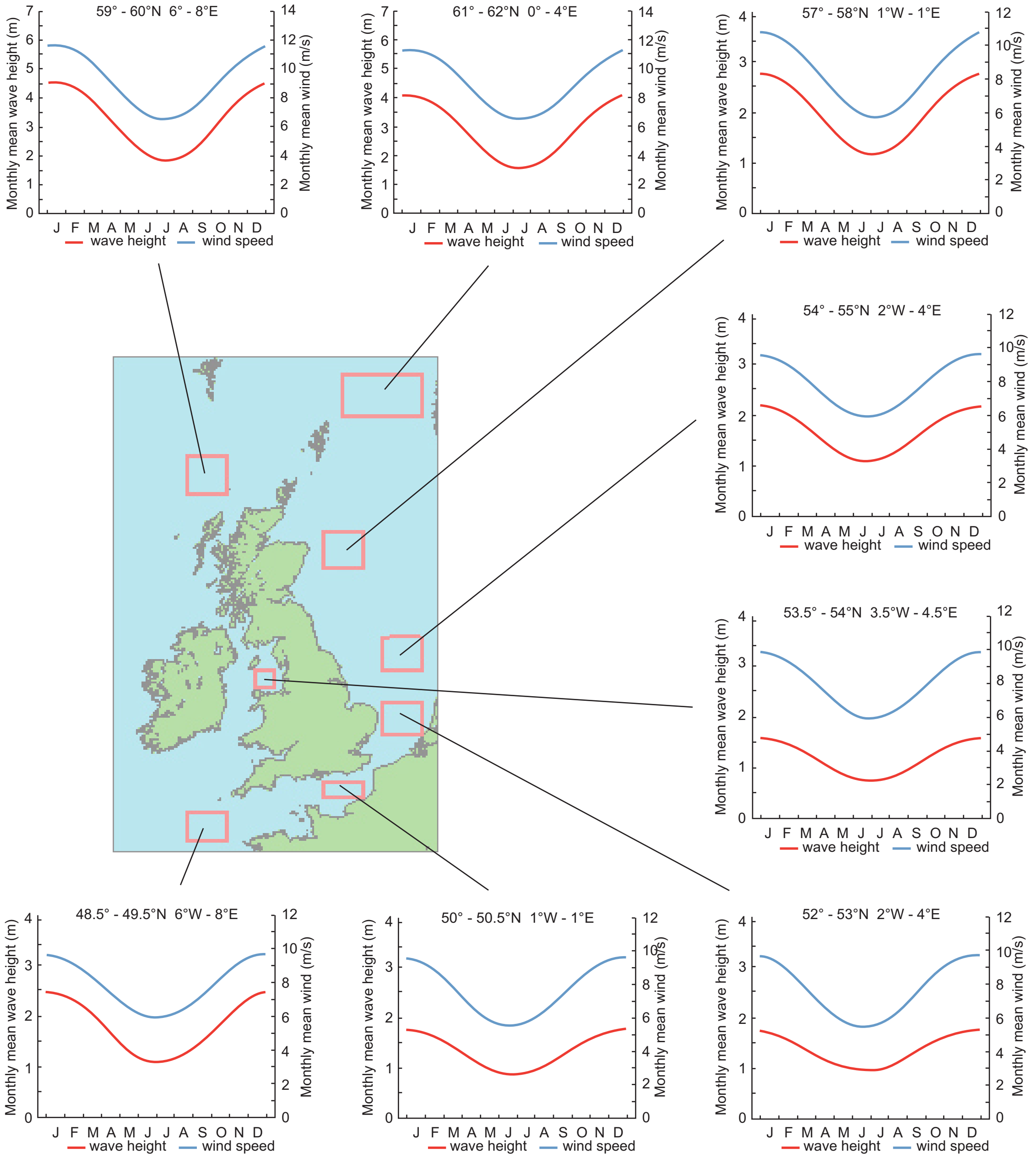


Figure 7.8. Monthly mean wave heights and wind speeds derived from satellite altimeter data from 1985 onwards. The location box indicates the area of averaging. Courtesy of Satellite Observing Systems Ltd.

Reliable long-term measurements of wave height in the North-east Atlantic, including UK waters, are available only since the 1960s (see section 2). Analyses of these wave data from ships and buoys give varying estimates of the change in wave height in the long term, e.g.:

- an increase in wave heights from about 2 to 3 m from 1962 to 1985 at the Sevenstones LV, off Land's End (Carter and Draper, 1988)
- an increase in wave heights of about 2.5 per cent per year from 1960-64 to 1970-74 at OWS India and OWS Juliet, and of between 1 and 2 per cent per year from 1978 to 1985 at OWS Lima (Bacon and Carter, 1991 and 1993)
- an upward trend in the annual mean value of significant wave height (Hs) of about 1.5 per cent per year from 1950-54 to 1980-84 at OWS Charlie, OWS Juliet and the Seven Stones LV (Barratt, 1991).

A review of the estimates is given by Carter (1999). The conclusion of a major review and study of the wave climate around the British Isles, carried out as part of the JERICHO project (Cotton *et al*., 1999), was that analysis of the wave data from ships and buoys shows that the mean winter wave height in the northeast Atlantic increased significantly between the 1960s and 1980s; and that the more recent analyses of satellite data from October 1992 to December 1997 confirmed that this increase continued into the early 1990's, with an acceptable value of 0.03 m/yr increase in the mean winter Hs in the northeast Atlantic.

Go to figure 1 in http://www.satobsys.co.uk/Jericho/webpages/jeriview.html to see the percentage increase in mean winter significant wave height in the Northeast Atlantic, 1985-89 to 1991-96.

At Sevenstones LV, Cotton *et al*. (1999) state that the acceptable value is an increase of 0.02 m/yr in mean wave height over a period of about 25 years. This trend seems to have persisted into the early 1990s at least, although recent winters have suggested a levelling off, perhaps the beginning of a decreasing trend.

Mean significant wave height (Hs) has been derived from wave measurements over the last 30 years at Shell UK platforms in the northern, central and southern North Sea, as part Shell's METNET network (Figure 7.9). In the northern North Sea there appears to be an upward trend in Hs for January–March until 1994-1995; analysis of Hs for the period 1973-1995 showed that it appeared to have increased by around 5-10 per cent (0.2-0.3 m).

(Leggett *et al*., 1996). Thereafter, Hs for January-March appears to have decreased. For the central North Sea, there is a suggestion that the trend for January–March is upwards until 1993/94, with a decrease thereafter. The October–December means peak around 1982/83 and 1983/84, with a similar high value in 1999/2000. For the southern North Sea, there is no discernible trend in Hs for January–March and only a slight indication of a downward trend from 1980/81 for October–December. Cotton *et al*. (1999) state that although the trend apparent at Sevenstones LV may have extended as far east as the northern North Sea, there is no evidence to suggest any similar increases in the central and southern North Sea.

7.5 WAVE CLIMATE AND THE NORTH ATLANTIC OSCILLATION

Waves are strongly related to wind conditions, particularly their 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 during the last 30 years or so. The WASA Group (1998) investigated evidence for increasing storminess during the 20th century using meteorological data. They concluded that the storm climate in the NE Atlantic and North Sea had undergone variations on decadal time scales and had indeed worsened in recent decades (1980 onwards). However, they found that the recent intensity was not unprecedented, being comparable to that at the start of the 20th century, with lower intensity in the intervening period. Also, there was no evidence for an increase in the number of storms or a tendency for storms to increase in intensity in recent decades. Since the NAO has increased in intensity during recent decades and

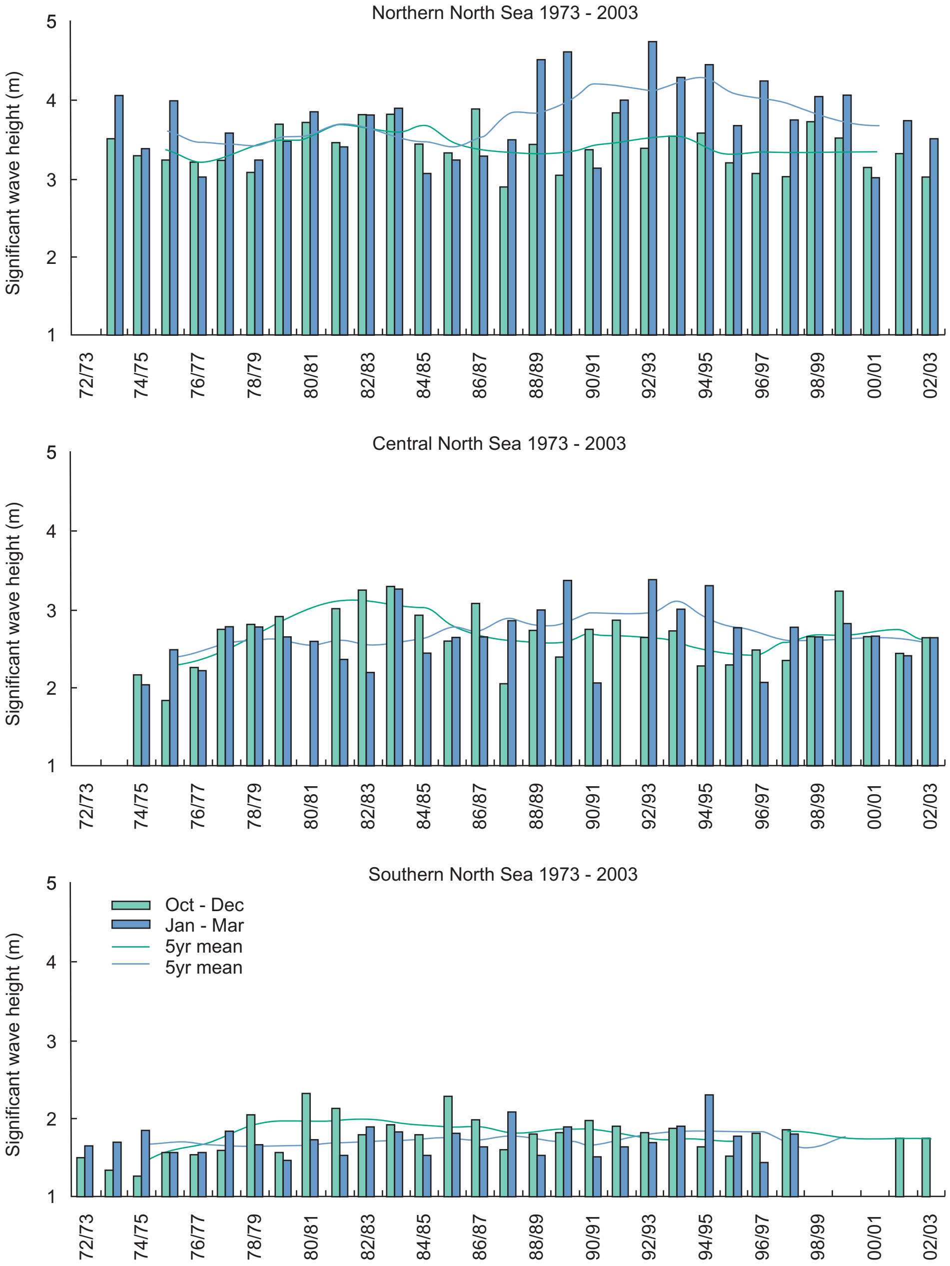


Figure 7.9. Mean significant wave height in the Northern, Central and Southern North Sea. With Overlayed 5 Year Running Mean - Derived from Measured Data. Courtesy of Ian Leggett, Shell Expro Metocean Services, Shell UK Ltd.

with it the westerly mean wind flow, the WASA group considered that any noticeable increase in Hs since the 1960s could be positively correlated with this, rather than with storm intensification; with a high or positive NAO index associated with increased wave height compared to a low or negative index. The influence of the NAO on the winter wave climate in the northeast Atlantic and UK waters has been studied in detail, primarily using satellite altimeter measurements of

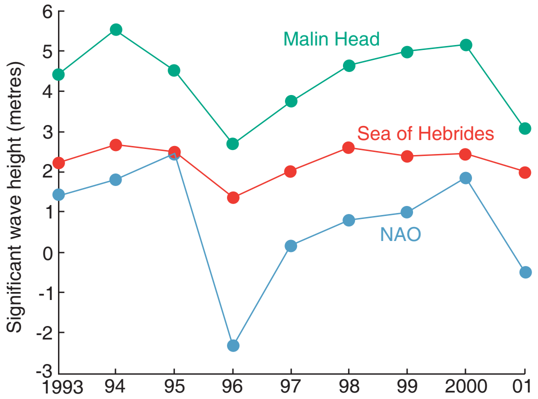


Figure 7.10. Wave height versus NAO Index at Malin Head and Sea of Hebrides. Courtesy of David Woolf, SOC

significant wave height (Cotton *et al*., 1999; Woolf *et al*., 2002 and 2003). As an example, figure 7.10 shows the relationship between monthly mean wave heights and the NAO over a 15-year period since 1985, generated from altimeter data.

Analysis of altimeter data has demonstrated that a large part of the inter-annual variability in monthly mean wave heights during these months can be described by a linear relationship of wave height anomaly to a North Atlantic Oscillation Index. The sensitivity of mean monthly wave height to NAO Index - estimated by linear regression analysis of an altimeter-based climatology - offshore of northern Europe is shown in Figure 7.11.

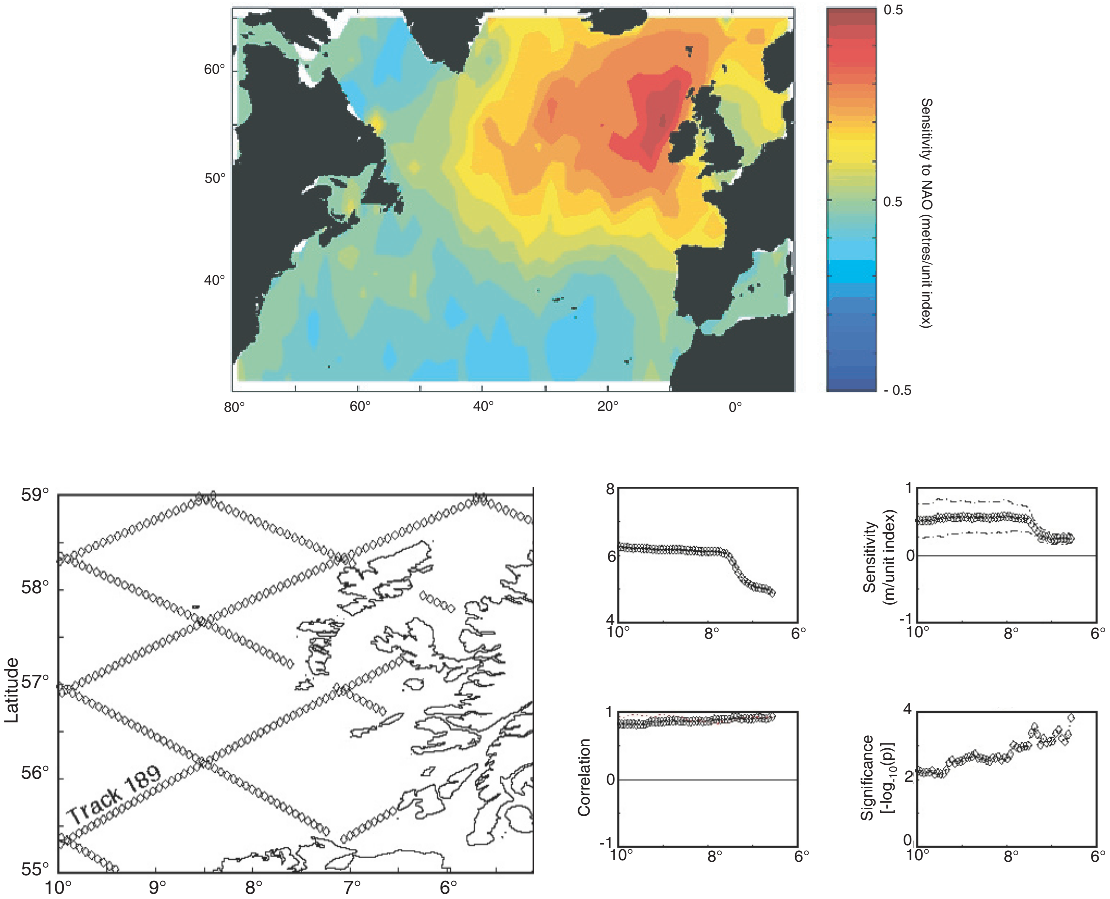


Figure 7.11. Sensitivity of winter monthly mean significant wave height to NAO around northern Europe. Courtesy of David Woolf, SOC

To the west of Scotland, the relationship is particularly strong - describing about 70 per cent of the variance and implying monthly mean wave heights varying from 3 metres to 7 metres 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 region as a whole. In terms of the sensitivity of the winter mean Hs 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 Hs, and a 1.28 m change in the 100 year return value (Cotton *et al*., 1999; Woolf et al., 2002 and 2003).

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

7.6 REFERENCES

Bacon, S. and Carter, D.J.T. (1991). Wave climate changes in the North Atlantic and North Sea. *International Journal of Climatology*, 11: 545-558.

Bacon, S., and Carter, D.J.T. (1993). A connection between mean wave height and atmospheric pressure gradient in the North Atlantic. *International Journal of Climatology*, 13: 423–436.

Barratt, M.J. (1991). Waves in the NE Atlantic. Offshore Technology Report OTI 90545, HMSO.

Carter, D.J.T. (1999). Variability and trends in the wave climate of the North Atlantic: a review. In Proceedings of the 9th ISOPE Conference, Cupertino, CA, USA, vol. III, pp. 12 -18. International Society of Offshore and Polar Engineers, Cupertino, CA, USA.

Carter, D.J.T. and Draper, L. (1988). Has the Northeast Atlantic become rougher? *Nature*, 332: 494.

Cotton, P.D., Carter, D.J.T., Allan, T.D., Challenor, P.G., Woolf, D., Wolf, J., Hargreaves, J.C., Flather, R.A., Li Bin, Holden, N. and Palmer, D. (1999). Joint Evaluation of Remote Sensing Information for Coastal And Harbour Organisations (JERICHO). Final Report to the British National Space Centre, project no: R3/003. 38 pages. Retrieved 10th September 2003 from the World Wide Web: http://www.satobsys.co.uk/Jericho/webpages/jeripdf.html

Jones, P.D., Jónsson, T. and Wheeler, D. (1997). Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. International *Journal of Climatology*, 17: 1433-1450.

Kushnir, Y., Cardone, V.J., Greenwood, J.G. and Cane, M. (1997). On the recent increase in North Atlantic wave heights. *Journal of Climate*, 10: 2107–2113.

Law, F.M., Farquharson, F., Brampton, A., Dale, M. and Flather, R.A. (2003). Environmental change indicators (including those related to climate change) relevant to flood management and coastal defence. Defra/EA R & D technical report FD2311-TR.

Leggett, I., Beiboer, F.L., Osborne, M.J. and Bellamy, I. (1996). Long-term metocean measurements in the northern North Sea. Pp 1 to 9 in Climate change offshore N.W. Europe, SUT, London.

Tucker, M.J. and Pitt, E.G. (2001). Waves in ocean engineering. Elsevier Ocean Engineering Book Series (v.5), Elsevier, Amsterdam, 521pp. WASA Group (1998). Changing waves and storms in the northeast Atlantic. *Bulletin of the American Meteorological Society*, 79: 741-760.

Woolf, D.K., Challenor, P.G. and Cotton, P.D. (2002). The variability and predictability of North Atlantic wave climate. *Journal of Geophysical Research*, 107(10), 3145.

Woolf, D.K., Cotton, P.D. and Challenor, P.G. (2003). Measurements of the offshore wave climate around the British Isles by satellite altimeter. Philosophical Transactions: *Mathematical, Physical and Engineering Sciences*, 361(1802), 27-31.

7.7 LIST OF LINKS TO MONITORING NETWORKS AND DATA SETS

Online search interfaces for catalogues and inventories maintained by the IACMST's Marine Environmental Data Network
http://www.oceannet.org

CEFAS Coastal Temperature Network
http://www.cefas.co.uk/publications/catalogue.htm

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.

HumberNet
http://www.northseanet.co.uk/humber/digitaldisplay.htm and http://www.northseanet.co.uk

Liverpool Bay Coastal Observatory
http://cobs.pol.ac.uk/cobs/ctide

Meteorological and Wave monitoring network (METNET)
Shell UK Exploration and Production Ltd., Aberdeen

Satellite missions
http://www.cls.fr./html/oceano/projets/enact/project_en.html
http://www.soc.soton.ac.uk/lso/noindex/lso_data.php

Southeast Regional Coastal Monitoring Programme
http://www.channelcoast.org

Strategic wave-monitoring network for England and Wales (WaveNet)
http://www.cefas.co.uk/wavenet

8. Circulation

SUMMARY OF CHANGES AND TRENDS

- The deep outflow of cold water from the Nordic seas over the Greenland - Scotland ridge has fallen by 20 per cent since 1950, suggesting comparable reduced surface inflow from the Gulf Stream and the North Atlantic Current.

- Maximum flow conditions in the North Atlantic Current and the Subtropical Gyre occurred in 1995 and 2000 and minimum circulation conditions between 1996 and 1998.

- Two pulses of inflow into the North Sea in 1988/89 and 1998 coincided with unusually strong northward transport of anomalously warm water through the Rockall Trough.

- Coastal flow conditions from the Irish Sea to Scottish coastal waters changed considerably after 1977, with a further change in Irish Sea outflow during 1980 to 1981, after which the flow pattern returned to that of 1977-1980.

8.1 INTRODUCTION

8.1.1 TYPES OF CURRENT

Tidal currents, or 'streams', are 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 - the general response is to amplify the semi-diurnal (two tides a day) component of the tide. Particularly strong responses occur in the Irish Sea and the Bristol Channel.

Meteorologically forced 'surge' currents are due to variations in wind stress and atmospheric pressure. The former depends upon water depth and increases in importance as the depth decreases whereas the pressure effect is independent of depth. Surge currents have time scales of hours to days according to storm duration, water depth and the extent of the storm.

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 and freshwater inputs from rivers and the atmosphere respectively.

8.1.2 CIRCULATION

The net movement of water, the circulation, is driven by 'residual' currents due to the net tides, mean meteorological forcing and the mean density distribution. (Currents due to upwelling contribute to exchanges but do not contribute significantly to the net movement.) The idea that circulation is a smooth, wide constant flow tends to be supported because it's difficult to measure accurately (see Section 2) and so it has only been measured where it's strong and persistent. In reality, circulation is variable in space and time, especially on short term (daily and monthly), seasonal and inter-annual timescales.

8.1.2.1 Short-term mean circulation

As tidal currents are primarily oscillatory, they usually contribute little to daily mean circulation, although exceptions can occur where the water depth is shallow or in regions near to a headland or island. However, the whole flow pattern may reverse over a tidal cycle, particularly in estuaries.

Over a few days, the net movement is likely to be determined by the last storm, because then the surge currents are likely to exceed both the tidal and density currents in strength, and so the daily or monthly mean circulation may even be the reverse of the long-term pattern.

Refer to web version of this report to see an animation of flow reversal with the tide in the Humber estuary.[AVI animation, 41 MB]. Courtesy of ABP Hull.

Refer to web version of this report to see an animation of tide and surge currents during a specific storm event west of Ireland in 1995.[AVI animation, 3.2 MB].Courtesy of Alex Souza, POL.

8.1.2.2 Seasonal mean circulation

This 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). In particular, residual currents are generated by seasonally occurring 'fronts', the sharp boundary between well-mixed and stratified (layered) regions, with flow tending to be along the front. Some regions tend to remain well mixed throughout the year where depths are shallow and tidal currents are strong enough to provide the energy for mixing, but other regions exhibit seasonal stratification when mixing is insufficient to mix down lighter water at the sea surface (the water may be lighter either because of solar heat input during summer or because of freshwater river discharge).

Refer to web version of this report to see an animation of the evolution of surface to seabed temperature differences, and hence thermal fronts, in UK waters during 1995 (from a numerical model).[AVI animation, 8.1 MB]. Courtesy of Alex Souza, POL.

Usually, a frontal system includes a narrow (typically a few kilometres wide) jet-like current driven by the horizontal density difference (Rodhe, 1998). In particular, jets are associated with the margins of cold (or salty) dense bottom-water pools that remain trapped in deep basins during the summer months after the onset of summer stratification. Although relatively narrow, they can transport water over many hundreds of kilometres in areas of the North, Celtic and Irish Seas (see Section 4). The timing of the onset of this seasonal circulation is dependent on wind mixing, surface heat fluxes and freshwater input and may vary by up to a month (Brown *et al.*, 1999; 2003).

There is also a vertical variation of the seasonal mean circulation because jets are stronger near the surface and the relative contributions to the residual current from surge or density currents may vary with depth. This is illustrated in Figures 8.1 and 8.2, showing the circulation at a site in Liverpool Bay over a six-week period in winter and over a year respectively. (During the latter period, the residual currents would have transported water over 1 000 km from the point of measurement.) Both figures show the typical variability in the vertical of an 'estuarine/coastal' type circulation, with flow near the bed in towards the coast and away from the coast at the surface.

The prime driving force is density for both the outflow and the inflow, although the near surface is more affected by the wind (Howarth, personal communication).

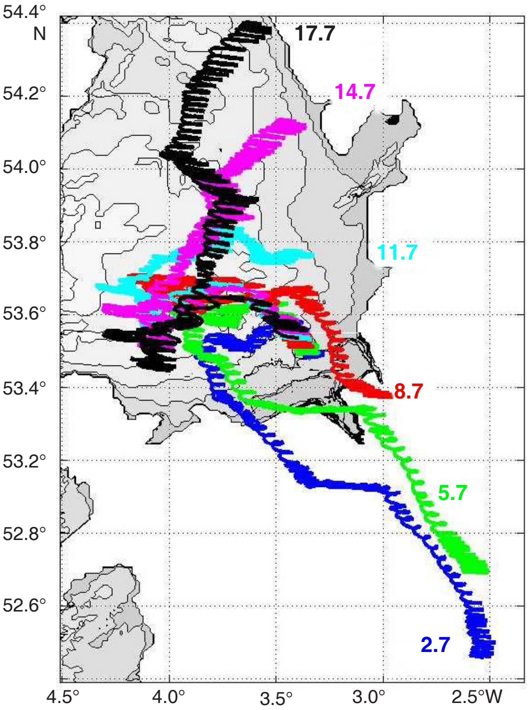


Figure 8.1. Progressive vector diagram of currents measured by an ADCP at the Liverpool Bay Coastal Observatory mooring, 23 January to 6 March 2003. Heights in metres above the seabed. Courtesy of John Howarth, POL

8.1.2.3 Long-term mean circulation

When averaged over a number of years, the long-term or 'climatological' mean circulation indicates some persistent features in UK waters but there are large uncertainties in estimates of its amplitude and a significant inter-annual variation in most regions (see sections 2 and 4).

The 'flushing time' is a concept used to represent the average time needed for complete replacement of the waters in a region. However, as it depends on both the circulation and also on the amount of mixing it is not easy to estimate and hides large local variations.

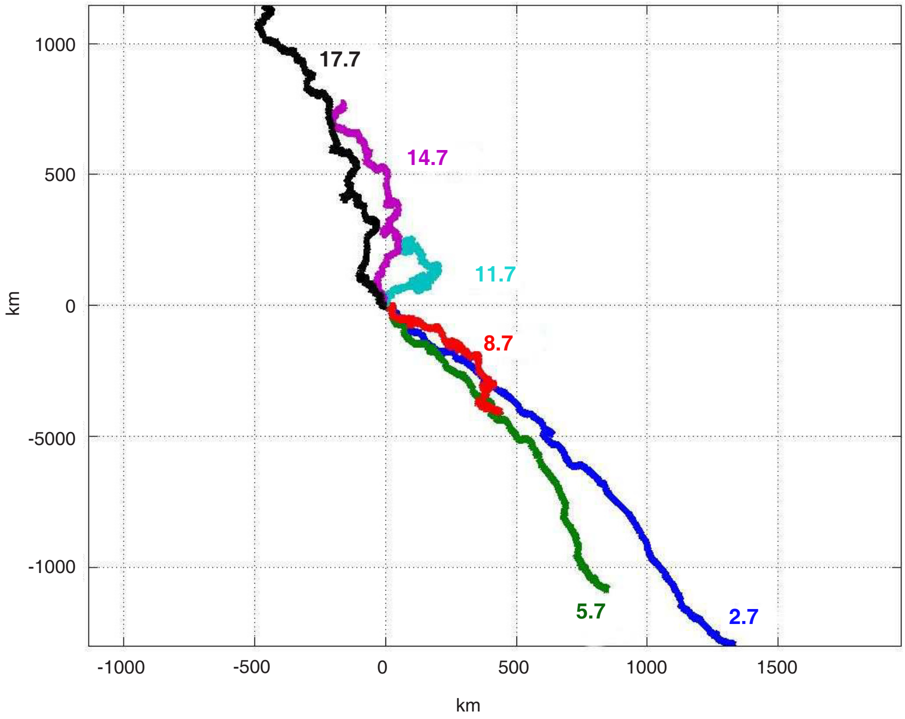


Figure 8.2. Progressive vector diagram of currents measured by an ADCP at the Liverpool Bay Coastal Observatory mooring, 7 August 2002 to 17 December 2003. Heights in metres above the seabed. Colour coding as for Figure 8.1. Courtesy of John Howarth, POL

8.1.3 THE SIGNIFICANCE OF CIRCULATION

The high density and specific heat of water means that it can store and transport large amounts of heat, so the role of 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, with some 30-50% of the energy carried by ocean currentsat mid latitudes and a higher proportion at lower latitudes (Bryden and Imawaki, 2001).

The overall movement and distribution of passive objects like eggs, larvae, nutrients, contaminants, flotsam and sediments are controlled by the circulation patterns. For example, the circulation flow off the north east coast of 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). On a smaller scale, the dispersal of herring larvae in the Blackwater estuary is dependent on the circulation in the area (Fox and Aldridge, 2000). In general, the movement will depend on the object's density – if neutrally buoyant or dissolved it will move with the water circulation; if it is particulate or heavier than water it will tend to sink and move less far; if it is floating it will be driven by the wind as well as the water circulation (see the chapter on Sediments for further details).

8.2 MEASURING CIRCULATION

The lack of spatially diverse and good quality long time series of observed currents makes the definition of long-term circulation and its variability difficult. Most long-term circulation patterns in UK waters have been inferred from the distribution of tracers like salinity or radionuclides or from numerical hydrodynamic models, optimised with any available observations.

8.2.1 MODELS

The use of models has to be treated with caution because experience from European seas projects such as ESODAE, NOMADS, NOWESP and PROMISE suggest that different models can give the closest reproduction of observations, hind-casting, at different times. In fact, occasionally, the outlier of an ensemble of hind casts from different models may be the closest to reality (Jones, 2002).

However, although there may be large variability in the hind-casting of day to day or month to month currents from different models, the models are more consistent when used to determine the long-term circulation. For example, as part of the NOWESP project, Smith et al. (1996) found that three different models from the Institute of Marine Research, the Institut für Meereskunde and the Proudman Oceanographic Laboratory showed similar and persistent patterns of variability in the water volume transports calculated across sections in the North Sea and in the English Channel when run for periods up to 39 years with long term meteorological forcing. They therefore indicated consistent long term or 'climatological' residual currents in broad agreement with the generally accepted circulation patterns inferred from observations (see sections 4.1 and 4.2). Although the transport calculations agreed very well in well-mixed water regions, there was poorer agreement in the deeper water regions of the northern North Sea where baroclinic effects due to density changes are important and were not well modelled. Also, agreement was poor in the Irish Sea because of model limitations, i.e. low resolution, between approximately 20 and 35 km, and unsuitable advection schemes which add additional structure such as eddies and gyres which are exaggerated when model resolution is poor. (In fact, the models gave a climatological residual flow direction from the north, contrary to the northerly transport indicated by observations (see section 4.3)).

The difficulty in obtaining consistent circulation patterns from models is illustrated from the results of the NOMADS2 project (Delhez *et al*., 2004), which compared nine 3-dimensional advection-dispersion models of the southern North Sea (to 57°N) run from November 1988 to October 1989. All the models used the same bathymetric, meteorological and hydrological data sets; the same initial and time-varying boundary conditions for water elevation, salinity, temperature and velocity) and the same prescription of the heat flux. However, the models varied with respect to horizontal and vertical resolution, the representation of surface wind stress and turbulence and the interpolation schemes used, i.e. the size of space and time steps. This led to large differences in some output parameters, e.g. there was a factor of 2.5 to 3 variation between models in the year-long volume residual fluxes across North Sea sections.

Delhez *et al*. (2004) concluded that much more development of 3-dimensional advection-dispersion models was needed before they are capable of delivering robust estimates of long term circulation patterns. Recently, POL's 3.5km 'ecosystem' model of the Irish and Celtic Sea (49 - 56°N and 2 - 10°W) has been run over a 40 year period from 1960 – 2000 using realistic meteorological and hydrological forcing, including inflows from 106 rivers. It has reproduced well the time series and interannual variation of bottom temperature and salinity at the Cypris station off the Isle of Man (and has also successfully reproduced the observed doubling of nutrients between 1950 and 1990 and the subsequent levelling off) (Proctor, personal communication). Such models indicate the potential to deliver 'state of the art' physics simulation, from which realistic circulation patterns could be derived, and point to the need for an eddy-resolving 50 year run of such models over the rest of the European shelf seas.

8.2.2 OBSERVATIONS

Observational data on circulation comes from current meter measurements, drifting buoys and floats, submarine and telephone cables (to measure induced voltages across channels) and the concentration distribution of 'tracers' like salinity and radionuclides (e.g. Caesium 137 and Technetium 99). However circulation is difficult to measure accurately and can only be measured where it is strong and persistent. There are problems with current meters and ADCPs because the circulation is a weak signal in the presence of much stronger signals (typically with a signal to noise ratio of about 1 per cent). The motion of floats is often difficult to interpret in continental shelf seas because of the usual short time of deployment and observation; and also because surface floats are affected by 'windage', the direct effect of the wind, so that their motion is not solely due to the current.) Circulation patterns can be determined well with tracers but the determination of current speed is difficult.

Descriptions of the monitoring networks which regularly measure currents and circulation are given in the chapter on Monitoring networks, including details of how to access near real-time data.

Also refer to the list of links to monitoring networks and data sets at the end of this chapter (section 6.).

8.3 CIRCULATION IN THE NORTH ATLANTIC AND ALONG THE CONTINENTAL SHELF EDGE

8.3.1 NORTH ATLANTIC

The North Atlantic Meridional Overturning Circulation (Namoc) is part of the current system that transports heat around the world. Surface currents, including the Gulf Stream and North Atlantic Current, transport (relatively) warm salty water into the Arctic. There the water loses heat and is diluted with fresh water from river inputs and the melting of ice and hence becomes denser; with deep colder fresher currents carrying the return flow southwards into the Atlantic. This ‘circulation conveyor belt’ helps drives Namoc and maintains the mild climate of northern Europe by warming the prevailing westerly winds blowing over the ocean surface.

The overflow and descent of cold dense water from the sills of the Denmark Strait and Faroe Shetland Channel is the principal means by which the deep Atlantic Ocean is ventilated and so is a key element of the Namoc. There is evidence (Dickson *et al*., 1999; 2002) that this system has steadily changed in character over the past four decades, resulting in a sustained and wide spread freshening of the deep waters south of the Greenland-Scotland ridge. Hansen *et al*. (2001) have monitored the deep outflow of cold water from the Nordic seas as it passes over the Greenland-Scotland ridge and show that the outflow has fallen by 20 per cent since 1950, suggesting comparable reduced inflow from the Gulf Stream and the North Atlantic Current.

The North Atlantic Oscillation (NAO) (see the chapter on Weather and climate) controls or modifies three of the main parameters that drive ocean circulation - wind speed, air/sea heat exchange and evaporation/precipitation. Pingree (2002) used satellite altimeter data from 1992 to 2002 to calculate sea level anomalies (sla) and thus determine the changes in North Atlantic circulation over that period. He showed that the long-term changes in the North Atlantic Current and the Subtropical Gyre transport during this period correlate with the winter NAO Index, with maximum flow conditions occurring in 1995 and 2000 and minimum circulation conditions occurred between 1996-1998. Years of extreme negative winter NAO Index resulted in enhanced poleward flow along the eastern boundary and anomalous winter warming along the west European Continental slope, as was measured in 1990, 1996, 1998 and 2001.

8.3.2 CONTINENTAL SHELF EDGE, INCLUDING ROCKALL TROUGH AND FAROE SHETLAND CHANNEL

Observations at the continental shelf edge indicate a poleward along-slope current, the European Slope Current (ESC), flowing along the entire length of the ocean-shelf boundary from the Goban Spur to north of Shetland, a distance of some 1600 km. The flow is forced by the combined effect of the steep topography and the mutual adjustment of shelf and oceanic regimes to meridional density gradients - the Joint Effects of Baroclinicity and Relief (JEBAR) effect (Simpson, 1998).

Currents and transports along the continental slope from the Celtic Sea to the Faroe Shetland Channel are summarised by Huthnance (1986). Estimated transports between the shelf break and the 2000m depth contour (probably the great majority) were fairly consistently poleward in the range 1 - 2 Sv (1 Sv = 10**6 m**3/s) from the Celtic Sea to the Wyville-Thomsen ridge. Mean current speeds were 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 about the ESC mean currents near the Celtic Sea (Pingree and le Cann, 1989; Pingree *et al*., 1999; Huthnance *et al*., 2001) indicates some evidence of seasonality with weaker flow in spring and stronger flow in autumn but does not change the overall transport estimate given by Huthnance (1986).

Holliday *et al*. (2000) and Holliday (2003) have 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.

Based on detailed year-round measurements during 1995-1996, Souza *et al*. (2001) found that the ESC at the latitude of the Malin Shelf (~56°N) west of the Hebrides 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 200m depth whereas in winter the flow was more nearly uniform in depth. The fastest mean flow was in 500 m depth 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 (Huthnance, personal communication).

At the Wyville-Thomsen Ridge (near 60°N with typical depth 400-500 m) there is a complex exchange of flow. Some of the deeper slope current from the Hebrides slope is probably diverted by the Ridge 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 the 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 (ICES 2003a). These additions result in an increased transport along the west Shetland slope, on average about 4.5 Sv with a spring minimum and autumn maximum (Huthnance, personal communication). 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 drifting floats. Released into the narrow slope current, floats 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).

Refer to the web version of this report to see an animation of the along-slope current, as measured by drifting floats (STEMgis).

8.4 CIRCULATION IN UK

Waters As discussed in section 8.1.2, circulation is variable in time and space and therefore it is 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) e.g. the north-easterly flow of the North Atlantic to the west of Ireland and Scotland, some aspects of flow in the North Sea, the north-easterly flow from the Dover Straits into the North Sea and the mean flow northwards through the Irish Sea. For this reason authors are reluctant to produce over-simplified maps of general circulation patterns.

The models discussed in section 8.2.1 show some consistencies in the pattern of long-term climatological circulation of the North Sea and English Channel, in broad agreement with those inferred from observations, (but not in the Irish Sea).

Refer to the web version of this report to see the table of annual mean transports (Sv) through shelf sections (see figure 8.4) for the period 1955-1993 and M2 residual transport from the POL model.

8.4.1 NORTH SEA

The dominant motion in the western and southern parts of the North Sea is tidal, whereas the wind is the dominant source of energy in the northern and eastern parts (Rodhe, 1998). The tides enter the North Sea from the Atlantic Ocean north of Scotland and sweep around it in an anticlockwise direction. Surges travel anti-clockwise: southwards along the eastern UK coast and then northeastwards along the coast of continental Europe. Tidally generated residual currents are generally small compared with density-driven currents and wind-driven currents, but are responsible for a significant part of the residual currents in the western and southern parts. The wind-driven currents are induced by mostly south-westerly and westerly winds, but easterly winds, which occur mostly in spring and summer, can reverse the broadly anti-clockwise circulation.

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 of about 30 to 40m deep (Howarth,

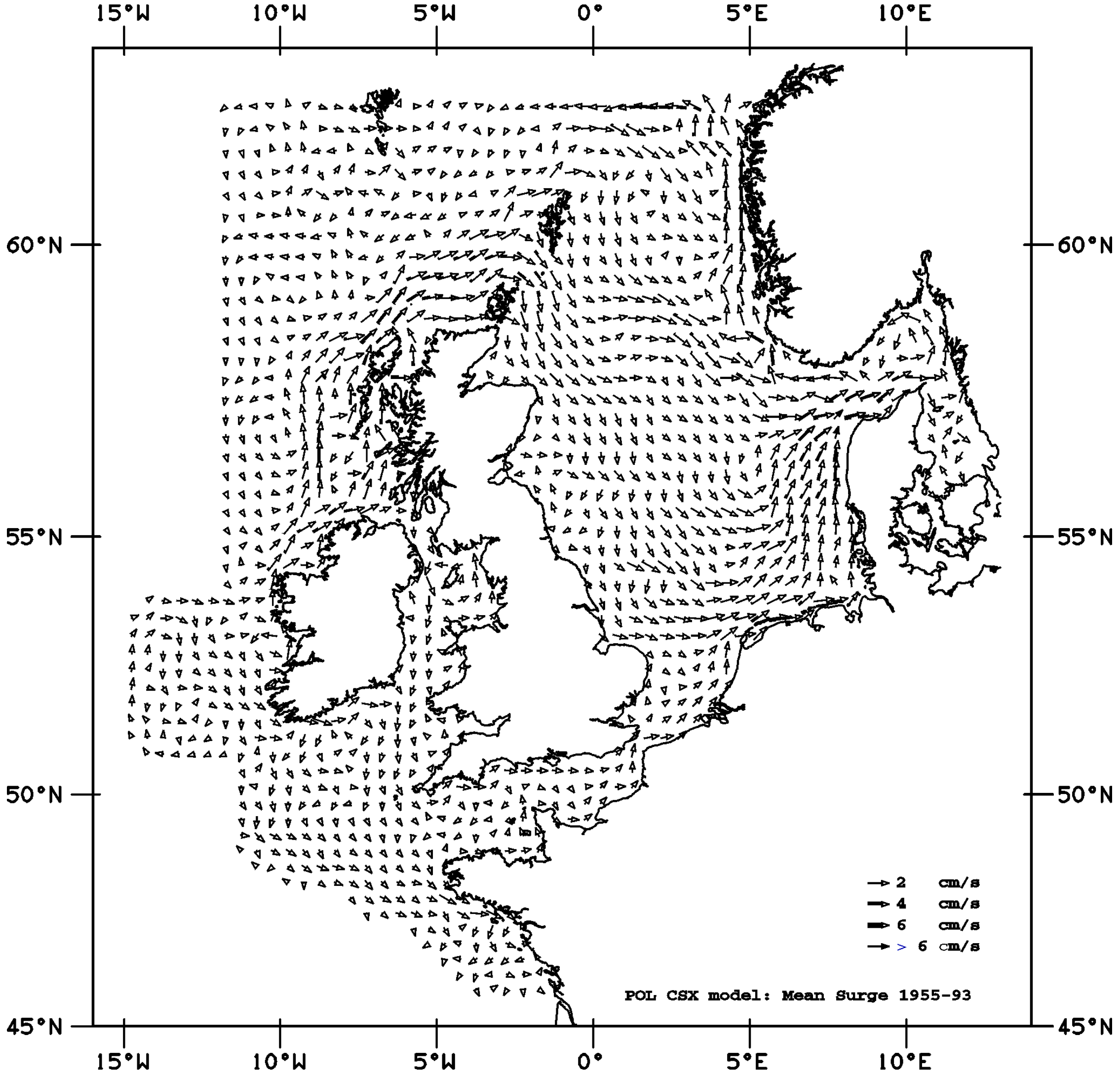


Figure 8.3. Climatological residual currents from the POL model based on annual means from 1955-1993 (Figure 2, Smith *et al*., 1996). Courtesy of Jane Williams, POL

2001). In autumn, heat loss at the surface leads to the surface mixed layer deepening and cooling until the bottom is reached in October/December. The tidal energy in the southern and western regions is strong enough to keep the water column well mixed most of the year, but some coastal regions stratify because of freshwater river discharge, with the fresher water tending to form a thin surface layer about 30km wide which stays close to the coast (Howarth, 2001).

The fronts in the northeast of the North Sea (outside UK waters) are related to the low-saline water in the Norwegian Coastal Current. The main front in the central North Sea separating the thermally stratified water in summer to the north from the well-mixed water from the south starts from Flamborough Head, bifurcates around the Dogger Bank and passes to the north of the Frisian Islands (Howarth, 2001). Some of the fronts in the southern North Sea are related to

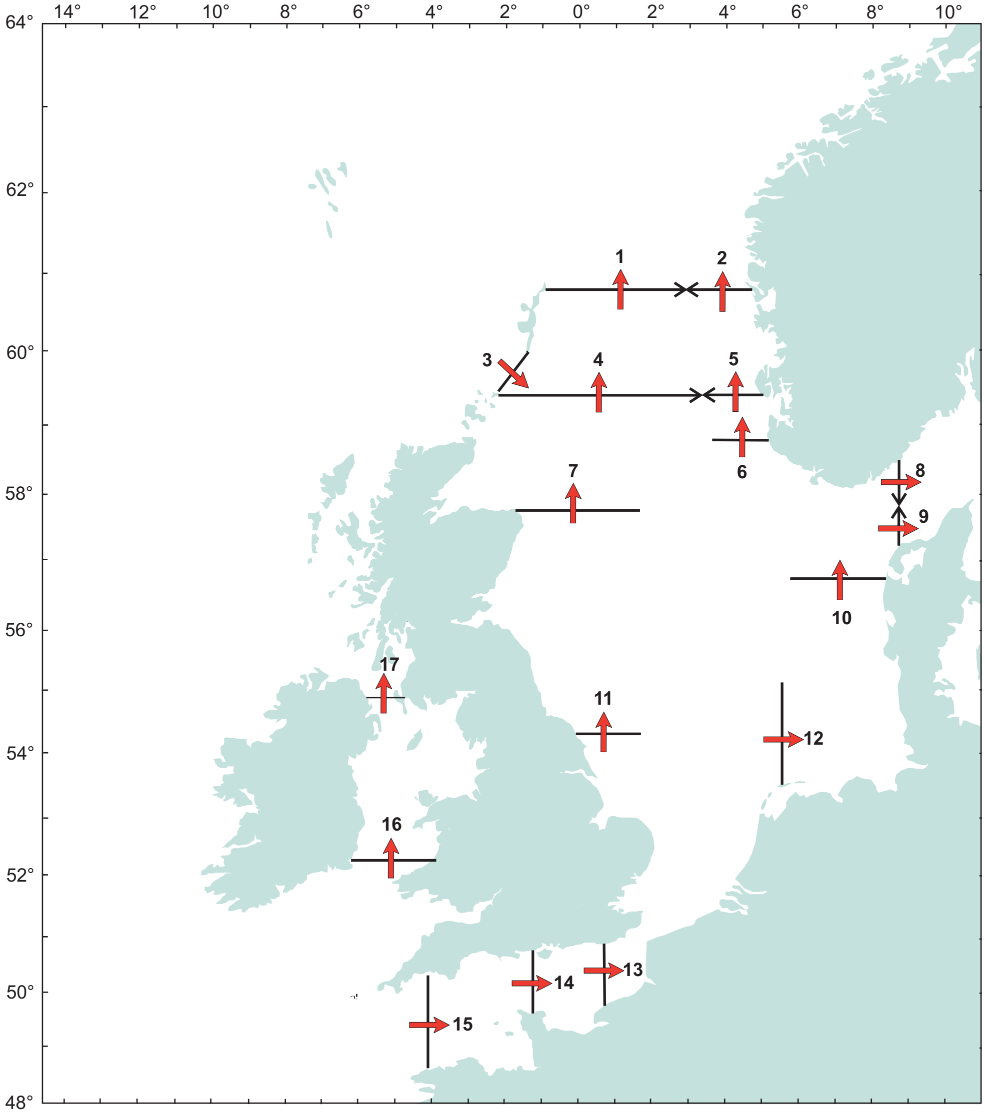


Figure 8.4. Locations and reference numbers of the shelf sections. Arrows indicate positive transport direction (Smith *et al.*, 1996). Courtesy of Jane Williams, POL

freshwater outflow from rivers, but most are tidal fronts (Rodhe, 1998).

Go to http://www.offshore-sea.org.uk/sea/dev/html_file/sea2_consult.cgi?sectionID=43 to see a schematic diagram of frontal zones and stratification of the North Sea (Figure 5.11).

A major contribution to the seasonal circulation of the central North Sea is the existence of a persistent and narrow (10 to 15 km) near-surface flow extending continuously for ~ 500 km along the 40 m contour between the Firth of Forth and the Dogger Bank, associated with strong bottom fronts bounding a pool of cold, dense bottom water isolated below the seasonal thermocline (Brown *et al*., 1999).

The overall pattern of the mean circulation in the North Sea is broadly anti-clockwise around the coasts, with weak and varied circulation in the centre. The mean coastal flow is southward past Scotland and England and into the Southern Bight, where there are inputs of salty water through the Dover Straits and of fresh water down the main rivers, and on into the German Bight, flowing northward past Denmark in the Jutland current to join the Norwegian Coastal Current in the Skagerrak (Rodhe, 1998; Howarth, 2001).

There are major inflows in excess of 1 Sv of water of Atlantic origin across the northern boundary but very little penetrates far into the North Sea. The larger portion flows along the western slope of the Norwegian Trench and recirculates in the Skagerrak, flowing 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 4.4) flows in east of Shetland and between Shetland and the Orkney Islands. However, most of the flow is guided eastwards to the trench by the topography along the 100 m-depth contour, and only a small part flows southward along the coast of Scotland and England. Less than 10 per cent of the inflow to the North Sea enters through the English Channel. The only major outflow from the North Sea is along the eastern side of the Norwegian Trench and is approximately 1.3 to 1.8 Sv. The bulk of the transport in the circulation is concentrated in the northern part of the North Sea and in the region of the Norwegian Trench, with the main outflow along the Norwegian coast in the NCC (Howarth, 2001).

The flushing time, for the complete renewal of the water, is about one to three years (Simpson, 1998).

Visit http://www.offshore-sea.org.uk/sea/dev/html_file/sea2_consult.cgi?sectionID=43 to see a schematic diagram of the general circulation in the northern North Sea (Figure 5.10).

Table 8.1 shows mean transport (Sv) across sections in the North Sea over 1987-1993 from three numerical models (Smith *et al*., 1996).

Table 8.1. Mean transport (Sv) across sections* in the North Sea over 1987-1993 from three numerical models (Smith *et al*., 1996). Courtesy Jane Williams, POL

Section	IfM		POL		IMR	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	-0.46	0.05	-0.15	0.05	-1.13	0.12
2	1.32	0.09	0.53	0.16	2.08	0.32
3	0.77	0.05	0.31	0.10	0.31	0.07
4	-1.11	0.07	0.12	-1.39	0.21	
5	1.32	0.07	0.46	0.14	1.61	0.24
6	1.03	0.06	0.35	0.11	1.59	0.19
7	-0.46	0.08	-0.13	0.07	-0.14	0.08
8	0.02	0.04	-0.23	0.06	-0.42	0.06
9	-0.09	0.04	0.24	0.07	0.39	0.06
10	0.25	0.07	0.15	0.06	0.42	0.09
11	-0.11	0.02	-0.01	0.01	-0.04	0.03
12	0.18	0.04	0.09	0.04	0.20	0.05

* Refer to Figure 8.4 for locations of sections in the North Sea

Holliday *et al*. (2001) conclude that two pulses of oceanic inflow into the North Sea in 1988 and 1998 coincided with unusually strong northward transport of anomalously warm water at the edge of the continental shelf through Rockall Trough (see section 3.2). However they point out that factors other than the strength of the shelf edge current may be important for timing of inflow events, including the influence of local wind-driven advection. For example, they report that while high flows were measured in the Norwegian shelf edge current in 1996 (Mork and Blindheim, 2000), the inflow to the North Sea in that year was low and southerly warm-water plankton did not penetrate into the basin. This reduction in flow is thought to be a consequence of the pronounced reversal of the NAO and its effect on local winds in the winter of 1995/96. In contrast, they point out that in the winter of 1997/98, when the NAO was positive, the warm waters of the shelf edge again contributed southerly oceanic plankton to the North Sea (Reid *et al*., 1998).

8.4.2 ENGLISH CHANNEL AND CELTIC SEA, INCLUDING THE BRISTOL CHANNEL

The residual flow along the English Channel is from west to east, driven by non-linear tides (due to strong tidal forcing from the Atlantic), predominantly south-westerly prevailing winds and density currents (primarily due to freshwater discharge from the rivers draining the south coast of the UK and the continental coast - most of the regions of strong tidal flow are continuously mixed). Prandle *et al*. (1993) estimated the net flux north-eastward through the Dover Straits as 0.11 Sv, but subsequent measurements by Prandle and Player (1993) revealed a complex flow pattern including the existence of an anticlockwise gyre off Cap Gris Nez; thus emphasising the difficulty in quantifying the long-term net flow.

Analysis by Pingree and le Cann (1989) of an extensive compilation of current meter data and observations of the distribution of the radionuclide Caesium 137 released from Sellafield and Cap de la Hague show a generally weak mean circulation in the Celtic Sea.

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 experiences strong thermal stratification, occurring where tidally-generated turbulent energy is insufficient to mix the increased surface heat input from solar heating throughout the water column. The summer seasonal circulation is dominated by strong anti-clockwise jets associated with bottom fronts bounding a cold saline pool (Brown et al., 2003) – the northward flowing jet on the eastern side of St George’s Channel transports water rapidly from the mouth of the Bristol Channel towards the Irish Sea.

There is an overall weak eastward residual flow in the Bristol Channel and the estimated flushing time is from 150 to 300 days. Prevailing south-westerly winds drive a flow northward along the Cornish coast and density gradients also contribute to the weak circulation, with depth-averaged flow into the channel in deeper water, and return down-channel flow in shallower waters. However, during periods of high freshwater input these flows are significantly enhanced, although no direct measurements have been made. There is a complex residual circulation within the Bristol Channel comprising of a series of closed eddies, arising primarily as water flows past headlands, bays and islands; but they contribute little to the overall mean circulation (Defra, 2000).

Along the northern coast of the Bristol Channel, between Carmarthen Bay and Nash Point, flow is also eastward. However as water is piled up into the channel an adverse pressure gradient is created, and this drives a depth-mean flow westwards along the central axis of the channel. This flow is then steered northward around St David’s Head and into the Irish Sea. There is also an indication of a large-scale, but weak, anti-clockwise recirculation at the mouth of the channel, the northward-flowing arm of which causes flow across the mouth of the channel at about 5°W (Defra, 2000).

8.4.3 IRISH SEA

Both surge and density driven currents contribute significantly to the overall long-term mean circulation of the Irish Sea. The latter are particularly important in the eastern Irish Sea where the differences between the saline oceanic inflows and freshwater input from the Rivers Dee, Mersey, Lune and Ribble cause horizontal and vertical density changes in Liverpool Bay. These flows are strongest in winter and spring but can be overwhelmed during periods of strong winds (Defra, 2000).

Refer to the web version of this report to see an animation of the 3D development of temperature structure across an Irish Sea cross section during 1998 (from a numerical model). Courtesy of POL.

The distribution of Caesium 137 discharged from Sellafield has been used to infer the mean surface water circulation in the Irish Sea (Jefferies and Steel, 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 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 anti-clockwise round the Isle of Man before rejoining the main flow to exit through the North Channel (Defra, 2000). The flushing time is more than one year (Simpson, 1998).

Most regions of the Irish Sea are continuously mixed, because of the strong tidal currents. 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 former, 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 that acts to retain material in the region (Hill *et al*., 1997) but which does not contribute substantially to the net circulation of water. Following the breakdown of stratification in autumn, the mean flow is then weakly northward until the following spring.

There is evidence that there has been a considerable change in flow conditions in the Irish Sea during the last thirty years. McKay and Baxter (1985) and Jefferies and Steele (1989) found that they could only obtain a reasonable fit between observations of the concentration of Caesium 137 and model predictions by changing the circulation pattern and strength in their numerical models. The former found that the coastal flow conditions from the northeast Irish Sea to western Scottish coastal waters had changed considerably since 1977, with a further change in Irish Sea outflow during 1981. The latter had to infer a factor of two change in the Irish Sea circulation in the mid 1970s, having to double the flow rate out of the North Channel from the end of September 1976. Also they inferred that a change in flow took place in the 1980-81 period, after which the flow pattern returned to that of 1977-1980.

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. For example, a positive Index results in a higher frequency of Atlantic storms, the centres of which track to the north of Britain and so promote northerly and westerly winds over the Irish Sea region. There will then be an increased incidence of storm surges in the eastern Irish Sea and Liverpool Bay, enhancing the contribution of surge currents to the overall circulation. Also, it is conceivable that changes in storm tracks may regulate the circulation and flushing of the region (Defra, 2000).

8.4.4 MINCHES, WEST SCOTLAND AND SCOTTISH CONTINENTAL SHELF

The mean flow through the North Channel is northwards, occurring as a series of pulses in response to the effects of the wind. However, overall outward flow is strongest on the eastern (Scottish) side of the channel, with a weaker surface return flow along the Irish coast, see Figure 8.5. Knight and Howarth (1999) give an estimate of the flow through the North Channel of 0.077 Sv, based on one year's measurements from July 1993 to July 1994.

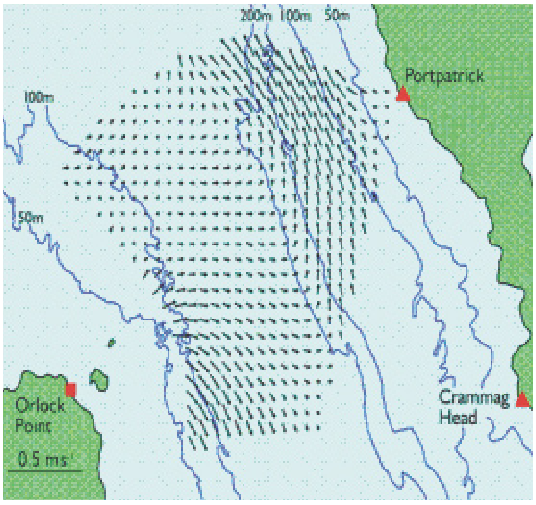


Figure 8.5. Surface mean flows in the North Channel measured by HF radar, July 1993 to August 1994. Courtesy of John Howarth, POL

There is considerable variability in the vertical structure of the flows through the North Channel. Figure 8.6 shows the relative magnitude and direction of mean flow over a 15-month period. The near-surface mean flow was directed towards the Irish Sea, depth-averaged mean flow was directed across the channel towards the Scottish coast and near-bottom flow was directed towards the Malin Shelf. However episodes of residual flow can be seen in the top two vector diagrams often in opposition to the direction of mean flow with larger temporal variations at the near-surface, while at the near-bottom the flow was more stable and showed less time variability. Strong winds from the southeast between 1st and 28th February caused the largest reversals of near-surface flow from the direction of near-surface mean flow (Knight and Howarth, 1999).

The salinity deficit of the water flowing out of the Irish Sea through the North Channel is enhanced further by the substantial discharge of freshwater from the Clyde Sea and other sources along the Scottish coast, including the Firth of Lorne. Under the influence of the earth's rotation, this low-density water moves northward in a well-defined Scottish Coastal Current (SCC) (Simpson, 1998).

The flow of the SCC in the Tiree Passage has been measured since 1981 (Inall and Griffiths, 2003). The along-channel residual flow shows a seasonal variation and has a mean value of 10.8 cm/s directed towards the north, with very few, short duration periods of flow reversal. The mean volume flow through the passage is calculated as 0.067 Sv, a similar figure to that for the North Channel outflow, although Inall and Griffiths state that this is clearly not the same water. (Caesium 137 studies (McKay *et al*., 1986) indicate the average dilution ratio of North Channel water to Atlantic water in the Tiree Passage to be approximately 3:1.) At the entrance to the Minch, the Scottish Coastal Current divides, with one branch flowing through the channel between the Outer Hebrides and the Scottish mainland and the other turning south and the west around Barra

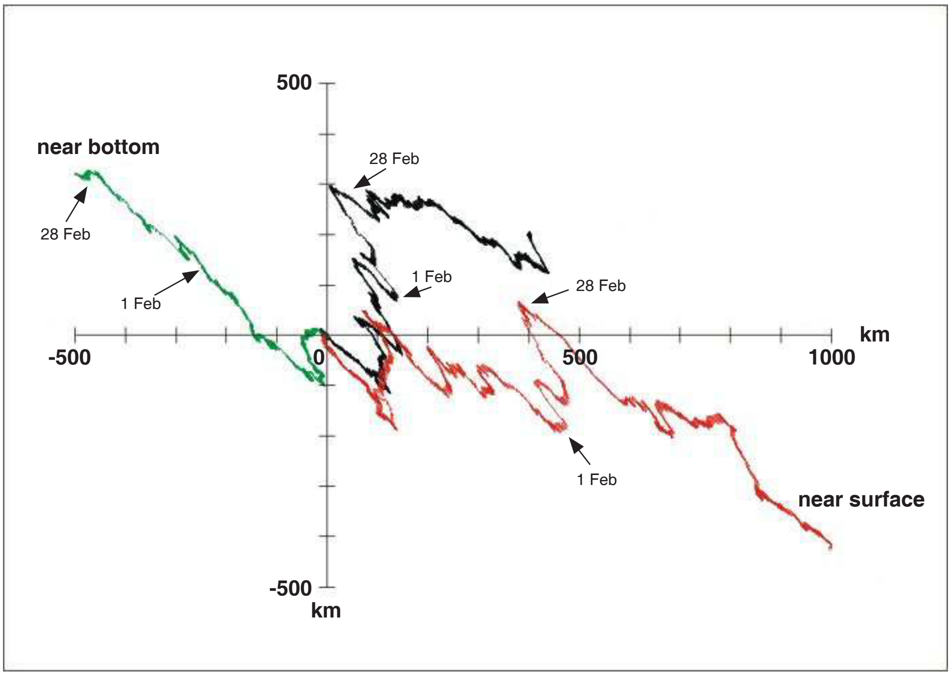


Figure 8.6. Progressive vector diagram of currents measured by an ADCP in the North Channel, 13 July 1993 to 28 October 1994. Courtesy of John Howarth, POL

Head before flowing northward up the west coast of the Hebrides. The flow is forced to a significant degree by wind stress, with the pulsed nature of the flow associated with the passage of depressions to the north of the British Isles (Simpson, 1998).

8.5 REFERENCES

Brown, J., Hill, A.E., Fernand, L., Horsburgh, K.J. (1999). Observations of a seasonal jet-like circulation at the central North Sea cold pool margin. *Estuarine Coastal and Shelf Science, 48*: 343-355.

Brown, J., Carillo, L., Fernand, L., Horsburgh, K.J., Hill, A.E., Young, E.F. (2003) Observations of the physical structure and seasonal jet-like circulation of the Celtic Sea and St. George's Channel of the Irish Sea. *Continental Shelf Research*, 23: 533-561.

Bryden, H.L. and Imawaki, S. (2001). Ocean heat transport in: Siedler, G., Church, J. and Gould, J. Editors. Ocean Circulation and Climate: Observing and Modelling the Global Ocean, San Diego CA, Academic Press, 455-474.

Defra (2000). Quality Status Report of the Marine and Coastal Areas of the Irish Sea and Bristol Channel. Retrieved 14th September from the World Wide Web: http://www.defra.gov.uk/environment/marine/quality/03.htm

Delhez, É.J.M., Damm, P., de Goede, E., de Kok, J.M., Dumas, F., Gerritsen, H., Jones, J.E., Ozer, J., Pohlmann, T., Rasch, P.S., Skogen, M. and Proctor, R. (2004). Variability of shelf-seas hydrodynamic models : lessons from the NOMADS2 Project. *Journal of Marine Systems*, in press.

Dickson R.R., Meincke, J., Vassie, I., Jungclaus, J. and Østerhus, S. (1999). Possible predictability in overflow from the Denmark Strait. *Nature*, 397: 243-246.

Dickson R.R., Yashayaev, I., Meincke, J., Turrell, W.R., Dye, S.R. and Holfort, J. (2002). Rapid Freshening of the Deep North Atlantic over the past Four Decades. *Nature*, 416: 832-837.

Fox, C.J. and Aldridge, J.A. (2000). Hydrographic circulation and the dispersal of herring larvae in the Blackwater estuary. *Journal of the Marine Biological Association of the UK*, 80(5): 921-928.

Hansen, B., Turrell, W.R. and Østerhus, S. (2001). Decreasing overflow from the Nordic seas into the Atlantic Ocean through the Faroe Bank channel since 1950. *Nature*, 411: 927 – 930.

Hill, A.E., Brown, J. and Fernand, L. (1997). The summer gyre in the western Irish Sea: shelf sea paradigms and management implications. *Estuarine Shelf and Coastal Sciences*, 44: 83 - 95.

Holliday, N.P. and Reid, P.C. (2001). Is there a connection between high transport of water through the Rockall Trough and ecological changes in the North Sea? *ICES Journal of Marine Science*, 58: 270-274.

Holliday, N.P. (2003). Extremes of temperature and salinity during the 1990s in the northern Rockall Trough: results from the 'Ellett line'. *ICES Marine Science Symposia*, 219: 95-101.

Howarth, M.J. (2001). North Sea Circulation. pp 1912 – 1921 *In* Encyclopaedia of Ocean Science volume IV, (Steele, J.H. Editor in Chief.) Academic Press.

Huthnance, J.M. (1986). The Rockall slope current and shelf-edge processes. *Proceedings of the Royal Society of Edinburgh*, 88B: 83 - 101.

Huthnance, J.M., Coelho, H., Griffiths, C.R., Knight, P.J., Rees, A.P., Sinha, B., Vangriesheim, A., White, M. and Chatwin, P.G. (2001). Physical structures, advection and mixing in the region of Goban Spur. Deep-Sea Research II, 48: 2979-3021.

ICES (2003a). The 2002/2003 ICES Annual Ocean Climate Status Summary. Prepared by the Working Group on Oceanic Hydrography, ICES, Copenhagen, Denmark. (Editors: Hughes, S.L. and Lavín, A.) Retrieved 4th October 2003 from the World Wide Web: http://www.ices.dk/status/clim0203/IAOCSS2002.PDF

Inall, M. and Griffiths, C. (2003). The Tiree Passage Time Series: 1981 – 2003. Retrieved 11th January 2004 from the World Wide Web: Retrieved 10th September 2003 from the World Wide Web: http://www.sams.ac.uk/dml/projects/physics/tiree/tiree.pdf

Irish, R. (2003). Monitoring of the quality of the marine environment, 1999-2000. Scientific Series, Aquatic Environment Monitoring Report, CEFAS, Lowestoft, 54, 98pp.

Jefferies, D.F. and Steele, A.K. (1989). Observed and Predicted Concentrations of Caesium-137 in Seawater of the Irish Sea 1970-1985. *Journal of Environmental Radioactivity*, 10: 173 – 189.

Jones, J.E. (2002). Coastal and Shelf–Sea modelling in the European context. Pp 37-141 *In* Oceanography and Marine Biology: an Annual Review 2002 (Gibson, R.N., M. Barnes and R.J.A. Atkinson, Editors). Taylor & Francis.

Knight, P.J. and Howarth, M.J. (1999). Flow through the North Channel of the Irish Sea. *Continental Shelf Research*, 19: 693-716.

Levitus, S., Antonov, J.I., Boyer, T.P. and Stephens, S. (2000). Warming of the World Ocean. *Science*, 287: 2225-2229.

McKay, W.A. and Baxter, M.S. (1985). Water transport from the north-east Irish Sea to western Scottish coastal waters. *Estuarine and Coastal Shelf Science*, 21: 471-480.

McKay, W.A., Baxter, J.M., Ellett, D.J. and Meldrum, D.T. (1986). Radiocaesium and Circulation Patterns West of Scotland. J*ournal of Environmental Radioactivity*, 4: 205-232.

Mork, K. A. and Blindheim, J. (2000). Variations in the Atlantic inflow to the Nordic Seas, 1955-1996. *Deep Sea Research*, 47: 1035-1057.

Pingree, R.D., and Le Cann, B. (1989). Celtic and Armorican shelf and slope residual currents. *Progress in Oceanography*, 23: 303-338.

Pingree, R.D., Sinha, B. and Griffiths, C.R. (1999). Seasonality of the European slope current (Goban Spur) and ocean margin exchange. *Continental Shelf Research*, 19: 929-975.

Pingree, R.D. (2002). Ocean structure and climate (Eastern North Atlantic): in situ measurement and remote sensing (altimeter). J*ournal of the Marine Biological Association of the United Kingdom*, 82: 681-705.

Prandle, D., Jago, C.F., Jones, S.E., Purdie, D.A. and Tappin, A. (1993). The influence of horizontal circulation on the supply and distribution of tracers. *Philosophical Transactions of the Royal Society of London, A*, 343: 405 - 421.

Prandle, D. and Player, R.J. (1993). Residual currents through the Dover Straits measured by H.F. radar. *Estuarine, Coastal and Shelf Science*, 37: 635 – 653.

Reid, P.C., Edwards, M., Hunt, H.G., and Warner, A.J. (1998). Phytoplankton change in the North Atlantic. *Nature*, 391: 546.

Rodhe, J. (1998). The Baltic and North Seas. Pp 699 – 732 *In* The Sea, Volume 11, edited by A. R. Robison and K.H. Brink, John Wiley & Sons. Inc.

Simpson, J.H. (1998). The Celtic Seas. Pp 659-582 *In* The Sea, Volume 11, edited by A.R. Robinson and K.H. Brink, John Wiley & Sons, Inc.

Smith, J.A., Damm, P.E., Skogen, M.D., Flather, R.A. and Pätsch, J. (1996). An investigation into the variability of circulation and transport on the north-west European shelf using three hydrodynamic models. *Deutsche Hydrographische Zeitschrift,* 48: 325 – 348.

Souza, A.J., Simpson, J.H., Harikrishnan, M. and Malarkey, J. (2001). Flow structure and seasonality in the Hebridean slope current. *Oceanologica Acta*, 24: S63-S76.

8.6 LIST OF LINKS TO MONITORING NETWORKS AND DATA SETS

Online search interfaces for catalogues and inventories maintained by the IACMST's Marine Environmental Data Network
http://www.oceannet.org

Argo project
http://www.metoffice.com/research/ocean/argo

HumberNet
http://www.northseanet.co.uk/humber/digitaldisplay.htm
and
http://www.northseanet.co.uk
Liverpool Bay Coastal Observatory
http://cobs.pol.ac.uk

Satellite missions
http://www.cls.fr./html/oceano/projets/enact/project_en.html
http://www.soc.soton.ac.uk/lso/noindex/lso_data.php

Tiree Passage time series
http://www.sams.ac.uk/dml/projects/physics

9. Sediment concentration and transport

SUMMARY OF CHANGES AND TRENDS

- The North Sea has both southerly and northerly offshore sediment transport - northerly transport in the central eastern regions of the southern North Sea, southerly transport nearer the UK coast and several areas of variation in the northern North Sea.
- The nearshore transport is predominantly southerly on N-S orientated sections and westerly on E-W orientated sections.
- The English Channel has both westerly and easterly offshore sediment transport. The nearshore transport is predominantly easterly, with some reversals in the lee of headlands.
- The Celtic Sea has a variable offshore sediment transport. The nearshore transport is predominantly northerly on the N-S orientated coasts and easterly on E-W orientated coasts.
- The Irish Sea has southerly and south-westerly offshore sediment transport on the North Wales coast south of the Lleyn Peninsula and northerly and north easterly offshore transport north of the Lleyn Penisula (Bardsey Sound). The nearshore transport is predominantly northerly on the N-S orientated sections of the coast and easterly on E-W orientated sections.
- Turbidity (water clarity) in the Menai Straits (Irish Sea) deteriorated from the mid 1960s to the late 1980s.
- There was no overall trend turbidity in the Irish Sea between 1987 and 1997.

9.1 INTRODUCTION

This chapter deals with the transport of sediment formed from mineral particles and does not consider the other two components of ‘suspended particulate matter’ (SPM): living plankton and phyto-detritus. (Plankton are considered in the Sector Report on Marine Fisheries). However, ‘turbidity’ is included and is a measure of the amount of SPM in the water, including organic and inorganic material, which results in the 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, chlorophyll and the water itself (Bowers *et al*., 2002).

Major sources of data and information for this chapter are the Futurecoast report and the Southern North Sea Sediment Transport Study Phase 2 (SNS2).

The Futurecoast study was commissioned by Defra and carried out by a team led by Halcrow Group Ltd. The study provides predictions of coastal evolutionary tendencies over the next century, based on the use of data sets, information and experience of coastal systems. The output from the study is available on an interactive CD (Defra, 2002) and includes reports, guidance, data and mapping at various scales.

The SNS2 (HR, 2002) was designed to provide the broad appreciation and detailed understanding of sediment transport between Flamborough Head and the North Foreland. The study was undertaken between 2000 and 2002 by a consortium comprising of HR Wallingford, CEFAS Lowestoft Laboratory and UEA Norwich, Posford Haskoning and independent consultant Dr Brian D'Olier. It built on the earlier Phase 1 study completed in 1996 (ABP 1996). Other useful review sources are the Strategic Environmental Assessment documents and reports produced by the Department of Trade and Industry (DTI, 2004) for parts of the North Sea, English Channel/Celtic Sea, Irish Sea and the Western Approaches.

9.1.1 THE SIGNIFICANCE OF SEDIMENTS

Sedimentary processes affect the coastal and marine environment in a variety of ways:

- the evolution of the coast, the foreshore and the seabed. Any net erosion or accumulation has consequences for the management of the coastline and of coastal and offshore sediment assets (see the chapter on "Changing coast and seabed"). The Foresight Flood and Coastal Defence Project (OST, 2003) has identified the role of sediments in coastal dynamics as a main 'driver' in changing the risk of coastal flooding around the UK coast.

- the transport of contaminants. Fine sediment particles can be maintained in suspension for all, or part, of the tidal cycle by tidally driven turbulence because of their low settling velocity. Although they usually represent only a small fraction of water column mass, these particles have a large surface area and act as adsorption hosts to various natural and pollutant chemicals, which are consequently transported with the sediment particles.

- the species composition and population of the marine ecosystem. In general, fine muddy sediments have a high content of organic matter that can support a rich community of molluscs, worms and crustaceans. Sandy sediments generally contain a fauna adapted for life in a relatively mobile substrate. Crustaceans dominate in reasonably stable sands and worms and bivalves become more common in muddier sands (Hawkins and Cashmore, 1993). Very coarse gravelly or pebbly sediments are often located in regions of very high currents and/or large waves, with a resulting different assemblage.

Turbidity also has an effect on the marine ecosystem - highly turbid water may inhibit growth by reducing both the amount of light available for photosynthesis (Dennison, 1987) and, in shallow waters, the amount of dissolved oxygen, because the water becomes warmer due to the absorption of heat from sunlight by the suspended particles.

9.1.2 SEDIMENTARY PROCESSES

The concentration of suspended sediment in UK waters depends upon a wide range of physical processes, and the presence or absence of fine sediment. Suspended sediment concentration (SSC) is the net result of the 'erosion-transport-deposition (ETD) cycle'. Sediment transport is initiated by the shear stress imposed upon the bed by waves and currents, and transport is predominantly brought about by advection due to a combination of surge-, tide-, wave- and density-induced currents. SSC is thus highly variable and at any one place can vary by more than one order of magnitude over periods of minutes and hours. Further, because in many cases the suspended sediment is derived from the seabed, SSC can vary greatly vertically in the water column, and spatially. Time-series data are thus essential to the effective description and understanding of SSC and its variations, and associated measurements of physical processes are vital in order to correctly ascribe cause and effect.

Sedimentary processes are primarily influenced by the sediment type and availability, and by the nature of currents and waves. In a wave-dominated environment (such as an exposed coast or in shallow water), waves will generally be the dominant mechanism for resuspending sediment into the water column, and the sediment is then transported by the current. In a current-dominated environment (typically offshore deeper water or in an estuary) the currents and waves may both be important stirring mechanisms, and again the current transports the mobilised sediment.

Most types and sizes of sediment grains are moved only when the waves and/or currents are strong enough to exceed its threshold of motion. For very fine grains, they will tend to be transported at the same rate as the transporting fluid. In contrast, for sands and gravel, once in motion under the action of currents, the rate of transport is generally proportional to the third or fourth power of 'excess' current speed or wave height ('excess' being the magnitude above the grain threshold of motion). Hence, the residual pathways of sediment transport may be very different to the distribution of the residual current (Soulsby, 1997).

The transport of suspended sediment is highly dependent on grain settling velocity. Generally, the transport of slowly settling particles is controlled by the residual circulation, but the transport of faster settling particles occurs via a series of episodes of resuspension from and settlement upon the sea bed, and therefore is controlled by specific tidal, wind and wave conditions (Prandle *et al*., 1993). For example, large bottom shear stresses induced by tidal currents can drive the transport of larger particles along the seabed (bedload) and induce the regular resuspension and transport of the fine sediments in the water column. Asymmetry between ebb and flood tidal currents can induce net sediment transport ('Stokes drift') (Simpson, 2001).

Very fine sediments (clay-size grains) will generally remain suspended in areas of strong tidal currents or significant wave action, but there are some regions around the UK where they can be deposited (such as the head of some estuaries). In contrast, silt-size particles may be periodically deposited and resuspended over semi-diurnal and monthly tidal cycles. In some cases, sand-sized particles may only be transported over a small part of the semi-diurnal tidal cycle (Prandle *et al*., 1993). Exceptions to these general rules apply in near-coastal, near-frontal or highly stratified areas where physical and biological processes can produce significant variability on small temporal and spatial scales, e.g. the persistent residual gyre observed in the Dover Strait (Prandle and Player, 1993; Prandle *et al*., 1993).

9.1.3 MEASUREMENT OF SUSPENDED SEDIMENT AND TURBIDITY

The measurement of suspended sediment and turbidity in situ involve various techniques. The primary method of measurements is using a device to measure optical back-scatter (OBS, often referred to as a nephelometer), using either instantaneous hand-held instruments of those which are pre-programmed to take readings and are deployed on moorings or beneath buoys. In these instruments, light is transmitted form the instrument into the water column and some light is reflected back from suspended particles and measured.

Other instruments measure the degree of transmittance of light between a transmitter and receiver (a 'Transmissometer'), assuming that most of the loss en-route represent obscuration by particles. Other instruments use the backscatter of sound (Acoustic backscatter instrument and Acoustic Doppler Current Profiler) to measure sediment and turbidity. All these instruments require calibration to obtain a measure of suspended sediment concentration (units are typically mg/l), which can be a complex process containing many uncertainties. For example, for the optical sensors, a number of factors have a significant impact on instrument response. A change in grain size from medium sands to fine silts may lead to a x100 increase in instrument response; flocculation of fine particles may decrease instrument response by x2; and the presence of plankton in suspension may lead to poor instrument calibrations of SPM concentration (Bunt *et al*., 1999).

Older-style traditional methods such as 'Secchi Disks', whilst easy to use, are of very limited use in comparing datasets or in deriving information about sedimentary processes, but may give some qualitative information on water clarity.

Some measurements from remote sensing sources involve multi-channel optical and near-infrared radiometer observations (e.g. the satellite–borne Advanced Very High Resolution Radiometer or the aircraft-borne Compact Airborne Spectrographic Imager). In particular, there is a relation between the concentration of near-surface SPM and the brightness or reflectance of the sea, provided that allowance is made for changes in absorption due to the concentration of phytoplankton species (Bowers *et al*., 2002).

Descriptions of the monitoring networks that regularly measure sediments and/or turbidity are given in the chapter on Monitoring Networks, together with details of how to access archived and near real-time data. Also refer to the list of links to monitoring networks and data sets at the end of this chapter (section 4.).

9.2 SEDIMENTS IN UK WATERS

The relative importance of the factors influencing sediment concentration and transport (sediment type and availability, currents and waves, see section 1.2) varies across the UK continental shelf. Generally speaking, currents tend to be more important offshore (>10m water depth), whilst waves tend to be the more dominant force in shallower nearshore areas (<10m water depth). The character of the shelf seabed is also highly variable, depending upon modern tidal and current patterns, and on the inherited nature of the seafloor (i.e. past patterns of sediment accumulation). Relatively shallow areas off southeast England give way to deeper areas to the north of Flamborough Head and west of the Isle of Wight. Sandy or gravelly areas occur in regions of strong tidal currents in the Bristol Channel and the southern North Sea. Finer sediments lie in areas where tidal currents are weaker, such as off Plymouth and in parts of the Irish Sea. Mobile sediments may be absent, and thus a rocky seabed occurs, in many nearshore areas and in areas swept by strong currents like the English Channel and near promontories of the west coast of England and Wales (Defra, 2002).

Visit http://www.bgs.ac.uk/products/digitalmaps/digsbs250.html to see a map of the broad-scale seabed sediment distribution in UK waters, based on the BGS product DigSBS250.

Refer to the web version of this report to access a sea bed sediment map of UK waters.This map is based on BGS product DigSBS250. Courtesy of Ceri James, BGS.

At a scale of tens of kilometres, the key feature of the offshore sediment transport in UK waters is that the sediment transport pathways tend to follow the large-scale orientation of the coast. There are a number of areas of divergence of bed-sediment transport paths (‘bedload partings’) and other areas of convergence (Stride, 1982, Stride and Belderson, 1991). The locations of these zones are subject to some temporal variation, especially when tidal currents are modified by storm-generated currents. Divergences occur where peak tidal currents are orientated in opposing directions, where tidal current velocities (and hence shear stresses) also tend to be high (Pingree and Griffiths, 1979). Zones of convergence, where sediment transport pathways meet, occur in between zones of divergence.

In contrast, the key features of nearshore sediment transport paths in UK waters are governed more by the predominant wave directions, which is from the northeast on the east coast and from the southwest on the west coast. Sediment divergences or convergences occur where there are significant changes in coastal orientation (e.g. headlands or embayments) and onshore/offshore movements in localised areas (especially major estuaries).

In some areas, where tides and wave forces are orientated in a similar direction, nearshore and offshore sediment transport pathways are aligned. In other areas, where tidal and wave forces are orientated in different directions, the nearshore and offshore pathways may run in opposite directions to each other.

Generally, mapped distributions of suspended sediment show highest concentrations in coastal zones, related to sediment resuspension from the seabed, river discharge and coastal erosion. In the coastal zone, near-bed suspended sediment concentrations can be several orders of magnitude larger during winter storms, compared with calm summer conditions, because the associated surge- and wave-currents enhance resuspension. These processes require ample availability of fine sediments, and in some areas prevailing there is relatively little fine sediment available to be resuspended during high energy events, so that any increased turbidity results from temporary resuspension of sand, and may be confined to the lower parts of the water column. Exceptions to these general conclusions apply in near coastal, near-frontal or highly stratified areas where physical and biological processes can produce significant variability in turbidity on small temporal and spatial scales; e.g. in persistent residual gyres or coastally trapped river water (Charnock *et al*., 1994), but it is important to separate the biogenic from the physical causes of turbidity.

Within an estuary, the sediments are a complex mixture of particles that have been brought down by the river or in from the sea. The driving forces for sediment transport are variable on a number of time-scales, ranging from the semi-diurnal tidal period through to the spring-neap cycle, and to the seasonal, with additional episodic transport events associated with storm surges and river floods. On time periods of decades, some UK estuaries are relatively close to a long-term equilibrium, with a large amount of sediment transported on each tidal cycle, but relatively little of it either imported (and accumulated) or exported to the shelf.

9.2.1 NORTH SEA

Visit http://www.offshore-sea.org.uk/sea/dev/html_file/sea2_consult.cgi?sectionID=33 to see a figure of the broad-scale seabed sediment distribution in the North Sea (figure 5.2).

More details are provided in a series of coastal maps produced in the Futurecoast report (Defra, 2002), including seabed sediments and an indication of the direction of movement of offshore sediment (both suspended and bedload). The following three North Sea maps are examples taken from Futurecoast (Figures 9.1-9.3).

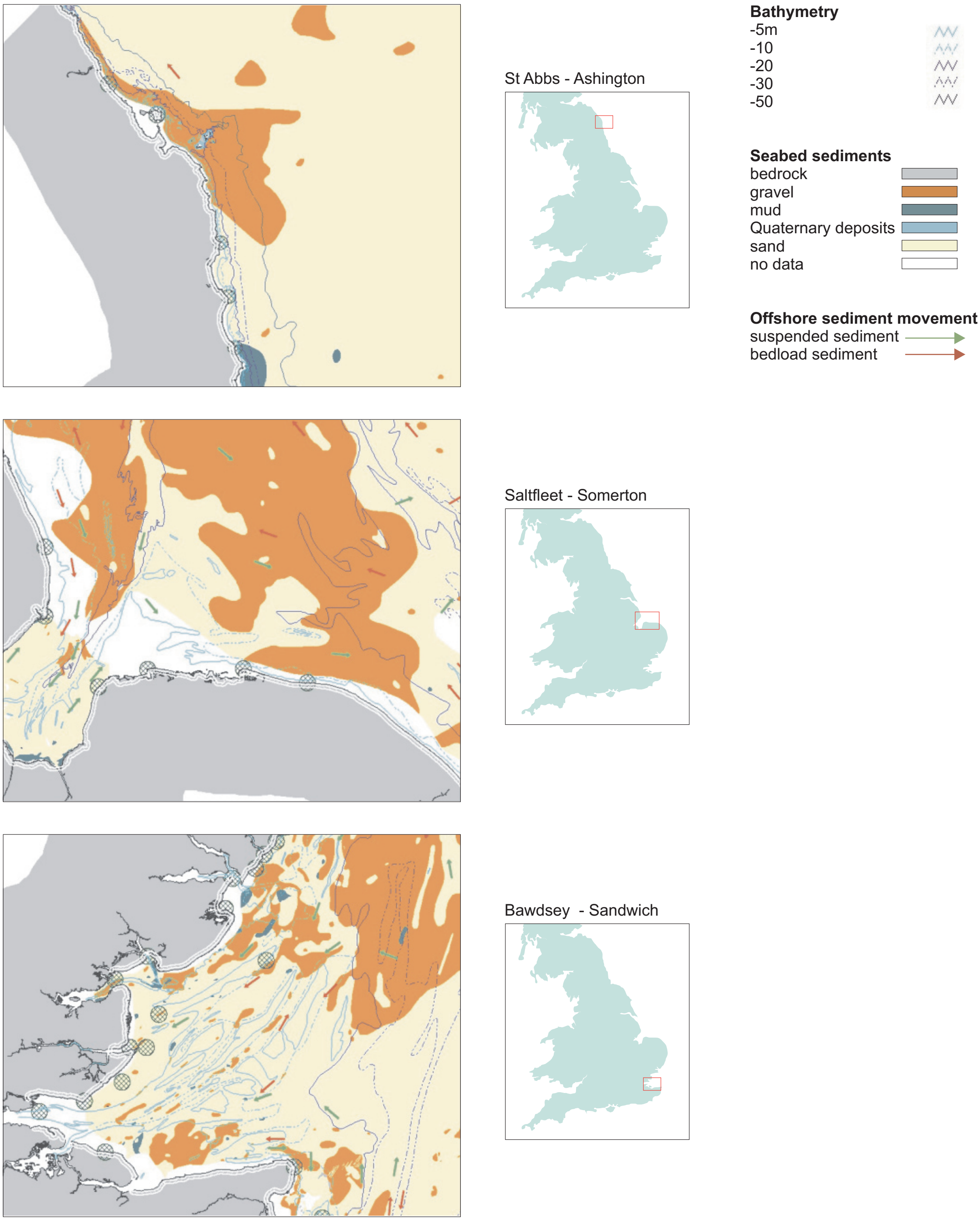
Refer to web version of this report to see an animation of SPM for UK waters for the year 1998. The scale is mg/l and the animation is based on output of a numerical model. [AVI animation, 7.4 MB].Courtesy of Alex Souza, POL.

The North Sea has both southerly and northerly offshore transport of sediment - northerly transport in the central eastern regions of the southern North Sea, southerly transport nearer the UK coast and several areas of variation in the northern North Sea. Bedload divergences occur due to the interaction of the different amphidromic points, with convergences in between. There are relatively few published field datasets of turbidity in the North Sea (exceptions include Jago and Bull, 2000). Historically, as might be expected, there are low average Secchi depth values (and hence high turbidity) in the southern North Sea (Aarup, 2002), probably due to sediment resuspension by the strong tidal currents (the data is available from http://www.ices.dk/ocean/project/secchi/).

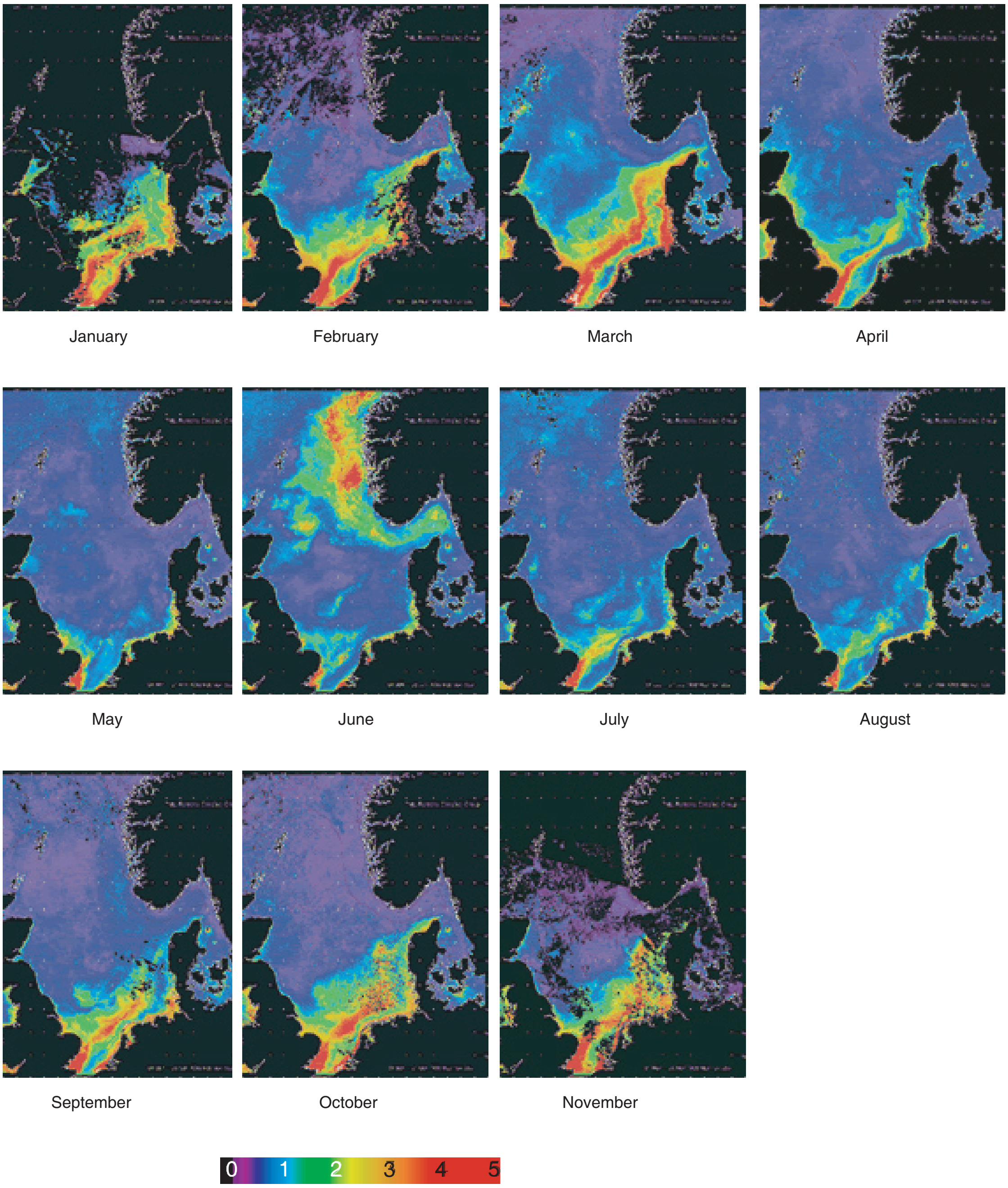
The nearshore sediment transport pathways are predominantly southerly on the N-S orientated sections and westerly on E-W orientated sections (e.g. North Norfolk). Coastal and offshore transport pathways are aligned where the tides and wave forces are orientated in similar directions, i.e. southerly transport from St. Abbs Head to Flamborough Head and around East Anglia on N-S orientated coasts. From Flamborough Head to the Wash, the coastal and offshore pathways run in opposite directions because tidal and wave forces are orientated in different directions.

The main nearshore source of sediments are the eroding cliffs on the East Anglian coastline and sediment transport divergences occur at the mouth of the River Tees and Tyne, Sheringham (North Norfolk), Clacton and at the North Foreland. The main offshore divergences occur at North Sunderland, Cromer, within the Thames Estuary and along a line from Dunwich to the Hoek of Holland. The main nearshore convergences for sediment are the Tees estuary, Humber estuary, the Wash, Stour and Orwell estuaries, the Thames and south of Flamborough Head. The main offshore convergence is off Flamborough Head. Onshore/offshore exchange occurs off North Norfolk.

A map showing seabed sediment transport indicators within the SNS2 study area is available by selecting the link to Appendix 15 at http://www.sns2.org/projects-outputs.html.



Figures 9.1-9.3. Example maps taken from Futurecoast for the North Sea



January February March April

May June July August

September October November

Figure 9.4. A series of satellite images of reflectance at 555nm during 1998, closely related to SPM concentrations.The imagesare NASA SeaWifs composites for the North Sea 1998 at a resolution of 1.1km [go to web version to see animated GIF, 1.4 MB]. Courtesy of NASA and PML Remote Sensing Group

9.2.2 ENGLISH CHANNEL AND CELTIC SEA, INCLUDING THE BRISTOL CHANNEL

9.2.2.1 English Channel

Visit http://www.offshore-sea.org.uk/sea/dev/html_file/sea2_consult.cgi?sectionID=33 to see a figure of the broad-scale seabed sediment distribution (figure 5.2).

More details are provided in a series of coastal maps produced in the Futurecoast report (Defra, 2002), including seabed sediments and an indication of the direction of movement of offshore sediment (both suspended and bedload). The following three English Channel maps are examples taken from Futurecoast (Figures 9.5-9.7).

The English Channel has both westerly and easterly offshore transport of sediment. Bedload divergences occur near to the amphidromic point off the Solent. The nearshore sediment transport is predominantly easterly, with some reversals in the lee of headlands. Coastal and offshore transport pathways are aligned where the tides and wave forces are orientated in the same direction, i.e. easterly transport in the eastern part of the Channel and westerly transport in the very western part. In the central part of the Channel, the coastal and offshore pathways run in opposite directions because tidal and wave forces are orientated in different directions.

The main nearshore divergences occur at Selsey Bill, Portsmouth Harbour, the Needles and Dungeness. The main offshore divergence occurs from the south of the Isle of Wight to the Contentin Penisula. The main nearshore convergences for sediment are near Ramsgate, Dungeness, Ryde and the Isle of Wight. Additionally, minor divergences and convergences are associated with each bay headland unit. The main offshore convergence is along a line from Hythe/Dungeness to Boulogne.

9.2.2.2 Celtic Sea including Bristol Channel

Details of seabed sediments and an indication of the direction of movement of offshore sediment (both suspended and bedload) are provided in a series of coastal maps produced in the Futurecoast report (Defra, 2002). The following two maps are examples taken from Futurecoast for the Celtic Sea and Bristol Channel (Figures 9.8 and 9.9).

The Celtic Sea has a variable offshore transport of sediment. The nearshore sediment transport is predominantly northerly on the N-S orientated coasts and easterly on E-W orientated coasts. Off the northern coast of Devon and Cornwall, coastal and offshore transport pathways run in opposite directions because tidal and wave forces are orientated in different directions. Sand moves westwards into the Celtic Sea in the outer and central Bristol Channel (Harris, 1988).

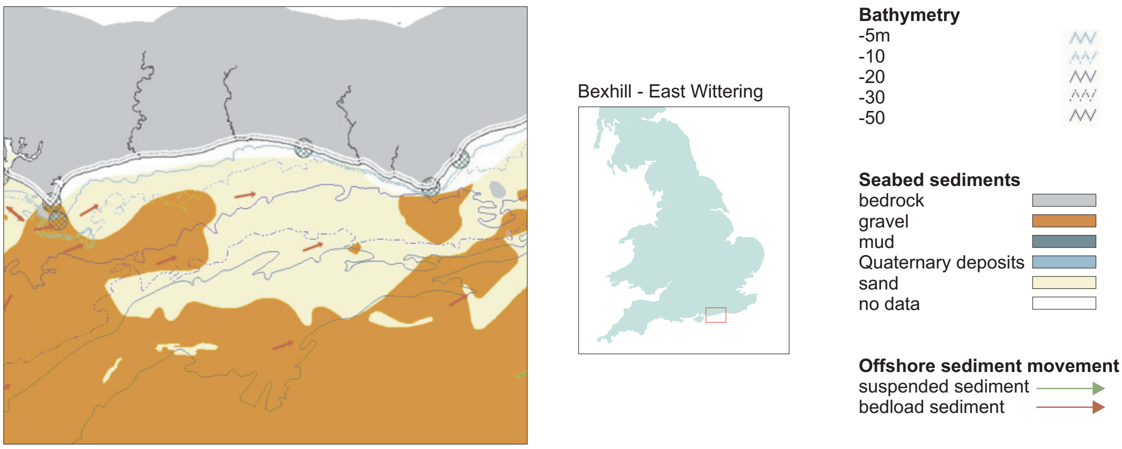
Nearshore, the main nearshore divergences of sediment are in Barnstaple Bay, along a line from Lavernock Point to Sand Bay (in the Bristol Channel) and in Carmarthen Bay. Onshore/offshore exchange occurs in the central portion of the Bristol Channel.

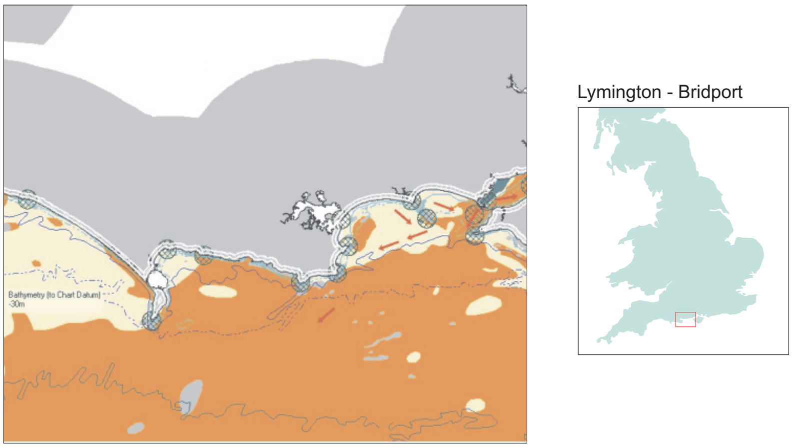
9.2.3 IRISH SEA

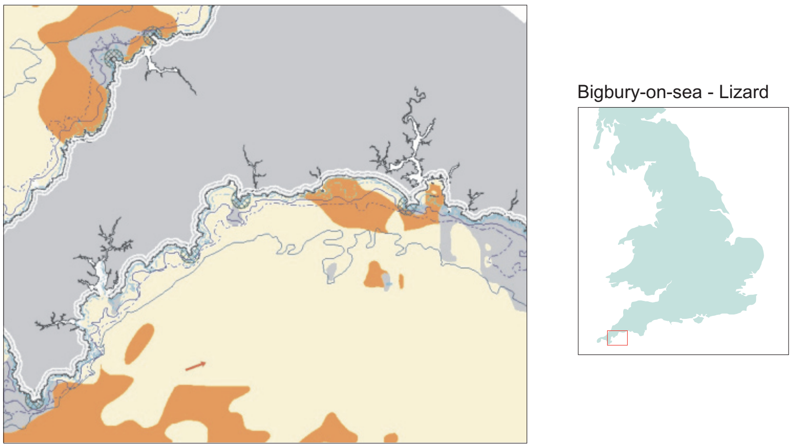
Figure 9.10 shows seabed sediments in the Irish Sea (courtesy of JNCC). http://www.jncc.goc.uk/marine/irishsea_pilot/pdfs/newsletter0303.pdf

Further details are provided in a series of coastal maps produced in the Futurecoast report (Defra, 2002), including seabed sediments and an indication of the direction of movement of offshore sediment (both suspended and bedload). The following three maps are taken fromFuturecoast and show seabed sediments for selected areas of the Irish Sea (Figures 9.11-9.13).

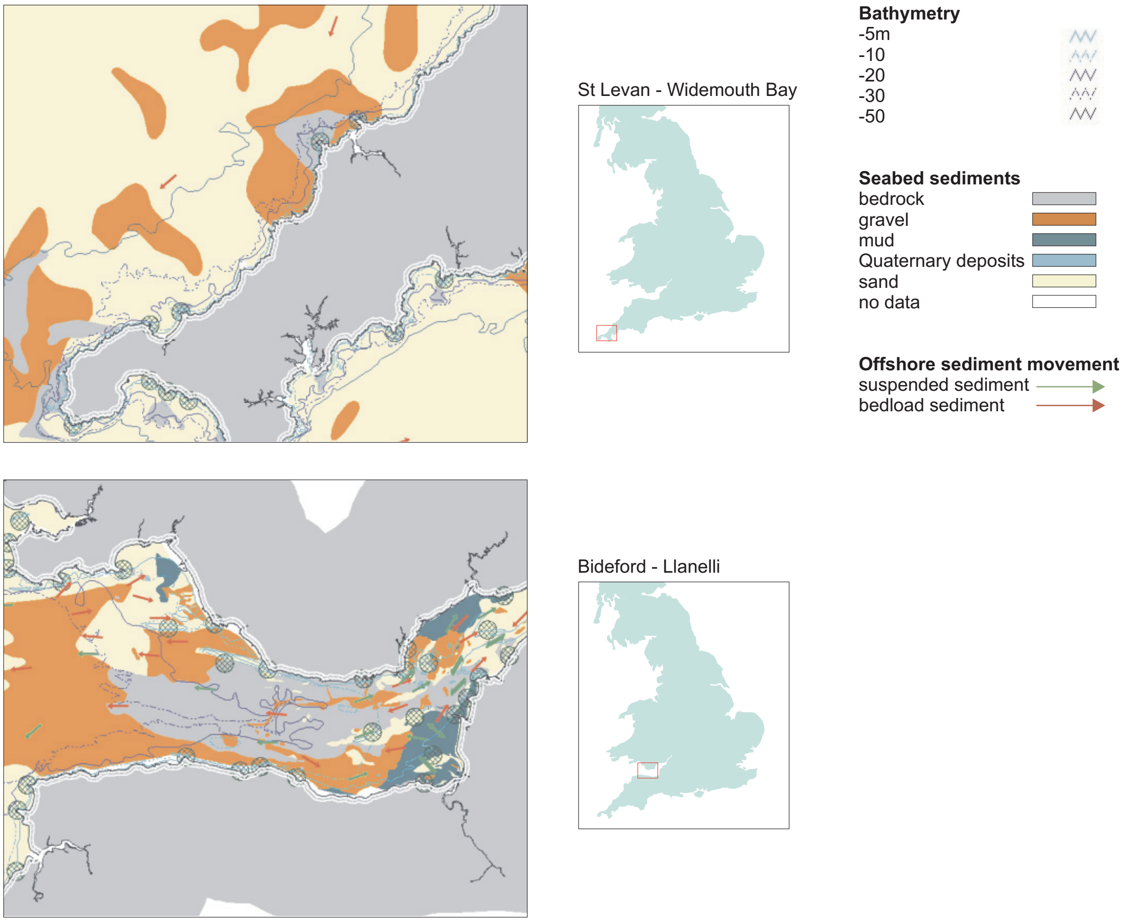
Figure 9.14 shows a series of satellite images of reflectance at 555nm during 1998, closely related to SPM concentrations. The images are NASA SeaWifs composites for the Irish Sea 1998 at a resolution of 1.1km [go to the web version to see animated GIF, 1.0 MB].



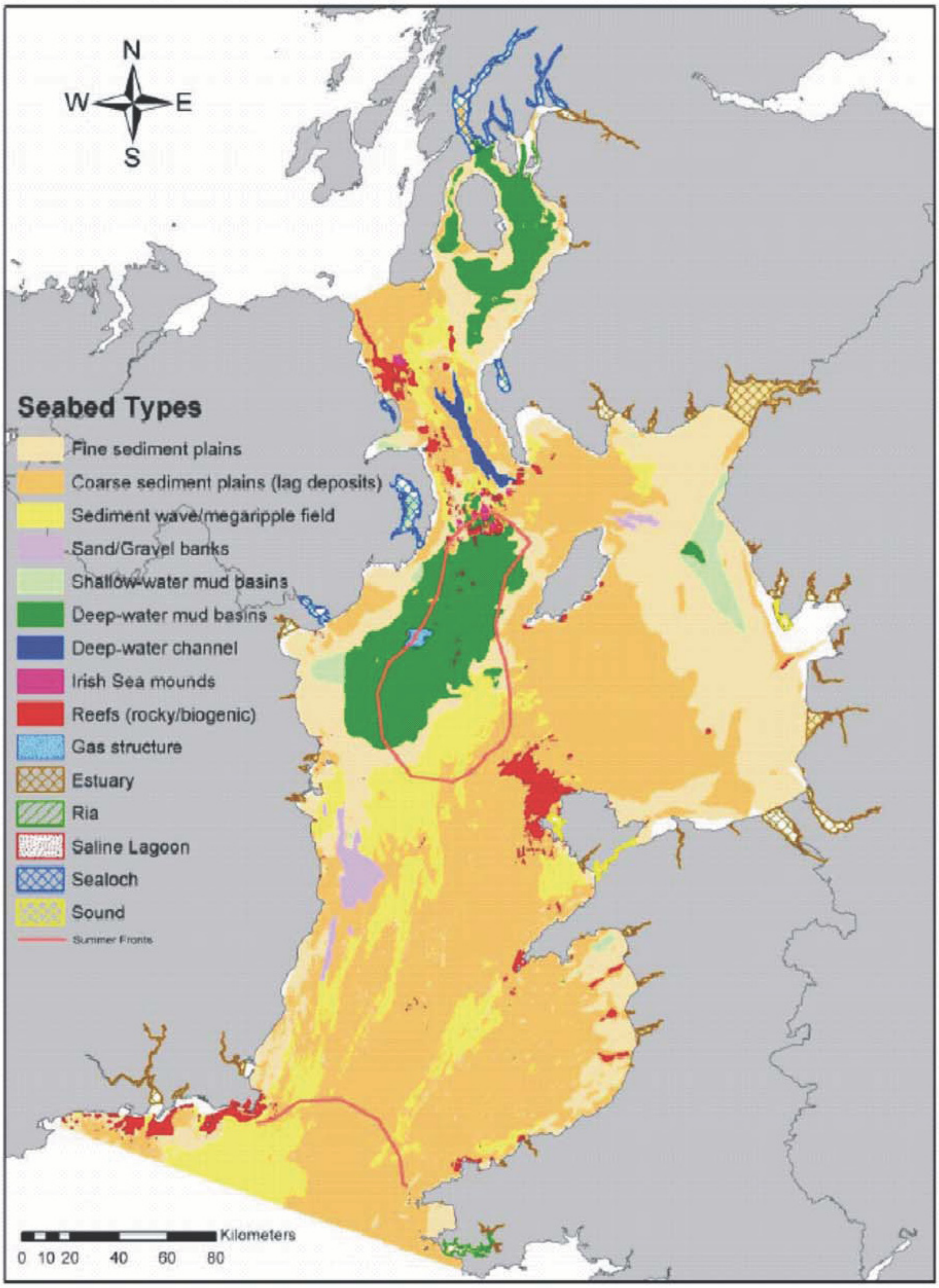




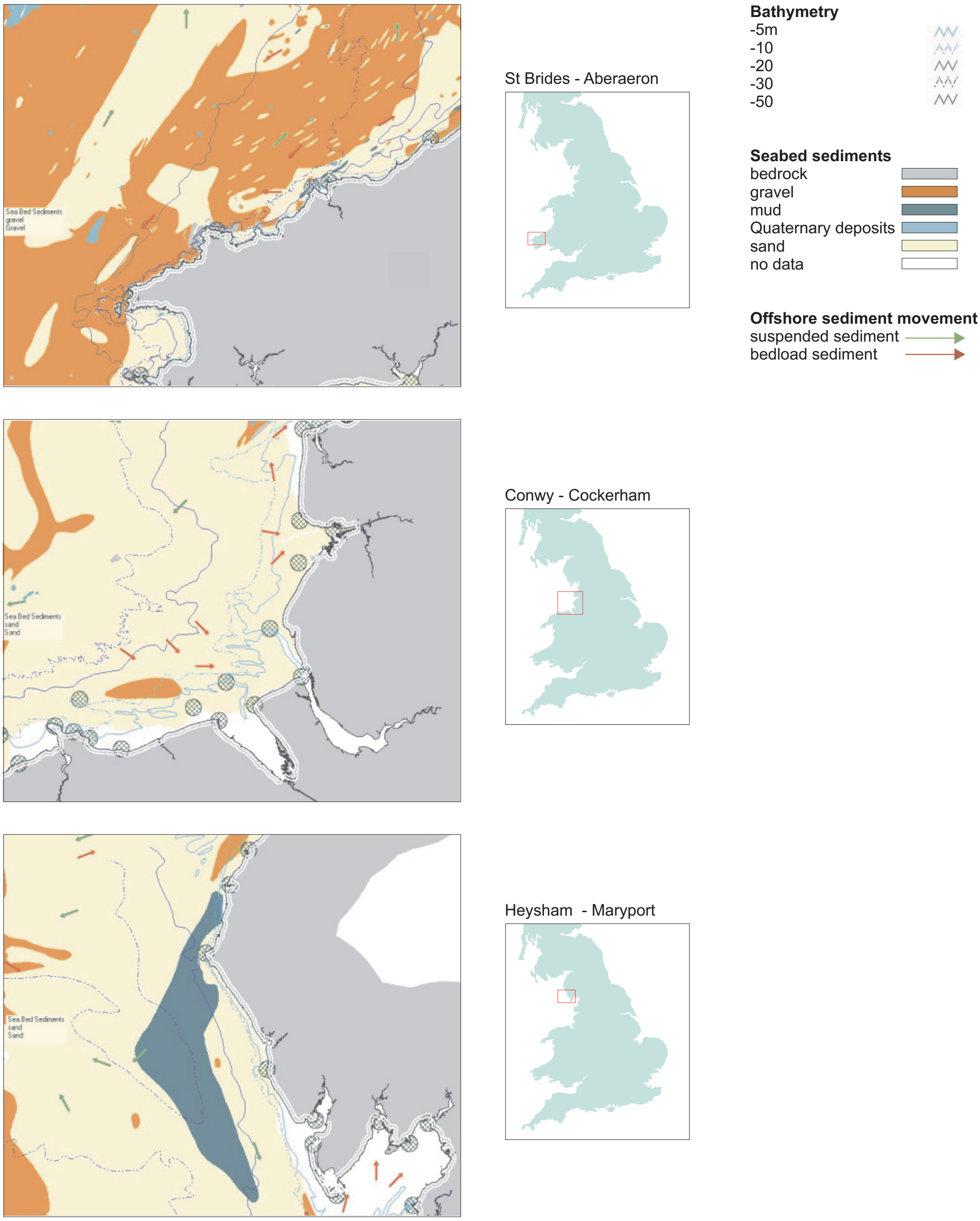
Figures 9.5-9.7. Example maps taken from Futurecoast for the English Channel



Figures 9.8-9.9. Example maps taken from Futurecoast for the Celtic Sea and Bristol Channel



Figures 9.10. Irish Sea seabed map. Courtesy of JNCC



Figures 9.11-13. Example maps taken from Futurecoast for the Irish Sea

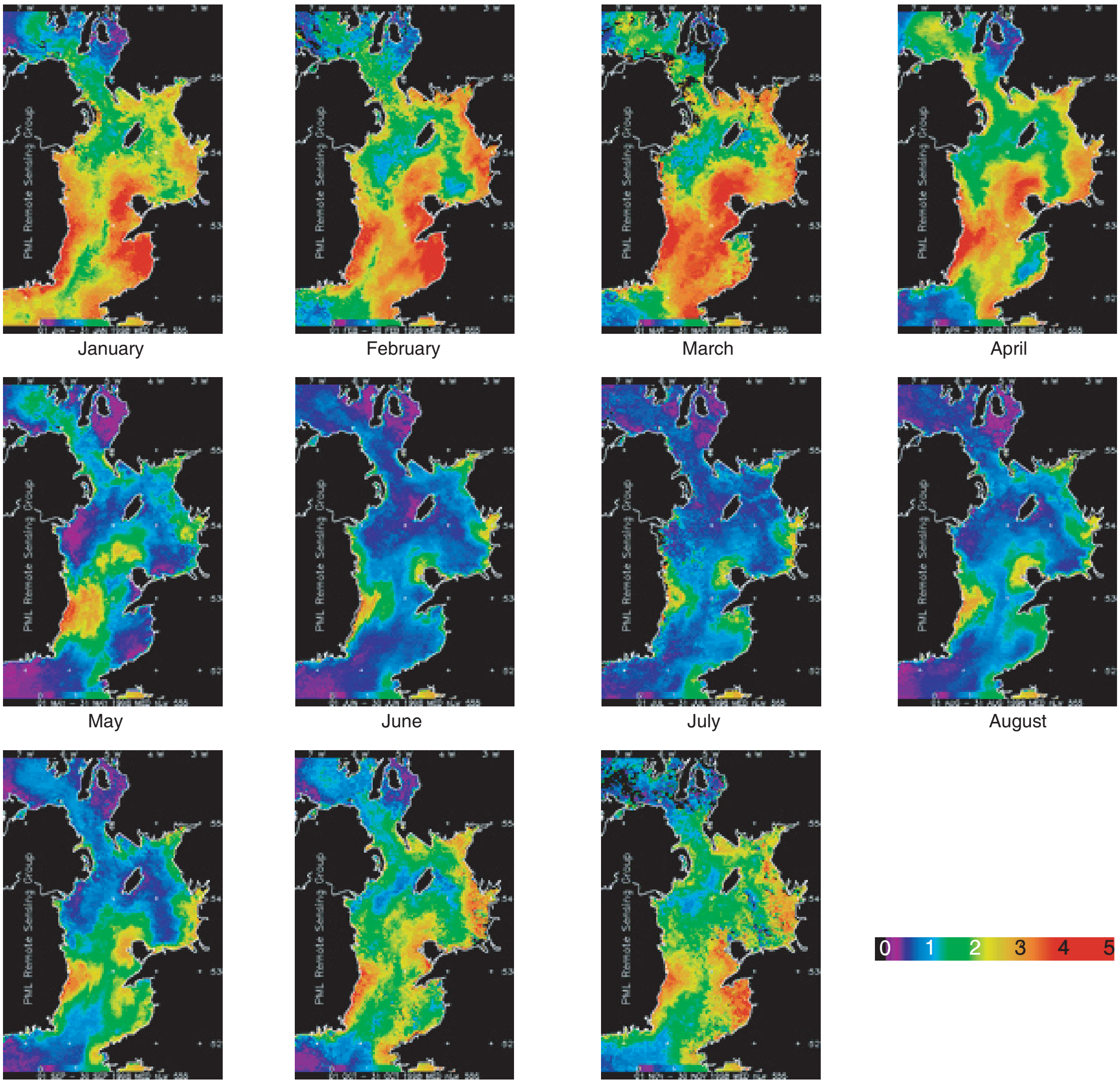


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Figure 9.14. Satellite images of reflectance at 555nm during 1998, closely related to SPM concentrations. The images are NASA SeaWifs composites for the Irish Sea 1998 at a resolution of 1.1km [go to the web version to see animated GIF, 1.0 MB]

Refer to the web version of this report to see an animation of SPM for UK waters for the year 1998. The scale is mg/l and the animation is based on output of a numerical model. [AVI animation, 7.4 MB]. Courtesy of Alex Souza, POL.

Analysis of satellite imagery by Bowers *et al*. (1998, 2002) shows the presence of two separate turbidity maxima, one off Wicklow Bay, the other off Anglesey. These areas correspond to the areas of strongest 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.

With respect to sea-bed sediments, the Irish Sea has southerly and south-westerly offshore transport of sediment on the North Wales coast south of the Lleyn Peninsula, but a northerly and north-easterly offshore transport path north of the Lleyn Penisula (Bardsey Sound). Bedload divergence occurs near to the amphidromic point in the eastern Irish Sea.

The nearshore sediment transport pathway is predominantly northerly on the N-S orientated sections of the coast and easterly on E-W orientated sections. Coastal and offshore transport pathways are aligned where the tides and wave forces are orientated in the same direction, i.e. northerly transport to the north of North Wales. Off the south and mid-Wales coast, the coastal and offshore pathways run in opposite directions because tidal and wave forces are orientated in different directions.

The main nearshore divergences of sediments are off the Lleyn Penisula (Bardsey Sound), off Anglesey, Formby and Bispham (Blackpool). The main offshore divergences occur from Ireland to Bardsey Sound and from Northern Ireland to Scotland. The main offshore convergences are west and east/southeast of the Isle of Man, Liverpool Bay and Morecambe Bay (Defra, 2002).

There is evidence that turbidity 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 below 1.5 m during that period (Lumb, 1990).

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 NAO Index.

9.3 REFERENCES

Aarup, T. (2002). Transparency of the North Sea and Baltic Sea – a Secchi depth data mining study. *Oceanologia*, 44(3): 323–337.

ABP (1996). Southern North Sea Sediment Transport Study - Literature review and conceptual sediment transport model. May 1996, Report No. R546, ABP Research and Consultancy Ltd, Southampton.

Bowers, D.G., Boudjelas, S. and Harker, G.E.L. (1998). The distribution of fine suspended sediments in the surface waters of the Irish Sea and its relation to tidal stirring. International Journal of Remote Sensing, 19: 2789 – 2805.

Bowers, D.G., Gaffney, S., White, M. and Bowyer, P. (2002). Turbidity in the southern Irish Sea. *Continental Shelf Research*, 22: 2115-2126.

Stride, A.H. and Belderson, R.H. (1991). Sand transport in the Bristol Channel east of Bull Point and Worms Head: a bed-load parting model with some indications of mutually evasive sand transport paths. Marine Geology, 101: 203-207.

White, M., Gaffney, S., Bowers, D.G. and Bowyer, P. (2003). Irish Sea turbidity is related to climatically induced changes in wind strength. Proceedings of the Royal Irish Academy, 103B: 83-90.

9.4 LIST OF LINKS TO MONITORING NETWORKS AND DATA SETS

Online search interfaces for catalogues and inventories maintained by the IACMST's Marine Environmental Data Network
http://www.oceannet.org

CEFAS Marine Environmental Real-time Observation System (MEROS)
http://www.cefas.co.uk/monitoring

DARD(NI) Coastal Monitoring Programme
http://www.afsni.ac.uk/services/coastalmonitoring

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.

HumberNet
http://www.northseanet.co.uk/humber/digitaldisplay.htm
and
http://www.northseanet.co.uk

Liverpool Bay Coastal Observatory
http://cobs.pol.ac.uk

Satellite missions
http://daac.gsfc.nasa.gov/data/dataset/CZCS/
http://daac.gsfc.nasa.gov/data/datset/SEAWIFS/
http://www.soc.soton.ac.uk/lso/noindex/lso_data.php

Southeast Regional Coastal Monitoring Programme
http://www.channelcoast.org

10. Changes to coasts and seabed

SUMMARY OF CHANGES AND TRENDS

- In Scotland, coastline changes were mainly accretional during the early and mid-nineteenth century. In most places accretion rates fell and erosional conditions ensued around the turn of the century but there was a general recovery to slight accretion during the period 1920 to 1960.

- Between 1969 and 1981, approximately 40 per cent of sandy beaches over 100m in length in Scotland were eroding, 22 per cent were stable and 11 per cent were advancing. 18 per cent showed evidence of both advance and retreat and the final 9 per cent were protected or backed by some other stable feature such as rocks.

- The northern coastline of Northern Ireland is principally hard rock, so coastal erosion is minor and localized. The coast to the west of the Bann River is an area of deposition. East coast beaches are generally of late-Holocene age and are not being renewed at a constant rate to match current sea-level rise, with some consequent beach loss.

- In England, the largest erosion rates (i.e. greater than 1m/yr) are along the east coast, with nearly 20 per cent of the locations in East England categorised thus. Some 13 of the 18 locations in North East England, where erosion exceed 1m/yr, fall along the South Yorkshire coast. By comparison, less than 5 per cent of locations in all other regions have such high rates; this is particularly noticeable in South West England and Wales.

- In East Anglia, mean annual shoreline retreat/advance rates ranged from between 72.9m/yr retreat to 64.1 m/yr advance since 1990. Mean annual volumetric changes rates of change ranged from a loss of 79,973.3 to an accretion of 65,048.0 cubic m/yr.

- On the south coast, the beach volume at Hurst Spit (Hampshire) fell from about 420,000 cubic m in 1997 to about 350,000 cubic m in 2001.

- The Mersey estuary had a net loss of volume of about 8 per cent between 1906 and 1977, with a small increase of 10 million cubic m thereafter.

10.1 INTRODUCTION

Major sources of data and information for this chapter are the Futurecoast report and the Foresight Flood and Coastal Defence Project.

The Futurecoast study was commissioned by Defra and carried out by a team led by Halcrow Group Ltd. The study provides predictions of coastal evolutionary tendencies over the next century, based on the use of data sets, information and experience of coastal systems. The output from the study is available on an interactive CD (Defra, 2002) and includes reports, guidance, data and mapping at various scales.

The Foresight Flood and Coastal Defence Project is managed by the Office of Science and Technology (OST) (http://www.foresight.gov.uk/fcd.html). Its aim is to produce a challenging and long-term vision for the future of flood and coastal defence that takes account of the many uncertainties, is robust, and can be used as a basis to inform policy and its delivery. The project is structured in three phases: Phase 1 covers “Drivers, scenarios and work plan”, Phase 2 covers “Impacts” and Phase 3 covers “Responses”.

10.1.1 THE SIGNIFICANCE OF CHANGES

Changes to the coastline, i.e. changes to coastal morphology, impact the natural ecosystem and human activities. (Analysis of the 1991 census data shows that 17 million people lived within 10 km of the coast in England and Wales. About 40 per cent of UK manufacturing industry is situated on or near the coast (OST, 2003).) Changes to the seabed affect biological communities and the human exploitation of offshore assets.

The Foresight Flood and Coastal Defence Project (OST, 2003) identified the role of coastal morphology as a main 'driver' in changing the risk of coastal flooding around the UK coast. Changes to the seabed, shoreline and adjacent land, coastal inlets and estuaries involve the erosion of material from the seabed and the shore, the movement of this material and its subsequent accretion (see the chapter on "Sediment concentration and transport"). Impacts can occur directly, because erosion at the shoreline leads to the loss of land and assets or to the undermining of existing defence structures; or indirectly, because the loss in level increases the exposure of the shoreline to wave attack and hence potentially increase the rate of erosion. Any changes to the bathymetry have effects on the propagation of tides, surges and waves, which may then increase erosion effects.

Coastal and offshore ecosystems are affected by changes to the coast and seabed. For example, any loss of intertidal zones, especially in estuaries, or any change in seabed sediment type will result in a loss of biodiversity (see the chapter on "Sediment concentration and transport").

The offshore coastal environment is an important source of sand and gravel for aggregates, beach nourishment (replacement of eroded sand and gravel) and other coastal protection schemes, land reclamation and contract fill (the use of material to fill holes and cavities in construction) (OST, 2003).

10.1.2 PROCESSES OF CHANGE

The UK coastline is an extremely dynamic environment that has altered significantly in the last 2,000 years and continues to be reshaped as a result of natural processes as well as by human intervention. As a result, the coastal zone of England and Wales is very diverse and includes coastal grasslands, cliffs, sandy or rocky beaches, dunes, salt marsh, mudflats and sand flats. In many cases present changes are a legacy of post-glacial Holocene influences.

Changes to the coast include changes in the shoreline position, due to eroding features such as cliffs and headlands or accreting features such as salt marsh or spits, and changes in beach profile, due to retreat, progress ('prograding' i.e. advancing seaward) or steepening. The pattern of change in beaches is such that in winter, when wave activity is normally at its greatest, the mean beach face level is drawn down and sediment is thought to move offshore into beach foot and offshore sandbars. In summer, some of the offshore material migrates shorewards again to build the beach to its greatest height of the annual cycle. Within this pattern the beach may rise or fall by more than a metre at any single location (McManus, 2003).

Changes to the seabed involve changes in bathymetry (the creation, movement and removal of banks and channels) and/or sediment type, both due to net deposition and erosion events.

The main processes causing the changes are variations along the coast in the rate of beach sediment transport (longshore drift), variations in time of the supply of river sediments to the beach, erosion of the nearshore seabed, landwards migration of the beach profile in response to sea level rise, loss of sand from the beaches to the nearshore seabed, wave attack on the cliff or back shore at and above the high water mark, cliff weathering and erosion (e.g. by winds, rainfall, freeze-thaw etc.) and land-sliding of cliff faces caused by saturation by groundwater flows (OST, 2003).

Coastal cells define units of shoreline within which natural longshore transport of sediment occurs. Since most cases of severe coastal erosion occur when longshore transport is interrupted, identifying coastal cells is the initial step in seeking to protect a shoreline against erosion or flooding prior. This procedure is now well-established for England and Wales (funded by Defra) but has only been applied to Scotland and Northern Ireland in a piecemeal manner (funded by local authorities) (OST, 2004a; OST, 2004b).

10.1.3 MEASUREMENT OF CHANGE

Descriptions of the monitoring networks that regularly measure changes to the coast or to the sea bed are given in the chapter on Monitoring

Networks, together with details of how to access archived and near real-time data.

Also refer to the list of links to monitoring networks and data sets at the end of this chapter (section 5.).

In addition, most ports carry out regular surveys of their approaches and harbour areas (see Figure 10.1 as an example).

Monitoring the evolution of the coast usually involves the collection of data from beach and bathymetric profiles and aerial photos, together with measurements of sea levels, waves, currents sediment samples and the study of surveyed maps over time. A full description of approaches to data collection and analysis is given in Bradbury (2000).

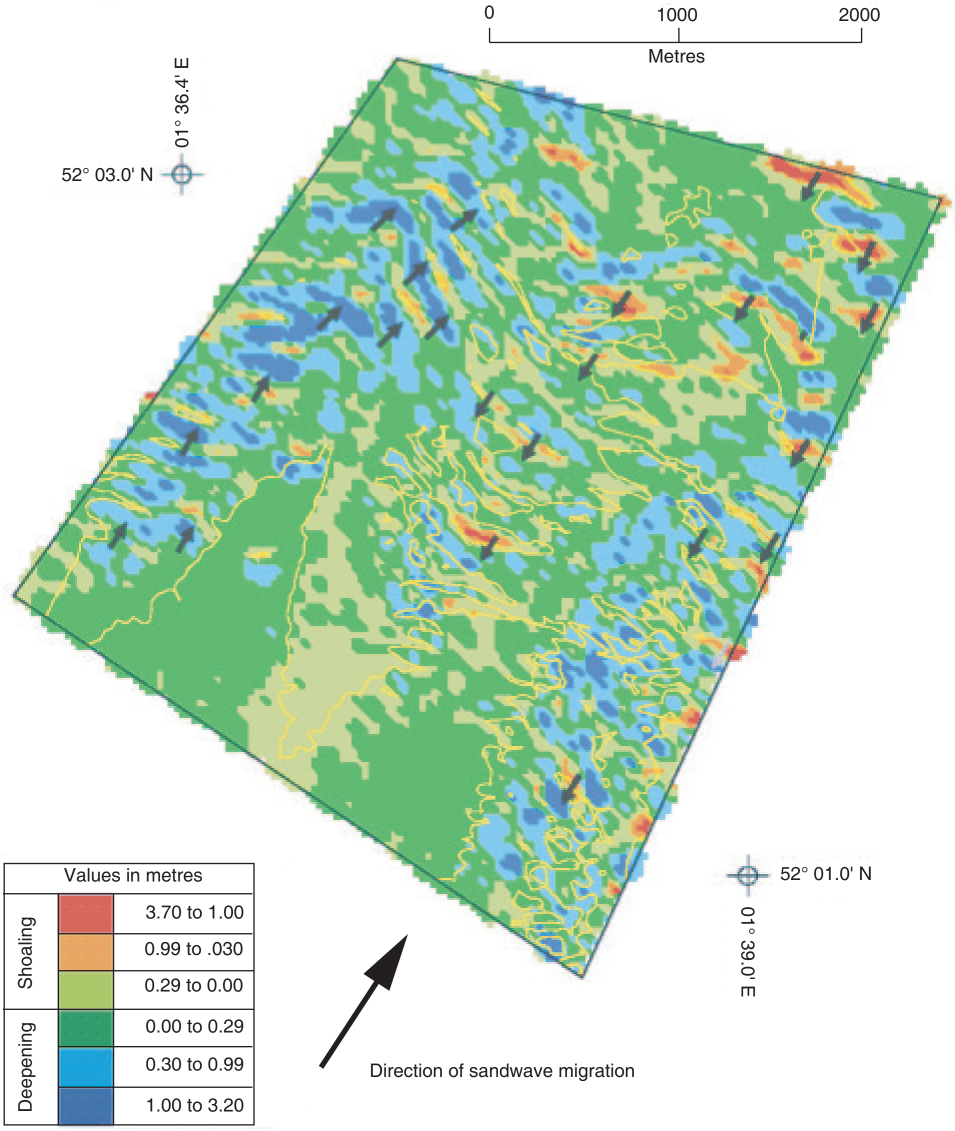
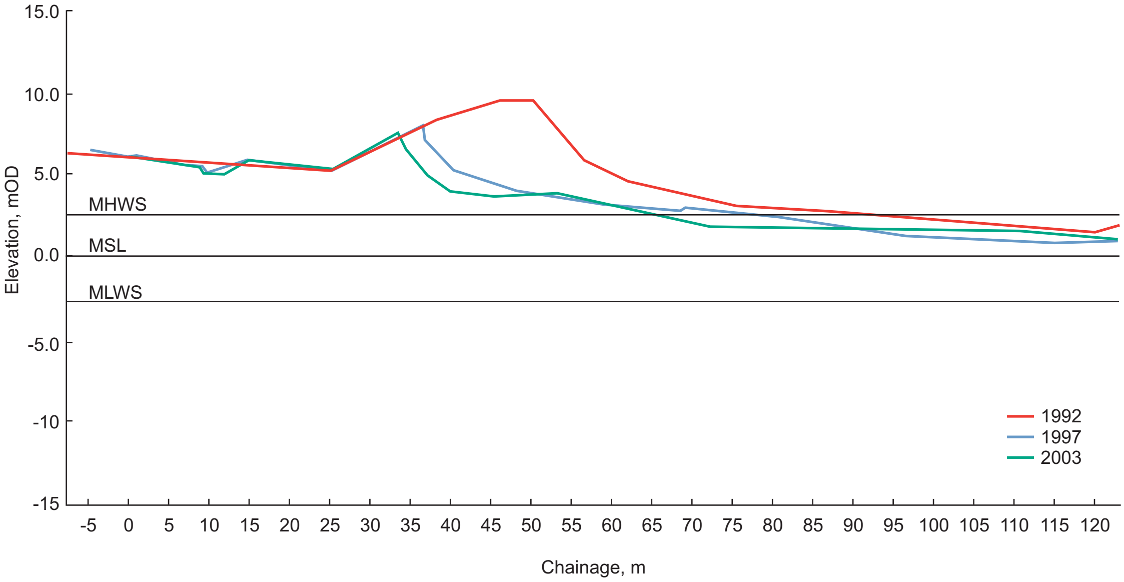
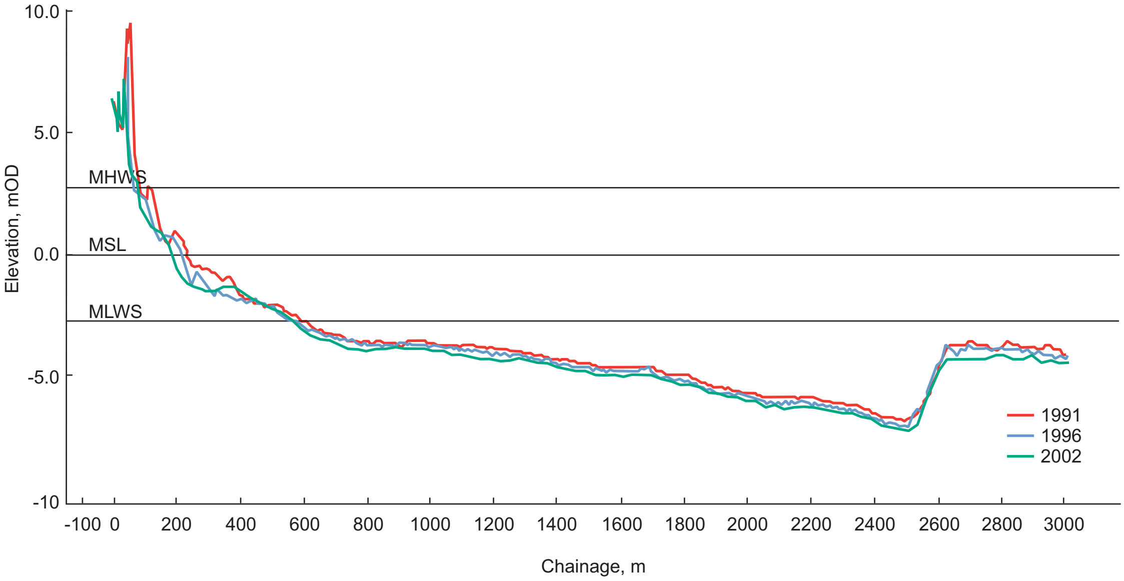


Figure 10.1. Changes in bathymetry in the Thames Estuary. Courtesy of the UK Hydrographic Office, reproduced under licence to the IACMST, © UK Hydrographic Survey (UKHO), 2004

Figures 10.2 and 10.3 show the typical profiles obtained during coastal monitoring and Figures 10.4 to 10.9 show how the data can be analysed to estimate shoreline and beach changes along a section.





Figures 10.2-10-3. Example of overlaid time series of beach topographic profiles at Holme-next-the-Sea (upper). Profiles displayed using bespoke software, developed for the Environment Agency. The beach topographic profile survey lines are displayed on a 1:1 scale. Site N1C1, Summer 1992, 1997, 2003. Example of bathymetric profiles at Holme-next-the-Sea (lower). The bathymetry survey lines are shown with an exaggerated vertical scale to enable easier viewing. Courtesy of EA Anglian Region

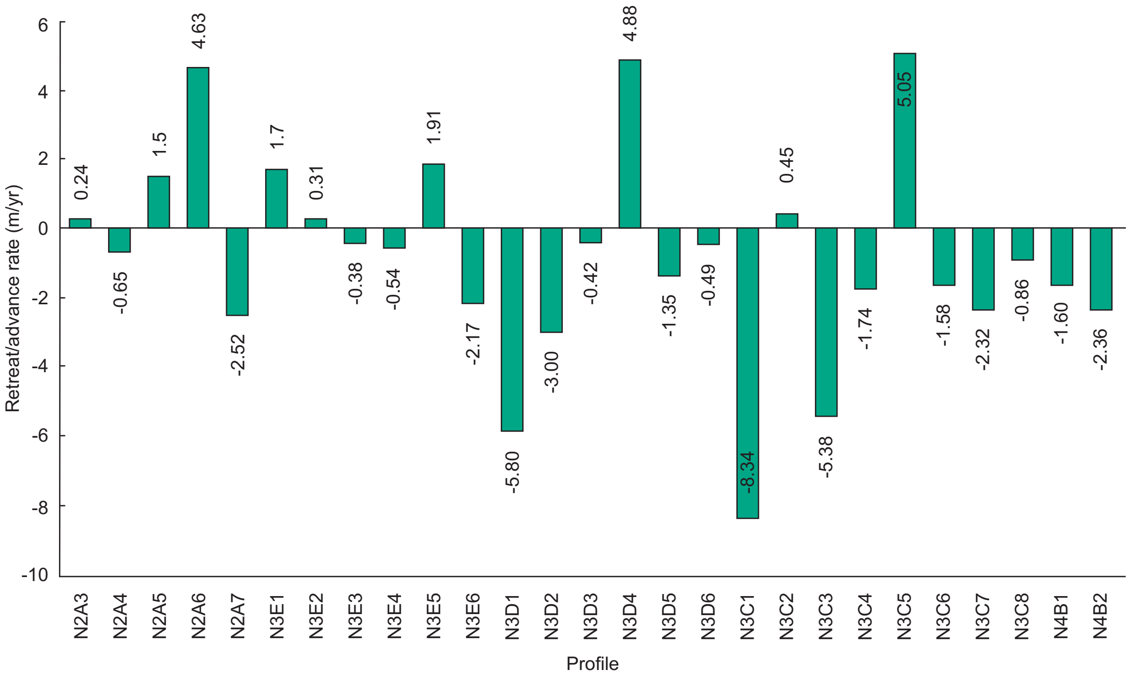


Figure 10.4a. Mean Annual Shoreline Retreat/Advance Rate at MSL. Summer 1991 to Summer 1999: Sheringham to Happisburgh. Courtesy of EA Anglian Region

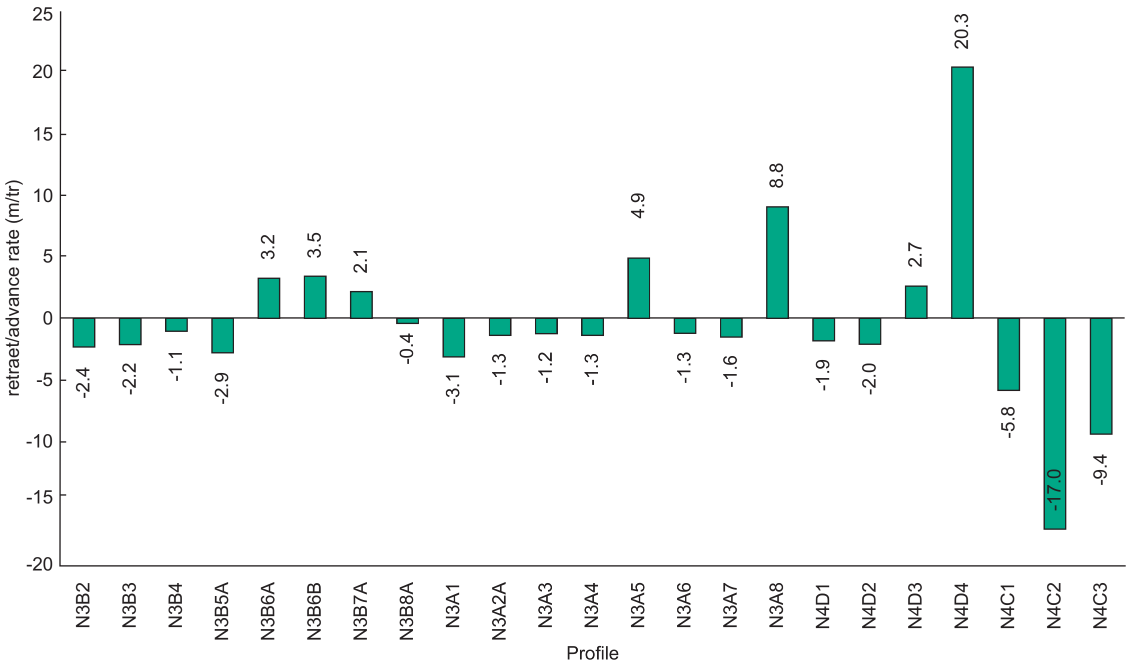


Figure 10.4b. Mean Annual Shoreline Retreat/Advance Rate at MSL. Summer 1991 to Summer 1999: Happisburgh to Hemsby. Courtesy of EA Anglian Region

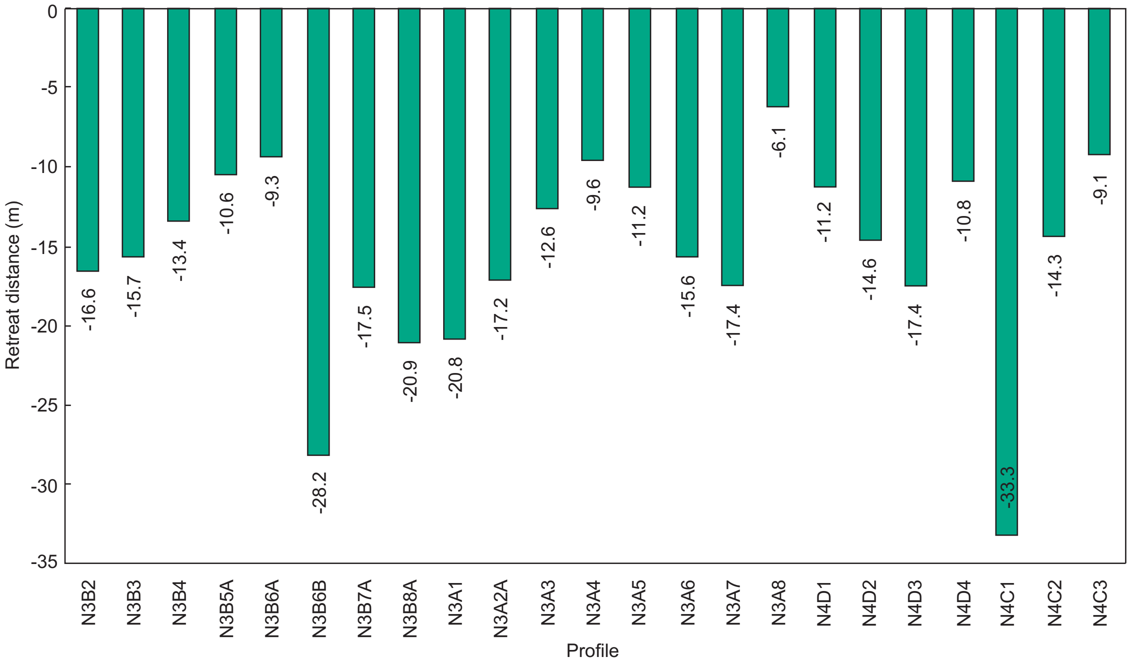


Figure 10.5. Maximum Shoreline Retreat Distance at MSL. Summer 1991 to Winter 2000: Happisburgh to Hemsby. Courtesy of EA Anglian Region

Figure 10.6. Mean Annual Beach Volumetric Change at MSL. Summer 1991 to Summer 1999: Happisburgh to Hemsby. Courtesy of EA Anglian Region

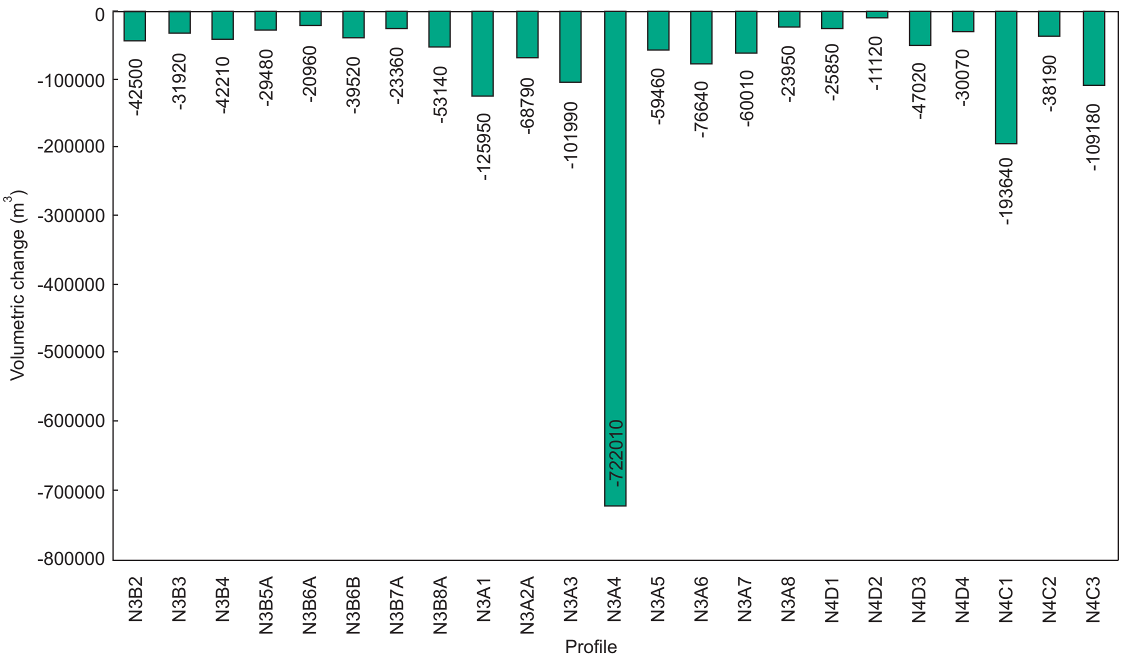
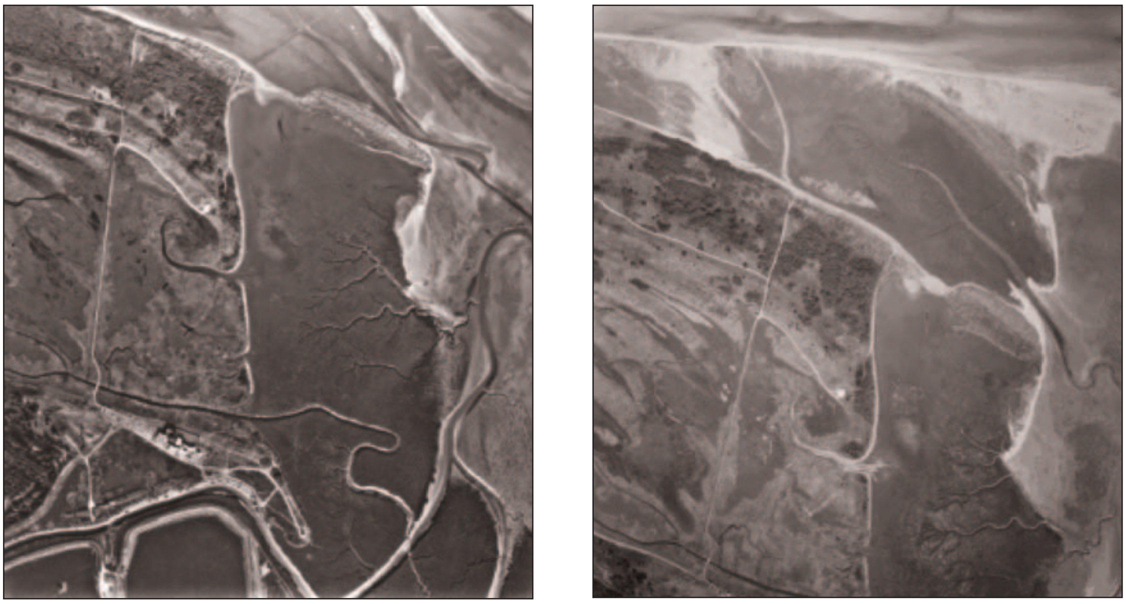


Figure 10.7. Beach Volumetric Loss at MSL. Summer 1991 to Winter 2000: Happisburgh to Hemsby. Courtesy of EA Anglian Region

The following are examples of aerial photos showing cliff erosion and salt marsh accretion for Gibraltar Point and two locations in Happisburgh.

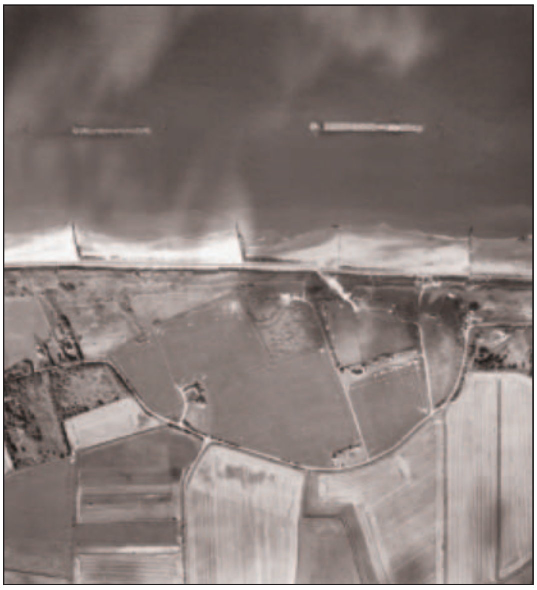


Gilbraltar Point 1991

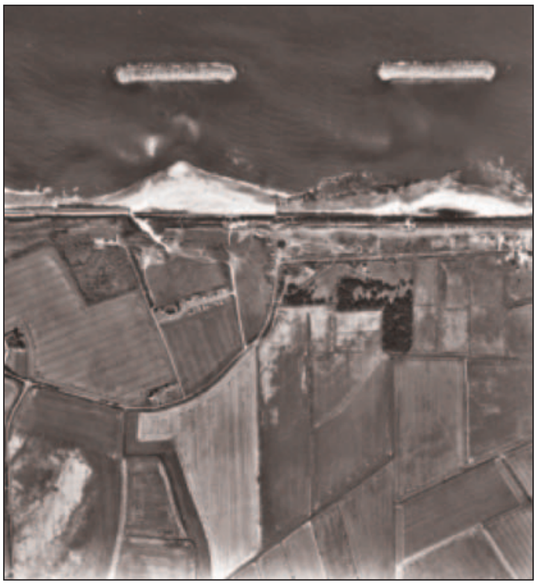
Gilbraltar Point 2002

Figure 10.8. Two aerial photographs of Gibralter Point taken in 1991 and 2002 (Courtesy of EA Anglian Region)

Happisburgh 1991



Happisburgh 1994



Happisburgh 1995

Happisburgh 2002

Happisburgh 1991

Happisburgh 2002

Figure 10.9. Six aerial photographs of Happisburgh taken at two locations. Courtesy of EA Anglian Region

The University of Newcastle has a pilot project at Filey to trial methods of measuring coastal evolution using ‘geomatic’ techniques (Buckley and Mills, 2000). Very small changes to the coastline are recorded by processing ERS-2 synthetic aperture radar (SAR) imagery, whereas more detailed results are gained in-situ by using Global Positioning System (GPS) equipment mounted on an all-terrain vehicle and by taking digital aerial photographs from a micro light aircraft.

Techniques for measuring bathymetry include the use of topographic survey lines, echo sounding (single- and multi-beam, side-scan sonar (single- and multi-beam), Light Detection and Ranging (Lidar), sweep systems and positioning systems (including GPS). Part of the scope of the “Integrated Coastal Hydrography” project (http://www.coastalhydrography.com/) is to evaluate suitable methods for gathering near-shore hydrographic data. Also, the ICH Metadata Web Portal enables users to upload and query information on past and future hydrographic surveys.

The principal method of recognising long-term change is reference to historic and modern Ordnance Survey maps.

10.2 CHANGES TO THE UK COASTLINE

10.2.1 SCOTLAND

Most of the coasts of the Highlands and Islands and many further south are rocky and change slowly. Therefore the potential for significant erosion mainly exists in beach and salt marsh environments or other areas where soft sediment such as till overlies the bedrock.

McManus (2003) details rates of change (m per year) of High Water Mark for southwest (1806 – 1974), eastern (1855 – 1959), western and northern Isles (1875 – 1998) and rates of seaward advance (m per year) of Low Water Mark on eastern beaches (1812 – 1972); and also changes to the beach width in the Moray Firth (1870 – 1970). In all areas the rates of coastal change have varied greatly through time. Changes were mainly accretional during the early and mid-nineteenth century. In most places accretion rates fell and erosional conditions ensued around the turn of the century but there was a general recovery to slight accretion during the period 1920 to 1960 (McManus, 2003).

A study (Scottish Coastal Forum, 2002) between 1969 and 1981 of all 647 sandy beaches over 100m in length in Scotland showed that approximately 40 per cent were eroding, 22 per cent were stable and 11 per cent were advancing. 18 per cent showed evidence of both advance and retreat and the final 9 per cent were protected or backed by some other stable feature such as rocks.

Erosion was most prevalent in Dumfries and Galloway, Shetland and the Western Isles and least marked in Lothian & Borders, Orkney and Strathclyde (Highlands and Islands). Prograding beaches were most common in Strathclyde, and Tayside & Fife and least common in Dumfries & Galloway, Grampian and Shetland. It is generally believed that the relative prevalence of coastal erosion in Scotland is due primarily to decreasing sand supply to beaches from the seabed and other sources.

A more recent report (OST, 2004a) states that the rocky and high indented coastline of mainland Scotland (especially on the west coast) and fragmented outlines of the Western Isles and Orkney and Shetland makes it difficult to define coastal cells using the same criteria adopted for England and Wales (Ramsay and Brampton, 2000). The most recent attempt (J Hansom, personal communication, quoted in OST, 2004a) identifies 7 cells along the mainland reserving a further 4 coastal cells for the Outer Hebrides and Orkney and Shetland. For the rocky coasts of the north and west where sediment is sparse and beaches often confined to deeply indented bays, individual cells are small and numerous. For such lengths of shoreline many small bays (or pocket beaches) are grouped together to form a much larger ‘sub-cell’ for management purposes – the hydraulic environment and general orientation of the coastline determining the grouping process.

According to OST (2004a), Quenlenuec *et al*. (1998) characterized some of these coastal cells as follows:

- Berwick to Aberdeen (cells 1, 2a, 2b and 2c): predominantly eroding but stable where there are rocky coasts or coastal defences
- Aberdeen to Inverness (cells 2d, 2a, 3b, 3c and 3d): mainly eroding but with important river coupling
- Inverness to Mallaig (cells 3, 4 5a): stable with eroding pocket beaches
- Mallaig to Carlisle (cells 6 and 7): predominantly eroding but stable where there are rocky coasts or coastal defences
- Mull/Islay/Jura/Skye (cells 5b and 5c) predominantly stable but with soft coasts eroding (pocket beaches)
- Orkney (cell 10): stable with eroding pocket beaches.

According to OST (2004a), as in England and Wales, most of the sediment reworked along the Scottish coast is fine grained and of marine origin, this includes the sand banks within the outer estuaries of the Solway, Clyde, Forth and Tay. Two exceptions are the inner Tay estuary (dominated by river-derived sands and gravels) and Spey Bay plus the shoreline to the west which is constantly replenished by river gravels from the Spey (Gemmell, Hansom and Hoey, 2001). Any reduction in sediment fluxes on the lower Spey (due to changes in runoff or land management) would starve Spey Bay and cause immediate erosion along cell 3b. This, however, is a special case and more generally there is minimal coupling between fluvial and coastal morphology around the Scottish coast.

10.2.2 ENGLAND AND WALES

Work undertaken as part of the Futurecoast study analysed historic Ordnance Survey maps (1:10,000 scale) extending back to the mid-19th Century. Part of this analysis included establishing retreat rates at over 1,000 locations around England and Wales. These measurements were obtained at intervals of between one and five kilometres, depending upon changes in geomorphological features and defence positions (OST, 2004c).

From OST (2004c), a review of this analysis is presented in Table 10.1 and Figure 10.10; the rates presented relate to the most landward feature in each case (either top of cliff or back of beach). These rates include the influence of coastal defences; where defences exist only post-defence rates have been quoted. Defended locations represent just over 450 of the locations, of which approximately half fall within the band of “little change”, therefore the other half, where

Table 10.1. Present average rates of shoreline movement (values are number of individual locations where shoreline position has been measured). From OST (2004c). Courtesy of OST

Region	Little change (movement less than +/- 0.1 m/yr)	Erosion				
		0.1-0.5 m/yr	0.5-1.0 m/yr	1.0-2.0 m/yr	Greater than 2.0 m/yr	Accretion (greater than 0.1 m/yr)
North East England	94	26	5	13	5	8
East England	77	14	4	16	7	11
South East England	89	35	12	6	2	30
South West England	191	61	12	4	1	48
Wales	114	31	9	0	2	33
North West England	22	15	4	1	2	25
Totals	**587**	**182**	**46**	**40**	**19**	**155**
Percentage	**57%**	**18%**	**4%**	**4%**	**2%**	**15%**

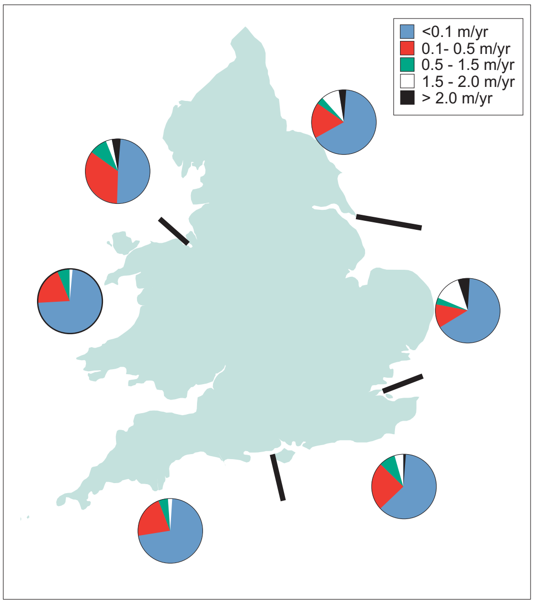


Figure 10.10. Regional difference in average rates of shoreline movement. Data from Table 10.1. From OST (2004c). Courtesy of OST

there is some form of defence management, have post-defence rates of change in excess of 0.1m/yr (some erosion, some accretion).

According to OST (2004c), it can be seen from Table 10.1 and Figure 10.10 that the largest erosion rates (i.e. greater than 1m/yr) are seen along the east coast, with nearly 20 per cent of the locations in East England categorised thus. It should be noted that some 13 of the 18 locations in North East England, where erosion exceed 1m/yr, fall along the South Yorkshire coast. By comparison, less than 5 per cent of locations in all other regions have such high rates. This is particularly noticeable in South West England and Wales, but reflects the nature of the broad geological differences between regions.

It should also be noted that coastal change, especially erosion, is not necessarily a linear or regular process and whilst these are average rates over a long period of time, they may often result from periodic events rather than be a continuous process. For example, in parts of North Norfolk a section of cliff may suffer a 40 metre failure in a single event, but only once every 40 years (OST, 2004c).

Further details on the current and potential rates of change for different coastal behavioural systems around England and Wales are presented in Table 10.2 from the Foresight Project (OST, 2004c), which better illustrate some of the variation within the regions.

Table 10.2. Present average rates of shoreline movement (values are number of individual locations where shoreline position has been measured). From OST (2004c). Courtesy of OST

Region	Little change (movement less than +/- 0.1 m/yr)	Erosion				Accretion (greater than 0.1 m/yr)
		0.1-0.5 m/yr	0.5-1.0 m/yr	1.0-2.0 m/yr	Greater than 2.0 m/yr	
North East England						
St Abb's Head to Flamborough Head	88	20	1	4	1	8
Flamborough Head to Humber Estuary	6	6	4	9	4	0
East England						
Humber Estuary to Weybourne	15	1	0	2	1	6
Weybourne to Felixstowe	39	9	4	10	3	4
Harwich to Thames Estuary	23	4	0	4	3	1
South East England						
Thames Estuary to North Foreland	22	0	4	4	1	0
North Foreland to Beachy Head	24	8	2	0	0	21
Beachy Head to Selsey Bill	16	5	3	0	1	4
Selsey Bill to Hurst Spit inc IOW	27	22	3	2	0	5
South West England						
Hurst Spit to Durlston	8	7	2	0	1	4
Durlston Head to Start Point	31	10	3	0	0	28
Start Point to Lizard Point	48	14	0	0	0	6
Lizard Point to Penlee Point	13	2	1	1	0	0
Isles of Scilly	12	5	1	0	0	0
Penlee Point to Hartland Point	44	16	4	1	0	5
Hartland Point to Morte Point	8	2	0	2	0	1
Morte Point to Brean Down	22	3	1	0	0	2
Brean Down to Severn Bridge	5	2	0	0	0	2
Wales						
Severn Bridge to Penarth	4	0	0	0	0	3
Penarth to Worms Head	23	2	1	0	0	2
Carmarthen Bay	6	1	1	0	0	5
Giltar Point to St David's Head	18	1	1	0	0	3
St David's Head to Bardsey Sound	31	15	4	0	1	7

Table 10.2. continued: Present average rates of shoreline movement (values are number of individual locations where shoreline position has been measured). From OST (2004c). Courtesy of OST. (continued)

Region	Little change (movement less than +/- 0.1 m/yr)	Erosion				
		0.1-0.5 m/yr	0.5-1.0 m/yr	1.0-2.0 m/yr	Greater than 2.0 m/yr	Accretion (greater than 0.1 m/yr)
Bardsey Sound to Great Orme's Head	30	10	1	0	0	11
Great Orme's Head to Welsh border	2	2	1	0	1	3
North West England						
Welsh border to Fylde	10	2	2	1	1	3
Morecambe Bay	0	2	0	0	0	4
Walney Island to Solway Firth	12	11	2	0	1	18
Totals	**587**	**182**	**46**	**40**	**19**	**155**
Percentage	**57%**	**18%**	**4%**	**4%**	**2%**	**15%**

Refer to web version of this report to see an animation of changes in salt marsh in Southampton Water from 1946 to 1996. Courtesy of ABP Southampton.

10.2.3 NORTHERN IRELAND

East coast beaches with backshore sediment deposits are generally of late-Holocene age (about 3,000 BP) and are not being renewed at a constant rate to match current sea-level rise (Julian Orford, personal communication, January 2004, based on his contribution to SNIFFER, 2002).

The northern coastline is principally hard rock, predominantly basalt, so coastal erosion is minor and localized, e.g. between Larne and Cushendall (OST, 2004b). However, the coast to the west of the Bann River tends to be an area of deposition. East coast beaches with backshore sediment deposits are generally of late-Holocene age (about 3,000 BP) and are not being renewed at a constant rate to match current sea-level rise (Orford and McFadden, 2002), with for example consequent beach loss at Newcastle (OST, 2004b).

10.3 CHANGES TO THE SEABED

The UK is located on the northwest corner of the European Continental Shelf where water depths are generally less than 300m. The main features of the bathymetry are 'open seas' exposed directly to the Atlantic e.g. the south-western Approaches, the southern Celtic Sea and the Hebridean Sea; and 'closed seas' bounded by landmasses e.g. the northern Celtic Sea, eastern part of the English Channel and southern part of the North Sea. Nearshore water depths are generally less than 50 m and the deepest areas of nearshore water (>100 m) are found to the northwest and northeast of Scotland, off the northeast of Northern Ireland, offshore of the east coast to the north of Flamborough Head, on the south coast to the west of Start Point, and also on the west coast off the western most tip of Wales. Many of the present day changes are best summarised in the associated animated web displays.

Visit http://www.bgs.ac.uk/products/digbath250 to see a map of the broad-scale bathymetry of UK waters, based on the BGS/HO product DigBath250.

Refer to the web version of this report for a broad-scale bathymetry map of UK waters. Based on the BGS digital bathymetry map DigBath250. Courtesy of Ceri James, BGS.

In the following regional sections, descriptions of the early bathymetric history for English and Welsh waters is taken from the Futurecoast report (Defra, 2002).

10.3.1 NORTH SEA

10.3.1.1 Early history

In Scottish waters, during the peak of the Ice Age around 18,000 years ago, sea level fell between 100m and 120m relative to the level of the land surface. Climatic amelioration started about 13,500 years ago and water levels rose rapidly. A further, short-lived re-advance of the ice occurred during the Loch Lomond stadial between 10,000 and 9,000 years ago. The final removal of the ice permitted the land masses to rise again and the highest post-glacial relative sea levels were reached during the period 5,000 to 6,500 years ago in different parts of Scotland as the different areas responded almost independently to isostatic readjustment (McManus, 2003).

In English waters, around 18,000 years ago the Late Pleistocene ice sheet had reached its maximum extent and covered the area of the modern eastern England coastline, as far south as north Norfolk. Sea level was approximately 130 m below present at this time. A narrow sea, many kilometres offshore, extended northwards from approximately the latitude of St Abb's Head to join the Norwegian Sea to the north. As the ice retreated, global sea levels began to rise rapidly. The unloading of the crust of northern Britain resulted in isostatic uplift which served to counteract the sea level rise and slowed the rate of flooding of former glaciated areas so that by 12,000 years ago the position of the coastline in this area had changed very little.

By 10,000 BP the area now occupied by the northern North Sea had begun to flood and the southern coastline had reached approximately the latitude of the Tees Estuary. At this time, the area of North Sea to the south was a low-lying land area traversed by river valleys. As sea level continued to rise the North Sea expanded southwards and by 9,000 BP the Outer Silver Pit had flooded and the Dogger Bank was a peninsula. By this time the Southern Bight area had begun to flood from the south through the Dover Straits. Marine influence reached the modern River Tyne valley between 8,900 and 8,400 BP. Sea level continued to rise rapidly so that by 8,000 BP extensive low lying areas around the growing North Sea had flooded to form broad intertidal areas. Connection between the northern North Sea and the Southern Bight was finally made around 7,500 to 7,000 BP with the final breaching of the land bridge that existed to the north east of Norfolk.

Around 7,800 BP the first marine influence reached the area of the Wash. Connection between the northern North Sea and the Southern Bight was finally made around 7,500 to 7,000 BP with the final breaching of the land bridge that existed to the north east of Norfolk when sea level was around 10 to 15m below its present level. At around 7,000 BP the Dogger Bank was still an island but by 6,000 BP it had become inundated and the coastline of the North Sea was similar to that of the present day. At around 7,000 BP isostatic rebound resulted in a sea level high during the mid Holocene which was up to 2.5 metres above present. The southern Northumberland coast and areas further to the south do not exhibit this rise so that there is a marked spatial difference in relative sea level history along this stretch of coastline. By 6,000 BP, the coastline of the North Sea was similar to that of the present day.

Visit http://www.geography.dur.ac.uk/research/groups/sea_level/images/results/tidal_02.gif for an animation of the changing paleobathymetry of the North Sea at 1,000-year time steps during the Holocene (8,000 BP).

Visit http://www.geography.dur.ac.uk/research/groups/sea_level/images/results/coast_11.gif for an animation of the changing east coast during the Holocene (8,000 BP).

10.3.1.2 Present day

Refer to the Sediment Concentration and Transport chapter (section 2.1) to see maps of present-day bathymetry, represented by –5, -10, -20 and –50 m Chart Datum isobaths. NOT TO BE USED FOR NAVIGATION.

Water depths are substantially shallower in the southern North Sea (<50 m) than to the north of Flamborough Head (up to 200 m).

The EA's Anglian Region has been monitoring the coast and estuaries between the Humber and the Thames since summer 1991. (For further details, see the chapter on Monitoring Networks.) An analysis of data for the period summer 1991 to winter 2000 has been carried out to determine the long-term trends for the coastline over that period (Julie Richards, personal communication). As an indication of the kind of information on shoreline movement and change that can be output from coastal monitoring work, we quote some values from the report. However all carry a strong 'health warning'!

Mean annual shoreline retreat/advance rates (the average distance that MSL has moved either landward (retreat) or seaward (advance) from summer to summer) ranged from between 72.9 m/yr retreat to 64.1 m/yr advance.

Maximum shoreline retreat distances during a six-month period at each beach profile (the maximum distance MSL has moved landward since summer 1991) had a greatest value of 1246.9 m and a least value of 0.9 m.

Mean annual volumetric changes rates of change at each beach profile (calculated using the volume of the compartment 500 m to either side of each of the beach profiles from summer to summer) ranged from a loss of 79,973.3 to an accretion of 65,048.0 cubic m/yr.

Maximum beach volumetric loss (where the compartment to 500 m either side of each beach profile has been reduced the most in volume in a six-month period) ranged from 1580.0 to 516,440.0 cubic m.

To see an animation of bathymetric changes in the Humber from 1851 to 1999 refer to the web version of this report. Courtesy of ABP Hull.

Refer to the web version of this report to see bathymetric data for the Humber and Blackwater estuaries (using STEMgis).

10.3.2 ENGLISH CHANNEL AND CELTIC SEA, INCLUDING THE BRISTOL CHANNEL COASTLINE

10.3.2.1 Early history

During the last two million years, glacio-eustatic sea level changes have repeatedly exposed the bed of the English Channel to sub-aerial conditions. These sea level low stands correspond to periods of glaciation in the northern hemisphere, the last such episode reaching a maximum around 18,000 BP. Although still controversial, the modern consensus of opinion is that the southern limit of glacial ice did not reach the English Channel, reaching only as far south as the English Midlands and South Wales.

Geological evidence suggests there was no marine connection between the North Sea and the English Channel prior to the middle Pleistocene (about 500,000 BP) and that a chalk ridge extended unbroken at this time from the North Downs across to the French coast. About 500,000 BP, a lake formed in the southern North Sea, ponded to the north by the ice sheet, and to the south by the chalk ridge across the Dover Strait. At some stage the lake overflowed and broke through the ridge to initiate a connection between the North Sea and English Channel; and the catastrophic flood, which accompanied this event, in filled and overdeepend the existing river system in the English Channel to form the present complex channel network. During subsequent periods of lower sea level, water from the Thames and Rhine catchments flowed though and widened the breach to form the Lobourg Channel. During periods of normal sea level the channels were drowned and partially in filled, and marine erosion attacked the marginal cliffs to widen the Dover Strait.

During the preceding interglacial period between 120,000 and 130,000 BP, sea level was similar to that of the present day and the English Channel was a shelf sea separating Britain from the European landmass. At this time beaches and cliffs existed along the south coast, remnants of which are preserved at a variety of locations. Raised interglacial beaches are found at a number of sites, but most in this area are now believed to date from an even earlier interglacial period. The raised beach at Portland Bill, which lies between 6.95 and 10.75 m OD, dates from the last interglacial. Offshore there is a palaeo cliff line that may date from this period and which could be used as a possible indicator of post-glacial coastal recession. The chalk ridge between Purbeck and the Isle of Wight may have been initially breached during this interglacial period when the gap was only approximately 11 km wide compared to 25 km today.

The flooding of the English Channel commenced from the west as sea levels began to rise. By about 10,000 BP the eastern end of the marine embayment had reached as far east as Beachy Head and Britain was still connected by dry land to the continent across the eastern English Channel and Dover Straits region. By 8,000 BP the entire English Channel and Dover Straits area was inundated but there was still a shallow land connection separating this water body from the North Sea. This connection was breached around 7,500 years ago linking the English Channel to the North Sea. Tidal models have shown that the opening of the Dover Straits initiated the strong eastward transport in the eastern Channel.

The transgression of the English Channel region probably led to the destruction or reworking of many of the fluvial terrace deposits to form either beaches which rolled onshore and/or marine bed forms in the shallow sea. As the transgression continued these newly formed shelf sediments may have moved extensively before sea levels reached approximately their present level about 5,000 BP. Since that time there may have been small oscillations in sea level. Additional sediment may then have been made available through coastal erosion.

During the glacial period, sea level in the Bristol Channel area was lower than at present. With the slow post-glacial rise in sea level, a marine transgression crossed the area (commencing about 8,000 BP). When sea level reached its modern level, about 5,000 years ago, the tidal regime and thus the modern sediment transport regime became established.

10.3.2.2 Present day

The western half of the English Channel is characterised by a fairly deep (100 m) central channel which runs (and shallows) in an west-east direction. The Celtic Sea is characterised by a deep (100-200m) channel running north-south.

Refer to the Sediment Concentration and Transport chapter (section 2.2) to see maps of present-day bathymetry, represented by –5, -10, -20 and –50 m Chart Datum isobaths. NOT TO BE USED FOR NAVIGATION.

Long-term, high quality beach monitoring programmes are in place at Bournemouth (since 1974), Herne Bay (since 1974) and Christchurch Bay (since 1987). Beach volume at Hurst Spit (Hampshire) fell from about 420 000 cubic m in 1997 to about 350 000 cubic m in 2001 (Bradbury *et al*., 2002).

To see an animation of bathymetric changes in Southampton Water from 1783 to 1996 refer to the web version of this report. Courtesy of ABP Southampton.

Refer to the web version of this report to see bathymetric data for Southampton Water and the Tamar estuary (using STEMgis).

10.3.3 IRISH SEA

10.3.3.1 Early history

The major estuaries of Cardigan Bay and Caernarfon Bay (of the Teify, Dyfi, Mawddach and Dwyryd rivers) are largely in filled with sediment and the latter three have major spits and dune complexes developed across their mouths. The spits began to form when sea level approached its modern level about 3,000 to 5,000 BP. Initially, silty sand accumulated landward of the barriers and kept pace with the rise in sea level, but eventually sedimentation overtook sea level rise and silty clay in filled much of the estuaries. For example, when Harlech Castle was built 800 years ago it was fronted by water and had an easy connection to the sea, but now it is surrounded by the extensive low-lying land of Morfa Harlech. Sediment is still accreting also in the Teify and Dyfi estuaries.

Prior to the early Holocene marine transgression, the eastern Irish Sea was covered by sediments laid down by the retreating glaciers and their associated fluvial systems, and late glacial muds. With the post-glacial rise in sea level these sediments were reworked and the additional sediment may have been brought into the area from the western Irish Sea. Sea level attained a level close to its present position about 5,000 BP, and the modern hydrodynamic regime has been operating since this time.

10.3.3.2 Present day

Refer to the Sediment Concentration and Transport chapter (section 2.3) to see maps of present-day bathymetry, represented by –5, -10, -20 and –50 m Chart Datum isobaths. NOT TO BE USED FOR NAVIGATION.

A century of bathymetric surveys in the Mersey estuary indicates a net loss of estuarine volume of about 10 per cent over 70 years (Thomas *et al.*, 2002). Detailed analyses of the bathymetric surveys in 1906, 1936, 1956, 1977 and 1997 by Lane (2003) indicated that most significant changes occur in the upper estuary and in the inter-tidal region within the inner estuary basin. The overall pattern is for the estuary volume to decrease by about 60 million cubic metres or 8 per cent between 1906 and 1977; after this period, there is a small increase of 10 million cubic metres.

Refer to the web version of this report to see bathymetric data for the Mersey and Ribble estuaries (using STEMgis).

10.4 REFERENCES

Bradbury, A.P. (2000). Strategic monitoring of the coastal zone – towards a regional approach. Report to the Coastal Groups of the MAFF Southeast region.

Bradbury, A.P., McFarland, S., Horne, J. and Eastwick, C. (2002). Development of a strategic coastal monitoring programme for southeast England. Defra Conference of River and Coastal Engineers.

Buckley, S. and Mills, J. (2000). GPS and the wheel – how integrating the world's greatest invention is helping to monitor coastal erosion. *Surveying World*, 9(1): 41.

Defra (2002). Futurecoast study. CD available from Defra, Ergon House, 17 Smith Square, London SW1P 3JR.

Lane, A. (2004). Bathymetric evolution of the Mersey Estuary, UK, 1906-1997: causes and effects. Estuarine, *Coastal and Shelf Science*, in press.

McManus, J. (2003). Trends of change in coastal landforms and processes. DRAFT report to Scottish Natural Heritage.

Orford, J. and McFadden, S. (2002). Coastal and Flood Defence, in Implications of Climate Change for Northern Ireland: Informing Development Strategy, Scottish and Northern Ireland Forum for Environmental Research (SNIFFER) 11/13 Cumberland Street, Edinburgh EH3 6RT.

OST (2003). Foresight Flood and Coastal Defence Project - Phase 1 Technical Report - Drivers, scenarios and work plan (Working Paper). Available at http://www.foresight.gov.uk/fcd.html

OST (2004a). Foresight Flood and Coastal Defence Project - Phase 2 Appendix H - Future risks of flooding and coastal defence in Scotland. Prepared by Alan Werritty and John Chatterton.

OST (2004b). Aspects of the Foresight project specific to Northern Ireland.. Prepared by Stuart Suter and John Chatterton. Foresight Flood and Coastal Defence Project - Phase 2 Overview Report, Chapter 2, Appendix I.

OST (2004c). Assessment of Future Coastal Erosion Risk. Prepared by K. Burgess, H. Jay, C. Green, R. Nicholls and E. Penning-Rowsell. Foresight Flood and Coastal Defence Project - Phase 2 Overview Report, Chapter 2, Appendix K.

Quenlenuec, R.E., Uhel, C. O. R. and Devos, W. (1998). CORINE: Coastal Erosion, European Commission, Brussels. Scottish Coastal Forum (2002). A strategy for Scotland's coasts and inshore waters. Prepared by George Lee, Scottish Natural Heritage. Available at http://www.scotland.gov.uk/environment/coastalforum/defence.pdf

Scottish and Northern Ireland Forum for Environmental Research (SNIFFER) (2000). Implications of Climate Change for Northern Ireland: Informing Strategy Development. SNIFFER, 11/13 Cumberland Street, Edinburgh EH3 6RT.

Thomas, C.G., Spearman, J.R. and Turnball, M.J. (2002). Historical morphological change in the Mersey Estuary. *Continental Shelf Research*, 22(1-13): 1775-1794.

10.5 LIST OF LINKS TO MONITORING NETWORKS AND DATA SETS

Online search interfaces for catalogues and inventories maintained by the IACMST's Marine Environmental Data Network
http://www.oceannet.org

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.

Southeast Regional Coastal Monitoring Programme
http://www.channelcoast.org

11. Conclusions and recommendations

The main conclusions on the present status and trends of marine processes and climate parameters in UK waters are given in the Executive Summary and in the Defra State of the Seas overview. They are as follows:

- The annual mean Central England Temperature has increased by about 0.5°C during the 20th Century. The 30-year mean of annual mean temperature in Northern Ireland and Scotland increased by about 0.3°C from 1873 - 1902 to 1961 - 1990. (Weather & Climate, section 3.3)

- The average number of storms in October to March at UK stations has increased significantly over the past 50 years. However, the magnitude of storminess at the end of the 20th century was similar to that at the start. (Weather & Climate, section 3.5)

- There is a tendency towards wetter winters in north-east England and drier summers in south-east England. There were no statistically significant trends in precipitation in Northern Ireland for the period from 1931-2000. (Weather & Climate, section 3.6)

- Annual sea surface temperature averaged around the UK coastline has increased by about 0.5°C for the period 1871 to 2000, with most coastal sites showing a warming trend. (Sea Temperature, section 4.3)

- Sea surface salinity (SSS) averaged over the northern North Sea from 1950 to 2002 shows decreasing salinity since the 1970s. There is no discernible trend in mean SSS in the English Channel from 1900 to the early 1980s. SSS averaged over the Irish Sea from 1950 to 2002 shows a decrease in both winter and summer. (Salinity, section 5.3)

- There are local short-term variations in tide and surge levels at UK sites but no long-term trends. (Sea Level, section 6.2)

- After adjusting for land movements, ‘absolute’ mean sea level (MSL) around the UK coast has increased by about 1mm per year during the 20th Century. ‘Relative’ MSL, due to the combined effect of absolute MSL changes and land movements, is increasing around most of the UK coast but remains constant or is decreasing along some northern coasts. (Sea Level, section 6.3)

- UK MSL shows an increase in the rate of rise towards the second half of the 19th Century but is now rising on average less fast, i.e. there has been a decrease in the rate of rise in the 20th Century. Trends in UK extreme sea levels match MSL trends closely. (Sea Level, section 6.3)

- Wave data from ships and buoys indicate that the mean winter wave height in the northeast Atlantic increased significantly between the 1960s and 1980s. Satellite data confirm that this increase continued into the early 1990s. (Waves, section 7.4)

- In the northern North Sea, there was an upward trend of about 5-10 per cent (0.2-0.3 m) in mean significant wave height (Hs) for January–March for the period 1973-1995, but a decrease thereafter. In the central North Sea, the trend in Hs for January–March was upwards until 1993/94, with a decrease thereafter. In the southern North Sea, there is no discernible trend in Hs for January–March from 1973 to date. (Waves, section 7.4)

- At Sevenstones LV, off Land's End, the acceptable value is an increase of 0.02 m/yr in mean wave height over a period of about 25 years. This trend seems to have persisted into the early 1990s at least, although recent winters have suggested a levelling off. (Waves, section 7.4)

- Two pulses of inflow into the North Sea in 1988/89 and 1998 coincided with unusually strong northward transport of anomalously warm water through the Rockall Trough. (Circulation, section 8.4)

- Coastal flow conditions from the Irish Sea to Scottish coastal waters changed considerably after 1977, with a further change in Irish Sea outflow during 1980 to 1981, after which the flow pattern returned to that of 1977-1980. (Circulation, section 8.4)

- The North Sea has both southerly and northerly offshore transport of sediment. The nearshore sediment transport is predominantly southerly on the N-S orientated sections and westerly on E-W orientated sections. (Sediment Concentration & Transport, section 9.2.1)

- The English Channel has both westerly and easterly offshore transport of sediment. The nearshore sediment transport is predominantly easterly, with some reversals in the lee of headlands. (Sediment Concentration & Transport, section 9.2.2)

- The Celtic Sea has a variable offshore transport of sediment. The nearshore sediment transport is predominantly northerly on the N-S orientated coasts and easterly on E-W orientated coasts. (Sediment Concentration & Transport, section 9.2.2)

- The Irish Sea has southerly and south-westerly offshore transport of sediment on the North Wales coast south of the Lleyn Peninsula and northerly and north easterly offshore transport north of the Lleyn Peninsula (Bardsey Sound). The nearshore sediment transport is predominantly northerly on the N-S orientated sections of the coast and easterly on E-W orientated sections. (Sediment Concentration & Transport, section 9.2.3)

- Turbidity (water clarity) in the Menai Straits (Irish Sea) deteriorated from the mid 1960s to the late 1980s. There was no overall trend turbidity in the Irish Sea between 1987 and 1997. (Sediment Concentration & Transport, section 9.2.3)

- Coastal changes in Scotland were mainly accretional during the early and mid-nineteenth century. In most places accretion rates fell and erosional conditions ensued around the turn of the century but there was a general recovery to slight accretion during the period 1920 to 1960. Between 1969 and 1981, approximately 40 per cent of sandy beaches over 100m in length in Scotland were eroding, 22 per cent were stable, 11 per cent were advancing, 18 per cent showed evidence of both advance and retreat and 9 per cent were protected or backed by some other stable feature such as rocks. (Changes to Coast & Seabed, section 10.2.1)

- The northern coastline of Northern Ireland is principally hard rock, so coastal erosion is minor and localized. The coast to the west of the Bann River is an area of deposition. East coast beaches are generally of late-Holocene age and are not being renewed at a constant rate to match current sea-level rise, with some consequent beach loss. (Changes to Coast & Seabed, section 10.2.3)

- In England, the largest erosion rates (i.e. greater than 1 m/yr) are along the east coast, with nearly 20 per cent of the locations in East England so categorised. Some 13 of the 18 locations in North East England, where erosion exceeds 1 m/yr, fall along the South Yorkshire coast. By comparison, less than 5 per cent of locations in all other regions have such high rates and this is particularly noticeable in South West England and Wales. (Changes to Coast & Seabed, section 10.2.2)

Listed below are recommendations

Long-term measurements of Marine Processes and Climate (MPC) data are crucial to plan and carry out the effective management of the UK's marine environment, by assessing its present state, identifying trends and changes and meeting future forecasting needs. (According to the UK's Inter-Agency Committee for Global Environmental Change, long-term monitoring should be regarded as a scientific activity in its own right and funded accordingly (quoted in

IACMST, 2000, 2001)). Since the last report on the status of the climate of UK waters (IACMST, 2001), several new marine monitoring networks have been set up, including the Liverpool Bay Coastal Observatory, the Southeast Regional Coastal Monitoring Programme and the strategic wave-monitoring network for England and Wales (WaveNet).

However, there is concern over the insecure future of some of the existing observation networks or long-term time series. An example is the Met. Office Marine Automatic Weather Station (MAWS) Network where two North Sea moored buoys (K16 and K17) have recently been taken out of service. There are no plans, at present, to reinstate them because the cost cannot be justified by the Met. Office if the sole purpose is to meet its own requirements. The Met. Office is currently reviewing all of its observing networks; this will be completed later in 2004. Another example is the long-running time series maintained by the Port Erin Marine Laboratory, which may be closed by Liverpool University in 2006.

Maintaining networks and data series can only be justified on the basis of a strong science case that assesses their value. But this should be in the context of value to the UK marine community as a whole. Inevitably, any assessment would have to include consideration of the future funding and operation of the measurements if the existing host organisation no longer has the resources. (Recently, the NERC Consortium Grant funding mechanism has been used to build a multi-institute team to run the Atlantic Meridional Transect out of the Plymouth Marine Laboratory).

Recommendation: Before a decision is made to close or reduce networks or long-term time series measurements, the host organisation should inform the IACMST; which should then take an active and pivotal role in arranging for an assessment to be made.

A considerable fraction of the data included in this report were not collected as part of any coherent national strategy or plan. Often in the past, regularly sampled time series have been maintained due to the efforts of dedicated individual scientists or single organisations. More recently, the GOOS Action Group has been working towards an Action Plan for the MPC sector of marine environmental monitoring which is aimed at producing a coherent and comprehensive programme of monitoring the marine environment around the UK as part of a Defra led activity following on from the Marine Stewardship Report ‘Safeguarding our Seas’.

Recommendation: The work undertaken by the IACMST GOOS AG in developing an Action Plan for the MPC sector input to a UK Marine Environmental Monitoring Strategy should continue and its recommendations implemented, including the development of headline indicators and standard protocols for collection and quality control.

It was difficult and time-consuming to obtain MPC data from some organisations; in fact some were not able to provide us with data known to exist. Also, most data is not collected, processed and quality controlled in a standard or consistent way. Therefore we consider that not all existing data is being used to its full potential. There are a variety of reasons for this, including lack of resources (time and/or money), especially if monitoring and processing data is not considered a high priority for funding, and barriers to low cost supply. Cowling (IACMST, 2004) is examining the present mechanisms of obtaining and supplying marine data and information in the UK, with recommendations to improve its accessibility and affordability. In the meantime, we repeat, and add to, a recommendation from the previous report.

Recommendation: Organisations should be encouraged and resourced to process and make available data in a timely and consistent manner to users and to national, regional and international data banks. Standardised metadata describing data holdings should be provided to recognised metadata directories (e.g. UK Directory of Marine Environmental Data, UK Inventory of Marine Monitoring Measurements).

The description of some MPC parameters was made easier because of the work already done in assembling, analysing and interpreting data. However, for all parameters, there is a need for a much more systematic integration and synthesis of all in-situ and remote-sensed observed data, including a thorough quality assessment. In some cases, the observed data should be integrated with output with data from numerical models, especially where the parameter is difficult to measure, e.g. waves and circulation, bearing in mind that caution is needed in handling model output. (The recent atlas of UK marine renewable energy resources (DTI, 2004) uses output from the Met. Office's UK waters wave model, albeit only from a three-year run of the model.)

Recommendation: For each MPC parameter, IACMST should organise a full assessment and synthesis of observed and modelled data in UK waters.

Most scientific analysis, interpretation and representation of MPC data is done without taking into account the needs of the data users from the marine environmental quality, fisheries, and nature conservation sectors; therefore resulting in 'products' which are not of immediate use. There is a clear need for additional interpretative work in order to deliver more usable products and management tools. For example, fisheries scientists/managers may be interested in a simple graphical representation of summer/winter temperatures over the years, or summary annual, seasonal or monthly statistics.

Recommendation: In consultation with user fora representing other marine sectors (e.g. CEFAS/FRS, JNCC and MEMG), IACMST should organise additional interpretative work on MPC parameters, including a workshop or symposium.

References:

Cowling (2004). Marine Data and Information – where to now? Report to the IACMST. (In preparation).

DTI (2004). Atlas of UK Marine Renewable Energy Resources: Stage 1. DTI Report R1067.

IACMST (2000). Review of Current UK Marine Observations in Relation to Present and Future Needs. Prepared by John Portmann. IACMST Information Document No. 7.

IACMST (2001). Climate of UK Waters at the Millennium: Status and Trends. Edited by Graham Alcock and Lesley Rickards. IACMST Information Document No. 9. (Also available at: http://www.oceannet.org/UKclimate-status).

12. Appendix: Glossary

ABMS	Annual Beach Monitoring Survey
ABP	Associated British Ports
ADCP	Acoustic Doppler Current Profiler
AVHRR	Advanced Very High Resolution Radiometer
BADC	British Atmospheric Data Centre
BODC	British Oceanographic Data Centre
CASI	Compact Airborne Spectrographic Imager
CEFAS	Centre for Environment Fisheries and Aquaculture Science
CPR	Continuous Plankton Recorder
CTD	Conductivity Temperature and Depth logger
CZCS	Coastal Zone Colour Scanner
DARD(NI)	Department of Agriculture and Rural Development (Northern Ireland)
Defra	Department of Environment Food and Rural Affairs
DTI	Department of Trade and Industry
EDIOS	European Directory of the Ocean-observing System
ENSO	El Niño/Southern Oscillation
ESC	European Slope Current
ESODAE	European Shelf Seas Ocean Data Assimilation and Forecast Experiment
FRS	Fisheries Research Services
GHG	Greenhouse Gas
GLOSS	Global Sea Level Observing System
GOOS AG	Global Ocean Observing System Action Group
GSA	Great Salinity Anomaly
GSM	Global System for Mobile communications
HF radar	High Frequency Radar
Hs	Significant wave height
IACMST	Inter-Agency Committee on Marine Science and Technology
IBTS	International Bottom Trawl Survey
ICES	International Council for the Exploration of the Sea
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IPCC	Intergovernmental Panel on Climate Change
JEBAR	Joint Effects of Baroclinicity and Relief
JNCC	Joint Nature Conservation Committee
JONSIS	Joint North Sea Information System
LV	Light Vessel
MAFF	Ministry of Agriculture, Fisheries and Food
MAWS	Marine Automatic Weather Station
MBA	Marine Biological Association of the United Kingdom
MECN	Marine Environmental Change Network
MED AG	Marine Environmental Data Action Group
MEMG	Marine Ecosystem Modeling Group
MIC	Marine Information Council
MPC	Marine Processes and Climate
MPMMG	Marine Pollution Monitoring Management Group
MSL	Mean Sea Level
Namoc	North Atlantic Meridional Overturning Circulation
NAO	North Atlantic Oscillation
NMMP	National Marine Monitoring Programme

NOAA	National Oceanic and Atmospheric Administration
NOMADS	North Sea Model Advection Dispersion Study
NOWESP	North-West European Shelf Programme
OWS	Ocean Weather Station
PEML	Port Erin Marine Laboratory
PML	Plymouth Marine Laboratory
POL	Proudman Oceanographic Laboratory
POT	Peak Over Threshold
PROMISE	Pre-Operational Modelling in the Seas of Europe
PSMSL	Permanent Service for Mean Sea Level
SAHFOS	Sir Alister Hardy Foundation for Ocean Science
SAMS	Scottish Association for Marine Science
SCC	Scottish Coastal Current
SNIFFER	Scottish and Northern Ireland Forum for Environmental Research
SOC	Southampton Oceanography Centre
SPM	Suspended Particulate Matter
SSC	Suspended Sediment Concentration
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
UEA	University of East Anglia
UKHO	United Kingdom Hydrographic Office
WASA Group	Waves and Storms in the North Atlantic Group
WMO	World Meteorological Organization