APPENDIX 3d - WATER ENVIRONMENT

A3d.1 INTRODUCTION

A number of aspects of the water environment are reviewed below in a UK context, and for individual Regional Seas:

- The major water masses and residual circulation patterns in UK seas
- Density stratification (influenced principally by temperature and salinity) and frontal zones between different water masses – these represent potentially important areas for biological productivity
- Tidal flows
- Overall patterns of temperature and salinity
- Wave climate
- Ambient noise

Recent assessments of changes in hydrographic conditions are summarised, based mainly on reports by DEFRA (2004a, b) and MCCIP (2007). Overall, significant anomalies and changes have been noted in sea surface temperature (SST), thermal stratification, circulation patterns, wave climate, pH and sea level – many appear to be correlated to atmospheric climate variability as described by the North Atlantic Oscillation (NAO). Larger-scale trends and process changes have also been noted in the North Atlantic (e.g. in the strength of the Gulf Stream and Atlantic Heat Conveyor (more properly characterised as the Meridional Overturning Circulation (MOC), or the Atlantic Thermohaline circulation (THC) e.g. Trumper 2005), Northern Hemisphere (Weijerman *et al*. 2005) and globally (IPCC 2007a). There are varying degrees of confidence in the interpretation of observed data and prediction of future trends.

Finally, the specific environmental issue of eutrophication is summarised. This is an area of concern in specific geographical areas, notably the southern North Sea and various coastal and estuarine locations.

A3d.2 UK CONTEXT

The history of broadscale studies of North Sea circulation and hydrographic patterns (e.g. temperature and salinity distribution) was briefly reviewed in SEA 2. The existence of the Fair Isle current was first demonstrated in the late nineteenth century, using surface drift bottles and sea-bed drifters (Fulton 1897). Long-term datasets available for the North Sea were listed by Clark *et al*. (2001), and more recently by DEFRA (2004b) and MCCIP (2007) – these include the MAFF Sea Surface Temperature and Salinity Data Set (ship routes to and from the UK, 1963 to 1990); the Institut für Meereskunde (Hamburg) Climatological Atlas of Salinity and Temperature for the North Sea (1968 to 1985); and the Netherlands Institute for Sea Research (NIOZ) Marsdiep Sea Surface Temperature and Salinity Time Series (1860 to present).

Circulation patterns in the English Channel, and exchange with the North Sea via the Dover Strait, have been studied using radioactive tracers (Bailly du Boisa *et al*. 1995, 1997); while there is a long history (>100 years) of monitoring sea temperatures and stratification around the Plymouth area of the western English Channel (Southward *et al*. 2005. Daily sea temperatures have also been recorded for over a century in the Northern Irish Sea at Port Erin, Isle of Man, where long term monitoring of offshore nutrients, salinity and chlorophyll has been carried out for around 50 years, and plankton since the 1990s (Government

Laboratory (Isle of Man) 2008). Hydrographic monitoring including temperature, salinity, nutrients and chlorophyll has been carried out at Menai Bridge, Anglesey sporadically since 1948 and regularly since 2000 (Evans *et al.* 2003).

Hydrographic processes in the North Channel, Sea of the Hebrides and Minches have been sporadically studied over a long time period (see below for references), with particular focus on the distribution of radionuclides from Sellafield and a long-term mooring deployment in the Tiree Passage maintained by the Dunstaffnage Marine Laboratory.

Since the pioneering Porcupine and Lightning studies of 1868-1870 (Wyville Thomson 1874), the Faroe-Shetland Channel, and to some extent the Rockall Trough, have been one of the most studied oceanic regions of the world. Two hydrographic sections across the Channel have been surveyed by the Aberdeen Marine Laboratory for over a century (Turrell *et al*. 1999a, 1999b). Long-term monitoring of water exchange between the Atlantic and Nordic seas was described in SEA 1.

The measurement of waves is a relatively recent development, with only very crude instruments available prior to about 1955 (DEFRA 2004a). 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 light vessel, 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.

On behalf of the GOOS (Global Ocean Observing System) Action Group which reports to the Inter-Agency Committee on Marine Science and Technology (IACMST), Reid and Portmann (2006) carried out a review of monitoring of the marine environment by organisations based in the UK. The main focus of the review initially was measurements related particularly to the physical marine environment. However, the remit was broadened to include chemical and biological observations in order to extend the usefulness of the collected information to the wider interests of the DEFRA-led Marine Monitoring Coordination Group (MMCG) which has now been disbanded and replaced by the Marine Assessment and Policy Committee (MAPC) and Marine Assessment and Reporting Group (MARG).

The IACMST's Marine Environmental Data Network website (http://www.oceannet.org) is the portal to two working groups:

- UK GOOS – GOOS is a permanent global system for observations, modelling and analysis of marine and ocean variables. It provides a platform for international collaboration in operational oceanography.

- Marine Environmental Data and Information Network (MEDIN which combines the Marine Data and Information Partnership - MDIP, and the Marine Environmental Data Action Group – MEDAG) and aims to coordinate accessibility and availability, and providing online search interfaces for UK marine environmental data – data resource areas include:
    - Wave data catalogue
    - Current meter data

- Tide and sea level data catalogue
- Cruise summary report database
- Foreign cruises in UK waters
- Marine monitoring programmes (UKDMOS and EDIOS)
- Marine environmental datasets (over 700 UK marine environmental data sets and submitted by over 100 UK organisations)

Initiatives from which data are available via OceanNET include the Joint Evaluation of Remote sensing Information for Coastal defence and Harbour Organisations (JERICHO) project (waves; Cotton *et al*. (1999)), the EU 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 Global Sea Level Observing System (GLOSS) project (sea level) and the Natural Environment Research Council (NERC) Land Ocean Interaction Study (temperature, salinity, waves, sediment/ turbidity, coastal data) and North Sea Project (temperature, salinity, currents and circulation, sediment/turbidity).

A3d.2.1 Water masses and circulation

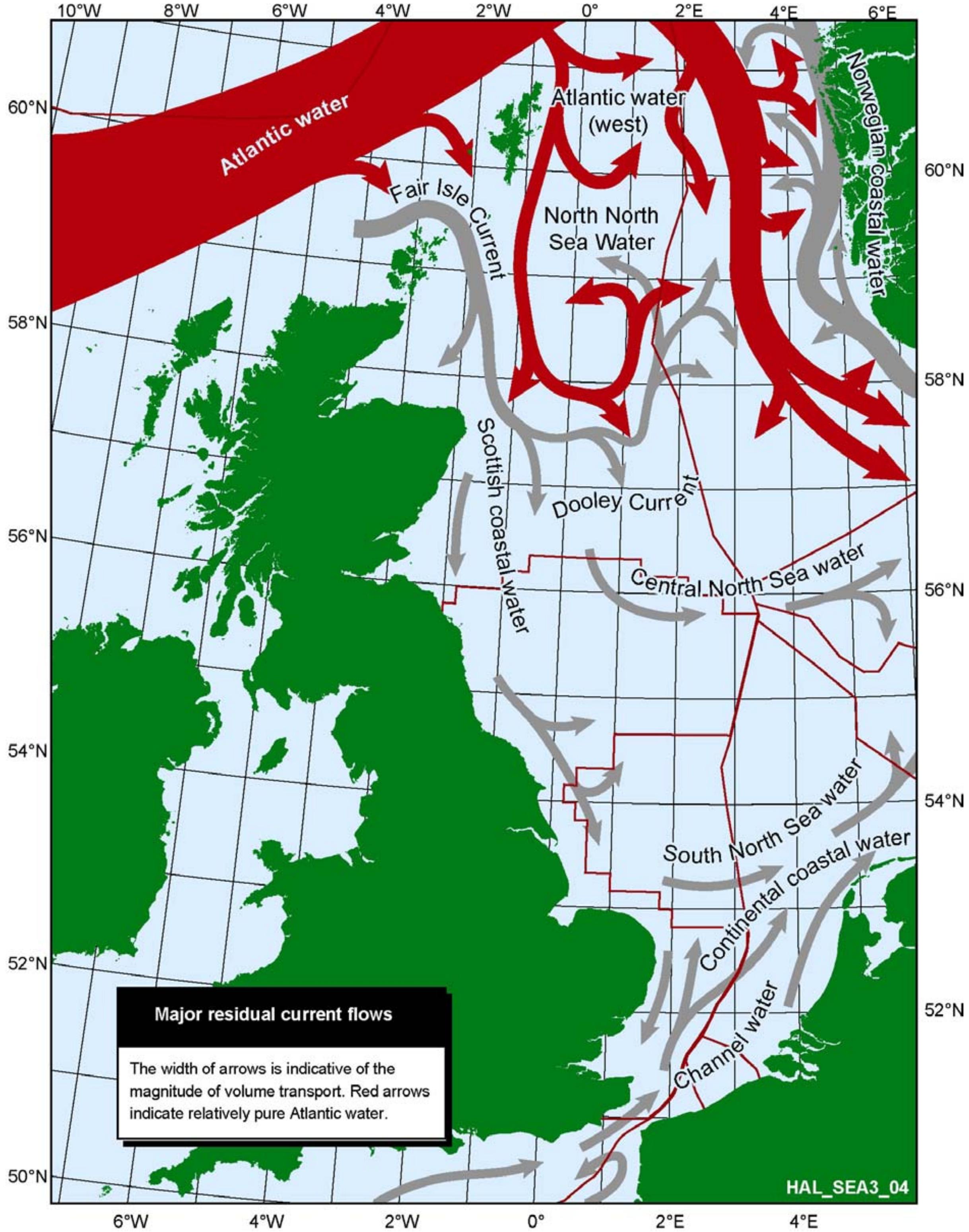
The western continental shelf edge and shelf slope are influenced by two main oceanic circulation systems of the North Atlantic - the sub polar and sub tropical gyres. The main branch of the North Atlantic Current (NAC) sweeps eastwards from the western North Atlantic before turning in a more northerly direction and flowing to the west of the Hatton Bank. Smaller southerly branches of the NAC enter the Hatton-Rockall area from the north and circulate over the Rockall Bank and further to the south. A branch of the NAC travels north-eastward across the Rockall Plateau and through the Rockall Trough towards the Faroe-Shetland Channel.

A poleward flowing shelf edge current (SEC) is present along the continental margin and occupies the upper part of the slope typically above 700m, on both sides of the Wyville Thomson Ridge. Near the southern boundary of Regional Sea 8 it makes an excursion across the slope and onto the shelf (Ellett *et al.* 1986, Souza *et al*. 2001) before continuing its path along the slope at the southern end of the Hebrides. The SEC is associated with a relatively strong northward flowing coastal current, the Scottish Coastal Current (SCC) which, although a persistent feature (Simpson & Hill 1986), exhibits spatial variation and is modified by both winds and atmospheric pressure gradients.

North of the Wyville Thomson Ridge, there is substantial inflow to the North Sea via the Fair Isle current and to the north-east of Shetland. Sources and circulation of water in the North Sea as a whole were summarised by SEA2, which identified (after Turrell 1992, see Figure A3d.1) the major water masses in the North Sea as Atlantic water, Scottish coastal water, north North Sea water, Norwegian coastal water, central North Sea water, south North Sea water, Jutland coastal water and Channel water. The main inflow to the North Sea occurs along the western slopes of the Norwegian Trench, with minor inflows from the Channel and Baltic. These inflows are balanced by outflow mainly along the Norwegian coast, with most of the water probably passing through the Skagerrak.

The generalised pattern of water movement in the North Sea may be strongly influenced by short-medium term weather conditions, resulting in considerable seasonal and interannual variability. Drastic differences in Atlantic water inflow from year to year, caused by atmospheric forcing, explain some of the observed large scale differences in salinity between years (OSPAR 2000a). Storm events may also generate nearbed, wave-induced currents sufficient to cause sediment mobilisation.

Figure A3d.1 – Major water masses and residual circulation in the North Sea



A3d.2.2 Stratification and frontal zones

Fronts or frontal zones mark boundaries between water masses, including tidally-mixed and stratified areas, and are numerous on the European continental shelf. Around the UK, the Flamborough and Islay Fronts have been studied, as has density stratification of the water column in the western English Channel and Irish Sea.

Density stratification is well developed in the summer months of most years in the central and northern North Sea, with the relative strength of the thermocline determined by solar heat input and turbulence generated by wind and tides. The shallow parts of the southern North Sea remain well mixed throughout the year due to tidal action (OSPAR 2000a) although the Kattegat, Skagerrak and Norwegian Trench region of the North Sea have a stable salinity stratification all year. Density stratification in the central and northern North Sea breaks down after September due to increasing frequency and severity of storms and seasonal cooling at the surface.

Satellite imagery shows that at the southern boundary of Regional Sea 1, the central North Sea from Flamborough Head to the Frisian Islands is frequently characterised by a thermal front marking transition zones between mixed and stratified water in the North Sea (Pingree and Griffiths 1978, Becker 1990). Usually, a frontal system includes a narrow (typically a few km 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 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. 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). A persistent narrow (10-15km) near-surface flow between the Firth of Forth and the Dogger bank has been noted (Brown *et al.* 2001, DEFRA 2004b), driven by bottom density fronts that fringe the dense pool of cold winter water formed in the central North Sea following stratification.

The Islay Front, between the Scottish and Irish coasts is a complex, seasonally distinctive front in which both salinity and temperature play a role in controlling the density structure. The Islay Front is also associated with strong residual currents parallel to the front, and enhanced phytoplankton standing crop (Simpson *et al*. 1979).

In coastal areas, surface heating and settled weather in late summer and autumn can often cause temporary thermoclines to develop (Heath *et al.* 1999). Temperature and salinity patterns are more complex within the semi-enclosed firths and estuaries (see below).

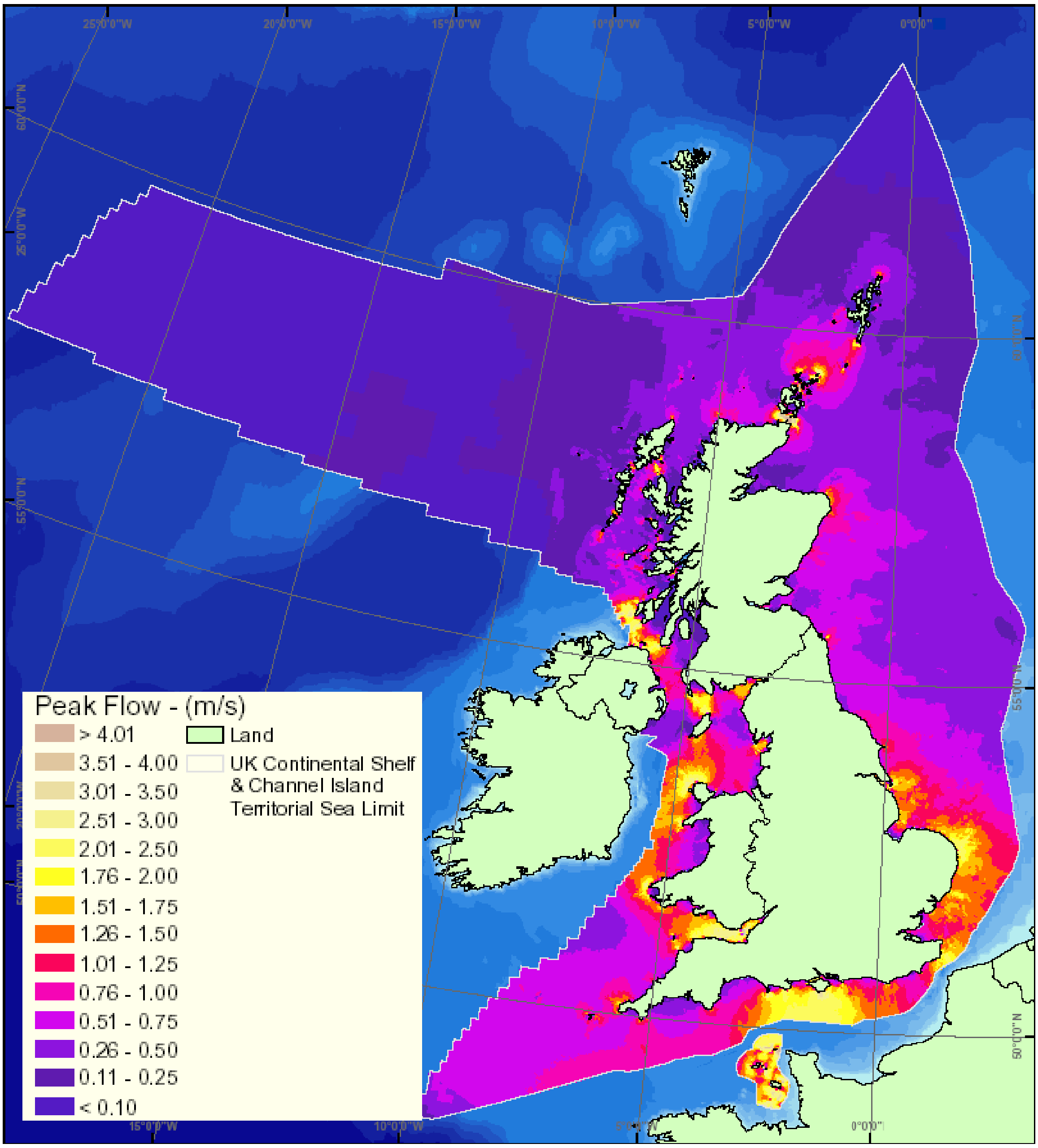
The UKSeaMap project (Connor *et al*. 2006) developed maps to represent the seasonal ecological character of the water column, using surface salinity, surface to bed temperature difference and frontal probability (i.e. the number of days the horizontal temperature difference between neighbouring modelled locations exceeds 0.5ºC, divided by the number of days in this season over the 10-year run). This analysis emphasized the importance of the Flamborough Front; and also frontal development around the Dogger Bank, along the east coasts of mainland Scotland (north of the Tay), outer Moray Firth and Shetland in summer (See also Figure A3a.1.2 in Section A3a.1).

A3d.2.3 Coastal tidal flows

Maximum surface tidal streams which vary from 0.25 to 0.5m/s over much of the northern North Sea are in excess of 1.0m/s on the Orkney-Shetland Platform (Pantin 1991). Over the central North Sea, tidal currents are strongest in shallow coastal areas (see below), where the tidal stream is aligned parallel to the coast. Maximum surface current speeds are mainly in excess of 0.5m/s out to about 50km offshore, decreasing eastwards to less than 0.25m/s. (Gatliff *et al.* 1994).

Along the east coast of northern England and mainland Scotland, there is a general southern flood and northern ebb tidal flow, the pattern being complicated by coastal topography, fluvial flow and wind-induced currents. Tidal streams reach considerably higher velocities (3.5-4.5m/s) in certain parts of Regional Sea 1, notably in Shetland near Muckle Flugga, in Yell Sound, Linga Sound, Bluemull Sound and near Sumburgh Head; and around Orkney in Hoy Sound and the Pentland Firth (Figure A3d.2). Maximum east-travelling surface tidal streams of 5.3m/s are recorded on the west margin of the Pentland Skerries and near-bed spring tide currents are more than 2.75m/s near the head of the Sandy Riddle decreasing rapidly to around 0.875m/s further to the south-east (Holmes *et al*. 2004).

Figure A3d.2. Peak flow for mean spring tide



Source: Atlas of UK Marine Renewable Energy Resources: Technical Report http://www.berr.gov.uk/energy/sources/renewables/explained/wind/page27741.html

The tidal currents in the English Channel flood eastwards and ebb westwards with a maximum rate off Portland Bill at the western end of Regional Sea 3, where they may reach over 3.5m/s. For much of the central part of the English Channel the maximum speed of tidal currents is between 0.75 and 1.25m/s. One peculiar feature of the tides in the central part of the English Channel is the distortion of tidal curves due to the effect of shallow water.

The tide propagates into the Irish Sea from the Atlantic Ocean through both the St George's Channel and the North; the tidal waves from both directions meet to the south west of the Isle of Man causing this to be an area of very weak tidal currents (<0.35m/s). Areas of strong tidal currents (depth-averaged values up to 2m/s at spring tides) and hence of vigorous tidal mixing and peak bed stresses are generally throughout St George's Channel, north west of Anglesey, north of the Isle of Man and in the North Channel.

Through the North Channel and west of mainland Scotland, there is a general northern flood and southern ebb tidal flow, the pattern being complicated by coastal topography, fluvial flow and wind-induced currents with maximum tidal currents run in the North Channel and south of Islay (more than 4.0m/s inside Rathlin Island), Gulf of Corryvreckan, Sound of Islay, Firth of Lorne and Sound of Mull.

A3d.2.4 Temperature and salinity

Sea surface temperature and salinity values in the northern North Sea are to a large extent influenced by the flow of oceanic Atlantic waters into the North Sea through the Fair Isle Channel (Turrell 1992). Oceanic inflow combines with less saline coastal waters to make up a southern flow down the Scottish east coast.

In coastal waters, land run-off is important in determining temperature and salinity profiles. For example, in Regional Sea 7, strong temperature gradients may coincide with the low-salinity surface layer that can develop in sea lochs. Sea surface temperatures in Regional Sea 3 are strongly influenced by the movement of water along the English Channel which modifies the influence of continental Europe. In winter, relatively warm waters move up the English Channel, and average February temperatures range between 6.5ºC and 8ºC.

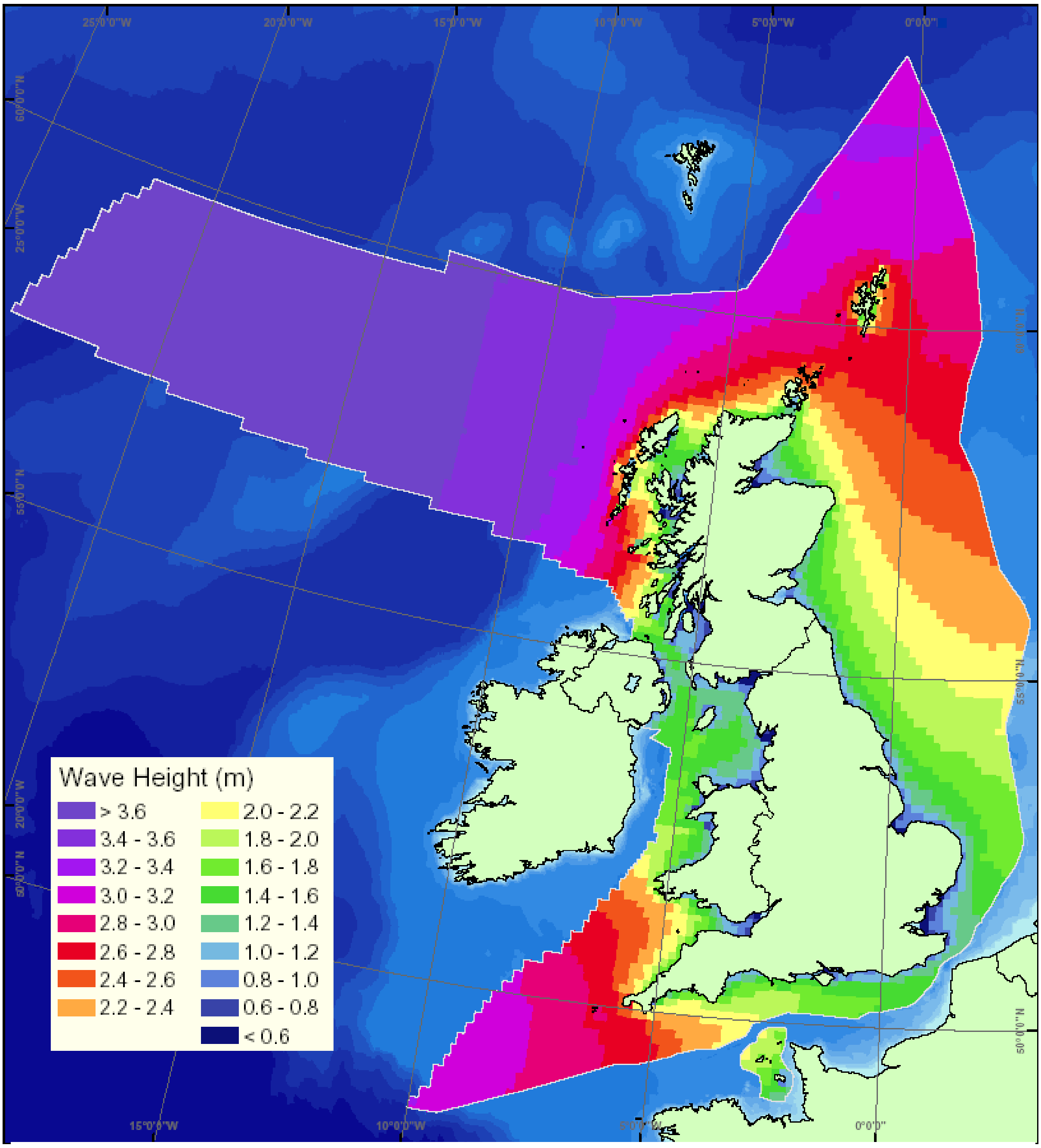
A number of water masses, characterised by their salinity and temperature characteristics, are known to be present in the deep oceanic channels of Regional Seas 9, 10 and 11, and studies have shown there to be distinct differences due to density stratification and separation by topographic features (notably the Wyville Thomson Ridge).

A3d.2.5 Wave climate

In British waters, the west coast of Ireland and the Western Isles experience the highest wave heights (long term mean significant wave height (Hs) of 3.0m (Figure A3d.3). The east coast of Shetland, Orkney and the mainland is more sheltered and less frequently exposed to large, powerful waves than the west. However, North Sea storms and swells can result in relatively large wave heights although only swell waves from the northeast are able to penetrate to the inner Firths due to the protection afforded by the coastal topography (Stapleton & Pethick 1996). Incident waves from this direction occur for only 29% of the year.

The wave climate is strongly seasonal with maximum mean wave heights peaking around January, although extreme waves may be encountered at other times, most notably between October and March. Seasonal variation, as derived from the Geosat, ERS-1, ERS-2, TOPEX/Poseidon and Jason altimeter data from 1985 onwards for an area east of Aberdeen, is around 1.5m (min 1.3m, max 2.8m) (DEFRA 2004a).

Figure A3d.3 – Annual mean significant wave height



Source: Atlas of UK Marine Renewable Energy Resources: Technical Report http://www.berr.gov.uk/energy/sources/renewables/explained/wind/page27741.html

The offshore oil and gas industry has collected data on wave heights over the last 30 years. The data for the northern North Sea indicate that mean significant wave height during the period January–March was raised between 1973-1995 by about 5-10% (0.2-0.3m), with a decrease thereafter.

There is considerable effort currently underway to determine the magnitude and causes of long-term changes in wave climate and storm frequency around the UK (see below).

A3d.3 FEATURES OF REGIONAL SEA 1

One site within Regional Sea 1 (Stonehaven) is sampled as part of the FRS Coastal Long-term Monitoring programme (1999-present); data are collected on water temperature, salinity, nutrients and phytoplankton. A secondary sampling site (temperature only) is located at Findon.

The tidal streams present in the Moray Firth are complex and variable in direction (Adams & Martin 1986). Due to the passage of the tidal wave across the outer Firth, tidal currents are stronger in this area than inshore, where topographically induced localised gyres occur (Adams & Martin 1986). Within the inner Moray Firth most of the area is subject to currents of less than 0.5m/s (Stapleton & Pethick 1996). In general, the tides in the outer Firth flood in a north to south easterly direction, reversing to ebb northwards. However, in the inner Firths of the Dornoch, Cromarty and Beauly/Inverness, the tides trend in a more easterly direction. Along the southern shore of the Firth, a notable feature of the tidal current pattern is a flood lasting approximately nine hours of the tidal cycle, with an insignificant ebb flow for the remaining three hours. This phenomenon occurs up to 8km offshore and is a result of the southern Moray coastline sheltering the area from the north flowing ebb current (Dooley 1973). The resultant residual current is an eastward flow along the southern shore of the outer Firth (Adams & Martin 1986).

South of the Tay estuary, the south-going flood tide forms a large clockwise eddy in St Andrews Bay spilling over Abertay sands into the main Tay channel (Charlton *et al*. 1975). Within the estuary, current velocities can be high with peak spring flood velocities of 1.15m/s to the south west of Buddon Ness. Sand waves to the west of the Newcombe shoal are evidence of considerable flow velocity (Charlton *et al.* 1975). River flow variations can have a significant effect on the tidal regime causing complex patterns of water movement (Ramsay & Brampton 2000).

Typical peak tidal flow velocities at Rosyth in the Firth of Forth are 0.7-1.1m/s on the ebb and 0.4-0.7m/s on the flood, with generally weaker flows to seaward of this location. In general, the flood currents are stronger on the north side of the Firth and the ebb stronger on the southern shore. Tidal currents produce a drift westwards along the northern and central Firth, compensated by an eastward flow of water along the southern shore. However, during certain times of year, usually late winter and spring, a seaward flow may also develop along the northern shoreline if the water near the coast becomes stratified.

North of the Farne Islands, the nearshore maximum tidal current speed during mean spring tides is 0.5m/s (approximately equivalent to 1 knot), increasing to about 0.7m/s in Tees Bay. The tidal current flow offshore runs more or less north to south, but closer to the shore the flow is affected by the form of the coast. For example, tidal currents are stronger around headlands such as Flamborough Head (up to 1.5 metres per second), and eddies or gyres may form within embayments such as Druridge Bay and Hartlepool Bay.

In winter, low salinity surface waters from land run-off within the inner Moray Firth and along its southern coast form a distinctive colder stream close to the southern shore which can be over 1ºC colder than bottom waters. Salinity distributions within the major estuary systems of the Forth and Tay have been extensively studied, partly in relation to their influence on contaminant dispersion. The River Tay and the River Earn together form the major systems draining into the Tay estuary, and between them contribute the greatest volume of freshwater of any river basin in the UK (Pontin & Reid 1975). The estuary is generally turbulent and well mixed, although there is evidence of a saline 'wedge' penetrating as far as the narrows at Tayport, where the vertical salinity difference is about 7‰. This wedge is probably formed by saline water coming over the Abertay sands from St Andrews Bay and plunging under the main flow coming down the main channel (Charlton *et al*. 1975). Within the Forth estuary (upstream of the bridges), the dominant water movement is tidal, with the influence of freshwater from rivers being relatively low. Further to seaward, there is more dilution from rivers on the south shore of the Firth than the north, leading to an outgoing stream of diluted water (32-34‰) along the southern side which is generally distinguished as far seaward as St Abbs Head.

Offshore wave data series collected from production facilities in Regional Sea 1, for example at Forties (1974-present), Frigg (1979-present) and Ekofisk (1980-present) provide some of the longest consistent periods of measurement in UK waters (DEFRA 2004b).

A3d.4 FEATURES OF REGIONAL SEA 2

The NERC North Sea Project (1987–1992) included studies of the Flamborough Head frontal system, Humber and Thames plumes and resuspension processes, and detailed study of the southern North Sea sandwave system. In addition to detailed studies of the Flamborough Head frontal system, Humber and Thames plumes and resuspension processes, a detailed study of the southern North Sea sandwave system was conducted.

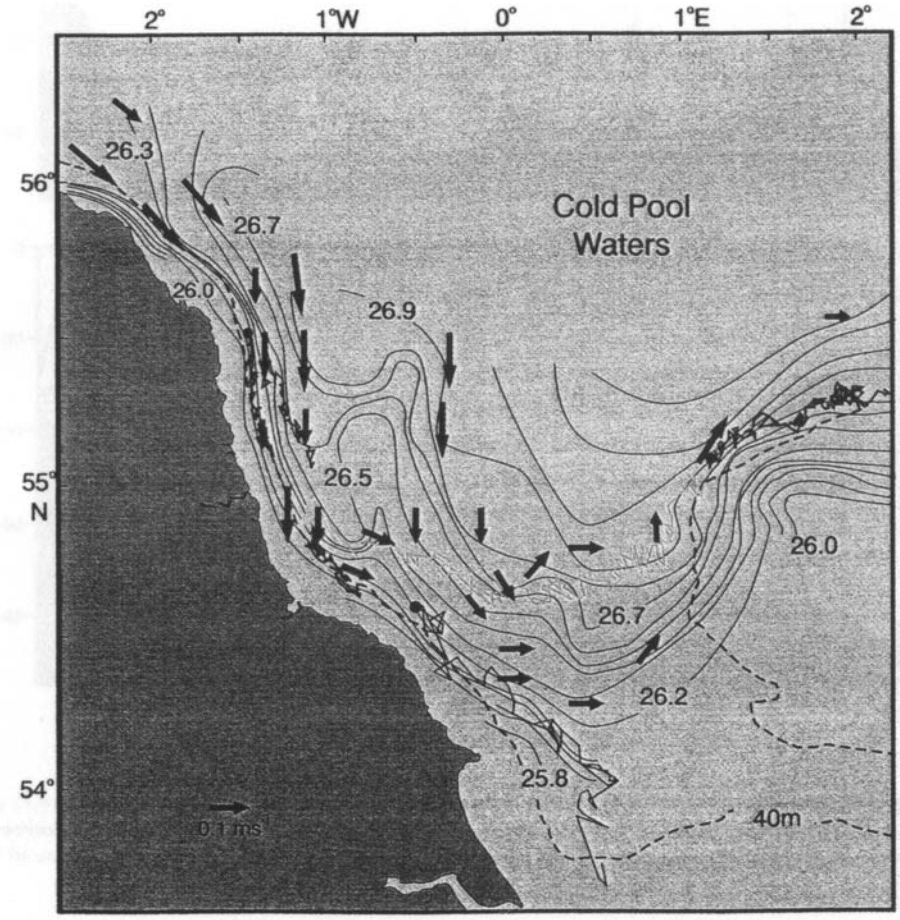
The NERC Land Ocean Interaction Study (LOIS) was a 6 year project (1992 - 1998) which aimed to quantify and simulate the fluxes and transformations of materials (sediments, nutrients, contaminants) into and out of the coastal zone. The main study area, embracing river catchments, estuaries and coastal seas, was the UK East Coast from Berwick upon Tweed to Great Yarmouth, concentrating on the Humber and its catchment, and to a lesser extent the River Tweed. LOIS comprised seven components studying riverine, atmospheric, estuarine, coastal and shelf processes, including a major geological study of the sedimentary record in a traverse of the coastal zone to determine how sediment fluxes have influenced sea level, climate and land use.

The Flamborough front has been intensively studied (Prandle & Matthews 1990, Lwiza *et al*. 1991, Gmitrowicz & Brown 1993) including a collaborative experiment in 1988 by MAFF, POL and UCNW which involved Ocean Surface Current Radar (OSCR), ship-borne Acoustic Doppler Current Profiler (ADCP), Lagrangian drifters and moored current meters. Observations of the physical structure of the region between the Northumberland coast and north Dogger Bank were made in 1996 using towed undulating CTD and satellite-tracked drifting buoys, to test for the presence of a summer cold pool system and associated jet circulation in this area (Brown *et al*. 1999). A more detailed survey of the coast from the Forth to Flamborough Head was also carried out in 1997 (Brown *et al*. 2001, Figure A3d.4). Strong bottom fronts were observed to bound a cold pool isolated beneath the thermocline, extending continuously for 500km along the 40m contour, from the Firth of Forth to the eastern end of the Dogger Bank. Persistent and narrow (10-15km) cores of cyclonic near-surface flow were also observed with velocities in excess of 0.1m/s.

Peak tidal current velocities are shown in Figure A3d.4. In general, maximum velocities are below 1.0m/s except in the vicinity of major headlands (Flamborough Head, Spurn Point and South Foreland) where peak velocities may reach 2.0m/s.

Significant local variations in patterns of semi-diurnal tidal and residual circulation occur in the vicinity of sandbanks. Bedforms and current meter measurements around the Leman and Well Banks, Smith's Knoll and Hewett Ridges have demonstrated residual near-bed currents to be strongest towards the bank crestline and in opposing directions on either side of the bank (Caston & Stride 1970, Caston 1972, Huthnance 1973). Current records on each side of Well Bank also demonstrated a clockwise near-bed residual circulation around the bank (Howarth & Huthnance 1984, Collins *et al.* 1995), with maximum semi-diurnal amplitude around 0.75m/s. This residual circulation pattern is considered to be important in the formation and maintenance of linear sandbanks and will also influence the dispersion of soluble and particulate contaminants.

Figure A3d.4 – The Flamborough Front



Source: Brown et al. (2001)

In winter, the waters in the north of Regional Sea 2 are some of the coldest areas of the UK (Jones *et al*. 2004c); however, sea-surface temperatures increase southwards (from 5 to 7ºC) in February. This is a result of a wedge of relatively warm water extending up from the English Channel which prevents water temperatures dropping below 5ºC. In August, temperatures again increase progressively to the south (from 14 to 16.5ºC), reflecting increased proximity to the warm European landmass. The waters here are also well mixed at that time of year and show no stratification, whereas in the north bottom temperatures are 2-3ºC lower than the surface temperatures.

The southern North Sea receives significant freshwater input from the rivers along its eastern boundary and is, as a consequence, less saline than the northern North Sea (DEFRA 2004b). Saline water of North Atlantic origin enters the southern North Sea via the Dover Straits, and this tends to lead to generally more salty water in the most southerly parts of the North Sea.

A3d.5 FEATURES OF REGIONAL SEA 3

Regional Sea 3 is characterised by a reasonably well-defined transition between two marine provinces, centred on the Solent. The Eastern Channel is largely influenced by cool Boreal water (which dominates the North Sea system), whereas the western part of the Channel is influenced by relatively warmer Lusitanean water, which comes in part from the Gulf Stream and in part from the water leaving the Mediterranean. Overall, there is a residual flow of water entering the North Sea from the eastern end of the English Channel, though this accounts for just 10% of the inflow into the North Sea.

Circulation patterns in the English Channel, and exchange with the North Sea via the Dover Strait, have been studied using radioactive tracers. For example, seven oceanographic campaigns carried out in the North Sea and Channel by the Marine Radioecology Laboratory (LRM) of La Hague have led to the drawing of general maps showing the distribution of the radionuclides 125Sb, 137Cs, 134Cs and 99Tc in seawater (Bailly du Bois *et al*. 1995, 1997). On this basis, it is possible to link the flux of radionuclides released from the nuclear fuel reprocessing plant at La Hague (125Sb and 99Tc) with the inventories of radiotracers observed in the southern North Sea. Hence, the most probable mean transit time of Channel waters entering the North Sea were calculated; Channel waters take 110–152 days to flow from Cap de la Hague to the Straits of Dover and 170–250 days to travel from there to the entrance of the Baltic. The water flux through the Straits of Dover was estimated to lie in the range 97,000–195,000m^3/s for the period between January and July 1988.

Within Regional Sea 3 there is only one weak front, which lies to the south-east of the Isle of Wight parallel to the coast. Generally speaking, the whole of the eastern Channel is non-stratified, due to the relatively shallow water depth combined with the effects of tidal and wind-generated water movements.

The tidal currents in the English Channel flood eastwards and ebb westwards. The maximum tidal current speed at the eastern end of the Regional Sea is at Dover (about 1.75m/s) owing to the restriction of the Channel. Stronger tidal currents occur off Portland Bill at the western end of the Regional Sea, where they may reach over 3.5m/s. Strong tidal currents, often with associated overfalls, occur off pronounced headlands such as Selsey Bill, St Catherine's Point and St Alban's Head. Within the main embayments, such as Rye Bay on the Kent/East Sussex border, Christchurch Bay, Poole Bay and Weymouth Bay, currents are relatively weak, especially in shallow water. For much of the central part of the English Channel the maximum speed of tidal currents is between 0.75 and 1.25m/s.

One peculiar feature of the tides in the central part of the English Channel is the distortion of tidal curves due to the effect of shallow water. A consequence of this is that tides have a marked double low water between Portland Harbour and Kimmeridge Bay. From Swanage to Southampton double high waters occur. In Poole and Christchurch Bays, this distortion results in a long stand of the tide at, or very close to, the high water level.

Sea surface temperatures in Regional Sea 3 are strongly influenced by the movement of water along the English Channel which modifies the influence of continental Europe. In winter, relatively warm waters move up the English Channel, and average February temperatures range between 6.5ºC and 8ºC. In August, surface water temperatures in the central English Channel are on average 16-16.5ºC (Lee & Ramster 1981). During the summer months, temperatures increase northwards from the middle of the English Channel towards the coast.

Although slightly lower than in winter (when averages are 35.0-35.2‰), salinity values remain relatively high in summer along the centre of the English Channel (between 34.75-35.0‰), owing to the eastward movement of Atlantic water. Salinity values decrease towards the coast in both summer and winter but normally remain above 34.5‰, except locally at river mouths where there is dilution from freshwater discharge.

A3d.6 FEATURES OF REGIONAL SEAS 4 & 5

The body of water present within Regional Seas 4 and 5 is Atlantic in origin. The driving force behind water movements in these regions is the North Atlantic Circulation (NAC; or Meridional Overturning Circulation, MOC). The NAC divides to the south west of Ireland, with one mass of water moving northeastwards off the western coast of Ireland and the other heading south eastwards towards the Bay of Biscay (Lee & Ramster 1981). Whilst the general near-surface direction of water movement is from the north west, there is also a gyre close to the southern Cornish coast at the entrance to the English Channel. A further deep-water current flows northwards from the Mediterranean, surfacing in the Western Approaches and continuing northwards and eastwards to influence the whole of the southwestern peninsula and beyond.

There are several consistent fronts within the western Channel. A front divides the shallows of Lyme Bay from deeper offshore water, approximately following the 40m contour. A second front runs south from Bigbury Bay, west of Start Point; a third is situated around Land's End; and a fourth runs from the north Cornwall coast in a northwesterly direction. A number of seasonal fronts appear periodically in the waters adjacent to the Scilly Isles; on the landward side of these fronts there is mixed water, while on the open sea side the water is stratified.

There are no distinct fronts in the Western Approaches as the water mass in this region remains stratified, with a distinct thermocline present during the summer months. The thermocline provides a marked vertical temperature gradient within a discontinuity layer which usually occurs somewhere between 100 and 500m depth. Vertical mixing is a critical factor for controlling primary production in shelf seas. For the Celtic Sea it had been postulated that one of the main contributors to the energy flux was internal waves, generated at the shelf break. This was tested by Green *et al*. (2008) who concluded that such internal waves are unlikely to be the main source of energy for mixing on the inner part of the shelf.

In the offshore part of Regional Sea 4, and in the open Atlantic Regional Sea 5, maximum tidal current speeds during mean spring tides range from 0.11-1.00m/s. Current speed maxima during mean neap tides are approximately 40-50% of these values (Lee & Ramster 1981).

On the English side of the western Channel, tidal currents flood eastwards and ebb westwards. The constriction of Atlantic water flow between Start Point and the Cotenton Peninsula on the French coast increases current speed and currents are at their strongest (in the region of 2m/s at mean spring tides) around headlands, such as Start Point, and in the Channel between the Isles of Scilly and the mainland. Within the main embayments, such as Lyme Bay, currents are relatively weak especially in shallow water. For much of the central part of the English Channel the maximum speed of tidal currents is between 0.75 and 1.25m/s.

Within the Bristol Channel, the ebb flow is dominant, with complex circulatory flows around the major sandbanks. On the northern side of the peninsula and into the Bristol Channel, current speeds steadily increase to a maximum surface ebb current of 4.6m/s off Foreland

Point, and a maximum flood current of 4.2m/s off Weston-super-Mare. Offshore, current speeds are slightly lower, ranging from 0.72m/s off Lundy to over 3.0m/s in the Bristol Deep off Avonmouth (Poulton *et al.* 2002).

The tidal range for the eastern part of Regional Sea 4 (i.e. the central Channel) is not particularly large; around 3.0-4.0m mean spring in Lyme Bay. Tidal range increases progressively offshore into the English Channel and is particularly high near the Channel Islands. On the northern side of the southwestern Peninsula, the mean tidal range at spring tides along the coast shows a steady and large increase north eastwards, from 5m at Land's End to 12.3m at Avonmouth. This increase is due to the amplification of the tidal movement as it is funnelled up the Bristol Channel and the tidal range of the Severn Estuary, at around 12m, is the largest in the UK and the second largest in the world. Within the Western Approaches, the tidal range at mean spring tides is between 3-4m (Lee & Ramster 1981).

Sea surface temperatures in Regional Seas 4 and 5 are strongly influenced by the NAC. In winter, relatively warm waters affect the coastal regions of the southwestern peninsula, with average February temperatures ranging from 9ºC (around Land's End) to 6ºC (at the mouth of the Severn Estuary, reflecting the close proximity of surrounding land). The waters around the Isles of Scilly are between 0.5-1 ºC higher than at adjacent mainland sites during the winter, while average February surface water temperatures at the edge of the continental shelf are 10.5ºC, more than 1ºC warmer than Cornwall's coastal waters.

In August, surface water temperatures in the Western Approaches are approximately 16ºC (Lee & Ramster 1981), though temperatures are likely to be slightly higher closer to the coast. At the shelf edge in August, surface water temperatures are on average 16ºC, with mean bottom temperatures only reaching 10-11.5ºC (Lee & Ramster 1981). In this area, a thermocline (temperature gradient) develops between the surface and bottom water during the late spring and remains throughout the summer.

Sea temperatures around the Plymouth area of the western English Channel were first monitored during the latter half of the 19th Century (Hawkins *et al*. 2003). To date, there have been three main sources of information: 1) offshore measurements taken by MBA vessels 15 miles off Plymouth (ICES station E1 – 50º02'N 04º22'W) 1903–1987 (Southward & Butler 1972; Maddock & Swann 1977); 2) sea surface measurements in Plymouth Sound (approx 50º22'N 04º08'W), taken by city authorities 1898-1989 (Cooper 1958) and by a local resident 1967-present; 3) sea surface data abstracted from authenticated sources by the Hadley Centre for Climate Prediction and Research for area 50-51ºN 04-05ºW from 1871-Present (http://www.badc.rl.ac.uk). These datasets are closely correlated with each other and to additional climate records for the area (Southward *et. al*. 1988). Sea surface temperatures are also now available from satellite observations, which are exceptional at quantifying local variability, but may not always correspond with in-situ measurements (Parker *et al*., 1995).

Mean annual sea surface temperatures in the western English Channel have undergone considerable interannual fluctuations during the 20th Century, but longer trends can also be observed, with a rise in temperature during the first half of the century, followed by a lowering of temperature in the middle 1950s, and return to high values in 1958-61. A marked decline in temperature occurred from 1962, and thereafter there was a period of cooler conditions. From the early 1980s temperatures increased slightly until 1990 and there was a substantial increase during the following decade of almost 1ºC, exceeding any changes in the previous 100 years. There is a close correlation with temperature trends in the northern Bay of Biscay (Southward *et al*. 2005).

The Atlantic origin of water within Regional Seas 4 and 5 produces a relatively high mean surface salinity of 35.2‰ in the summer off Land's End (Barne *et al*. 1996a). Salinity remains fairly constant into the English Channel (though it decreases closer to the shore due to freshwater inputs). Reduced salinity is more evident along the northern boundary into the Bristol Channel (with mean values of 34‰ being recorded from the mouth of the Bristol Channel between Bideford Bay and St Govan's Head.

A3d.7 FEATURES OF REGIONAL SEA 6

The SEA 6 technical report by Howarth (2005) covers many aspects of the oceanography and hydrography of Regional Sea 6. Daily sea temperatures have also been recorded for over a century in the Northern Irish Sea at Port Erin, Isle of Man, where long term monitoring of offshore nutrients, salinity and chlorophyll has been carried out for around 50 years, and plankton since the 1990s (Government Laboratory (Isle of Man) 2008). Hydrographic monitoring including temperature, salinity, nutrients and chlorophyll has been carried out at Menai Bridge, Anglesey sporadically since 1948 and regularly since 2000 (Evans *et al.* 2003).

The extent of Atlantic inflow to the region varies with changes to large scale circulation patterns in the North East Atlantic (e.g. as a result of atmospheric forcing), and weather, particularly the strength and direction of the prevailing winds. Freshwater run-off is important in determining the character of Irish Sea water masses particularly in coastal and nearshore areas. The Irish Sea receives freshwater run-off from a large area of land, approximately 43,000km^2 compared to a sea area of approximately 47,000km^2 with the majority of the run-off arriving in the eastern Irish Sea, down the Ribble, Mersey and Dee estuaries, into the Solway Firth and into Morecambe Bay. The region is also affected by significant freshwater input from the south via the Bristol Channel.

The mean or residual flow is weak, generally less than 0.1m/s and about 0.01m/s in most places. The main inflow of water is from the Atlantic, flowing south to north through St George's Channel. The main flow may veer 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). Transit times from Sellafield to the North Channel have been estimated in the range 6 to 12 months with a mean residence time for the Irish Sea of 1–2 years (Howarth 2005). Local wind forcing rather than tidal or density driven flow is the principal driving mechanism for flow through the North Channel (Knight & Howarth 1999) with the largest transports generated by along-channel winds. Initial measurements of transport in the North Channel were made by Prandle (1976). Subsequently, detailed measurement of currents across the North Channel (Howarth 1982; Brown & Gmitrowicz 1995; Knight & Howarth 1999) have shown that there is significant horizontal variability in the North Channel, with a long-term persistent southerly flow on the western side of the channel that can transport Atlantic water into the Irish Sea (Edwards *et al*. 1986).

Throughout much of the region tidal mixing is sufficiently intense to ensure that the water column remains well mixed throughout the year, although there are regions where temperature and/or salinity differences between water masses may result in stratification. However, stratification is a highly dynamic process and in some areas (e.g. Cardigan Bay) is only likely to develop during hot, calm conditions and can easily be mixed away by storms or spring tides. This is highlighted in Figure A3d.5 which describes temperature differences between surface and bottom waters on two dates, five days apart (potential areas of stratification are indicated by a temperature difference of about >3°C).

Four main frontal areas are identified in Regional Sea 6 (positions shown in Figure A3d.5):

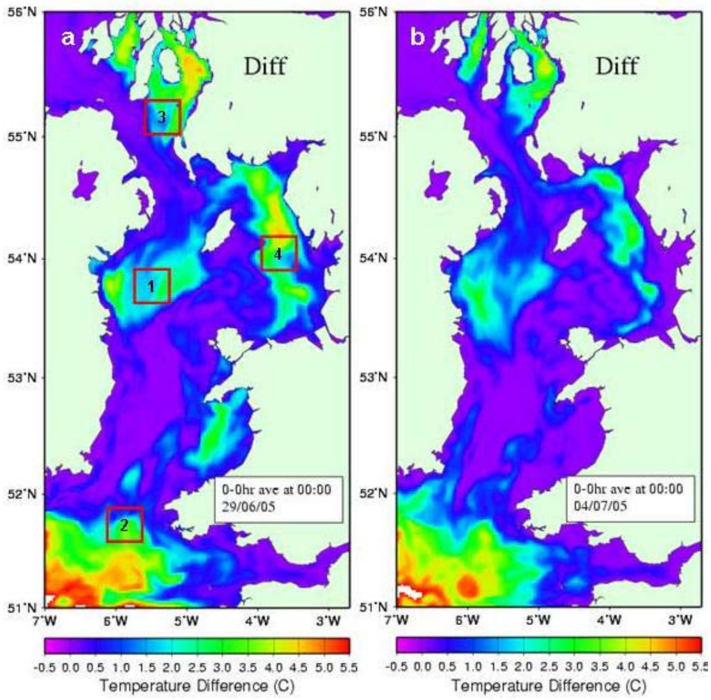
1. Western Irish Sea – in this area the maximum surface to bed temperature difference is around 5ºC. Bottom fronts drive strong (>0.2m/s) but narrow (10km wide) currents in an anticlockwise direction around the pool of colder water below the thermocline. This gyre tends to retain particulate and biological (e.g. plankton) material in the region.

2. The Celtic Sea is thermally stratified during summer and a surface front stretches across St George's Channel. To the south is a deep pool of cold, saline Atlantic water bounded by strong bottom fronts. These drive strong density flows (see below) which allow restricted circulation between the Irish and Celtic Seas.

3. A front separates the stratified regime of the Clyde Sea from the well mixed waters of the North Channel. Inputs from the River Clyde and other freshwater sources promote haline stratification throughout the year. During the summer, this is reinforced by strong thermal stratification.

4. Differences between saline oceanic inflows and freshwater input cause haline stratification in the eastern Irish Sea. The resulting density flows are strongest in winter and spring but can be overwhelmed during periods of strong winds. During the summer the haline stratification is reinforced by thermal stratification.

Figure A3d.5 – Stratification in the Irish Sea



Notes: POL modeling data of differences between surface and bottom water temperatures for a) 29 June 2005 and b) 4 July 2005.
Source: POL website - http://cobs.pol.ac.uk/cobs/sat/.

A strong north flowing jet current has been observed in the eastern St George's Channel in summer (Horsburgh *et al*. 1998). This jet current is density driven and associated with the Celtic Sea tidal-mixing front which forms between May and October. Peak velocities observed for this current were up to 28cm/s and there was an indication of a weaker southerly flow on the western side of the St George's Channel. The observations of this current were made during 1997 and some variability between years can be expected depending on the location of the Celtic Sea front.

There is considerable variation in the tidal range experienced around the Irish Sea. For example, Liverpool Bay experiences a very large tidal range (>10m on the largest spring tides, the second largest in the British Isles) whilst areas of very small tidal range (amphidromic points) are found in the vicinity of Arklow in St George's Channel and between Islay and the Mull of Kintyre in the North Channel. The tide propagates into the Irish Sea from the Atlantic Ocean through both the St George's Channel and the North Channel (Robinson 1979). The tidal waves from both directions meet to the south west of the Isle of Man causing this to be an area of very weak tidal currents (<0.35m/s). Areas of strong tidal currents (depth-averaged values up to 2m/s at spring tides) and hence of vigorous tidal mixing and peak bed stresses occur generally throughout St George's Channel, north west of Anglesey, north of the Isle of Man and in the North Channel (Howarth 2005). In shallow water, sudden changes in bathymetry and/or topography may generate locally high velocities near headlands, islands and estuaries (DEFRA 2000).

The largest storm surges are generally associated with storms tracking eastward between Inverness and Shetland and occur in the eastern Irish Sea, with maximum surge levels of about 2m predicted for the Lancashire and Cumbrian coasts associated with westerly winds, whilst the maximum surge levels are between 1.25m and 0.75m on the Irish coast and across the St George's Channel (Flather 1987). The impact of surges also depends critically on the state of the tide with the biggest risk of flooding occurring if the surge peak coincides with high spring tide (Howarth 2005).

Sea surface temperature is coolest in February or March with temperature decreasing from the deeper channel towards the coasts. A warm tongue, with a temperature above 7.5ºC, extends up to the North Channel where 8-8.4ºC is typical. The coolest water is towards the coast in the eastern Irish Sea. At this time of year the temperature is uniform with depth. The situation in the warmest month (August) shows a contrasting pattern,with the coolest surface water in the North Channel (12ºC; amongst the coolest waters on the west coast of Britain) and the deep channel (13-14ºC) and the warmest water close to the coasts, exceeding 16-17ºC in Liverpool and Cardigan Bays.

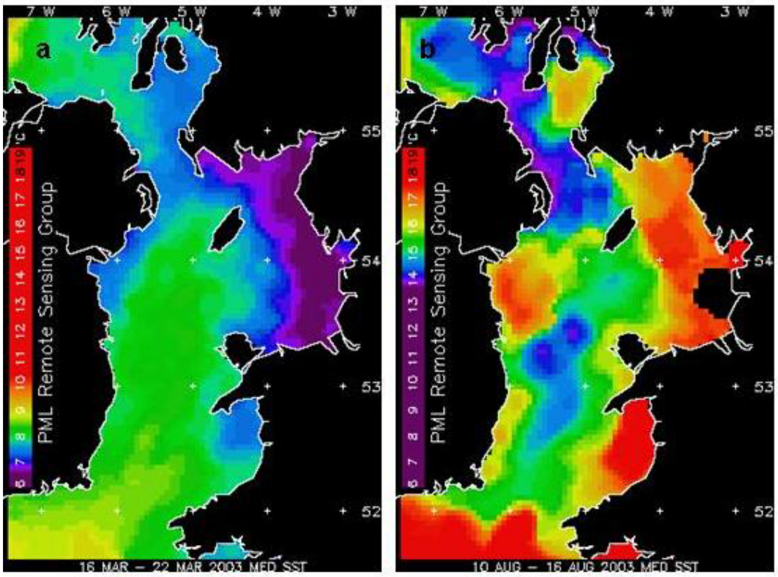
The long term temperature record shows a large degree of variability in the seasonal cycle, although a general increasing trend is apparent, indicating a rise of around 0.6ºC over the last 70-100 years, and particularly an increase in winter temperatures since 1990.

The annual mean salinity decreases from south (34.9‰) to north (34‰) and from the centre of the channel (34.3-34.9‰) to the sides (32.0-34.0‰) reflecting the northerly flow of oceanic Atlantic water whose salinity is gradually reduced by coastal freshwater input. Lowest values are found in the north-east, from the Solway Firth to Liverpool Bay, and in the Clyde Sea. Seasonal variations in salinity are small in most areas, although most noticeable near the coasts, being governed by the annual cycle of river flow.

Since the Irish Sea is sheltered with only two relatively narrow 'windows', along the axes of the St George's and North Channels, the majority of waves are locally generated, of fairly short period and hence steep. Swell waves are only present near the entrances of the St George's and North Channels; hence, the wind direction leading to the largest waves will depend very much on the locality, for instance in Liverpool Bay winds from the north-west cause the largest waves (Howarth 2005).

The annual mean significant wave height is greatest at the entrance to St George's Channel (about 2.3m) with values decreasing northwards. Lowest mean significant wave heights are experienced in sheltered coastal regions particularly Morecambe Bay and the Solway Firth (<0.6m). The 50-year return value of significant wave height varies between 8m within the Irish Sea to about 12m at its outer entrances. The effect of waves on processes such as sediment transport will be significant during storms especially in shallow areas of the eastern Irish Sea (Howarth 2005).

Figure A3d.6 – Sea surface temperatures in Irish Sea



Note: Composite satellite images taken between a) 16-22 March 2003 and b) 10-16 August 2003. Note change of temperature scale between images.
Source: PML Remote Sensing Group, Proudman Oceanographic Laboratory website - http://cobs.pol.ac.uk/cobs/sat/.

A3d.8 FEATURES OF REGIONAL SEA 7

In support of SEA 7, Inall & Sherwin (2006) reviewed available information on hydrographic characteristics and processes of the Scottish shelf. Hydrographic processes in the North Channel, Sea of the Hebrides and Minches have been sporadically studied over a long time period (Craig 1959, Prandle 1976, Ellet 1979, Ellet & Edwards 1983, Gillibrand *et al*. 2003, Baxter *et al*. 2008), with particular focus on the distribution of radionuclides from Sellafield (e.g. Livingstone *et al*. 1982, McKinley *et al*. 1981, McKay *et al*. 1986, Mackenzie *et al*. 1987). Subsequently the emphasis has been on development and validation of hydrodynamic models (e.g. Xing & Davies 1996, Pizzamei 2002, Davies & Xing 2003).

Direct water circulation measurements in the Sea of the Hebrides and Little Minch have been limited to *ad hoc* current meter deployments (Ellett & Edwards 1983), studies of the Scottish coastal current (Simpson & Hill 1986; Hill & Simpson 1989), an Acoustic Doppler Current Profiler (ADCP) survey in the Little Minch (Simpson *et al*. 1990), and a long-term mooring deployment in the Tiree Passage maintained by the Dunstaffnage Marine Laboratory. At a local, inshore scale, a large number of short-term (15 day semi-lunar period) current meter deployments have been made over the last decade in relation to consenting of aquaculture sites.

Four research cruises in the Minch and the Sea of the Hebrides during 1996-1998 were used to measure and map the seasonal variability of key physical, chemical and biological characteristics of the water column. In addition, recording current meters were deployed during the 1997 spring cruise to measure water movement through the study region. Data from these studies have been used to calibrate a coastal circulation model of the Scottish western continental shelf (Pizzamei 2002), with results indicating the presence of cyclonic gyres in both the North Minch and Sea of the Hebrides. The model also predicts a southward flow at depth through the *western* side of the Little Minch, as observed, whereas nearer the surface the expected northward transport is evident.

One site within Regional Sea 7 (Loch Ewe) is sampled as part of the FRS Long-term Ecosystem Monitoring programme (2002-present); data are collected on water temperature, salinity, nutrients and phytoplankton. In addition, since 2003, temperature has been monitored and weekly samples for salinity and nutrients are taken at Loch Maddy (North Uist).

Tidal flow, temperature, salinity and wave information presented below is largely drawn from Baxter *et al*. (2008) and the Atlas of UK Marine Renewable Energy Resources, supplemented by the relevant JNCC Coastal Directories (Barne *et al*. 1997c, f).

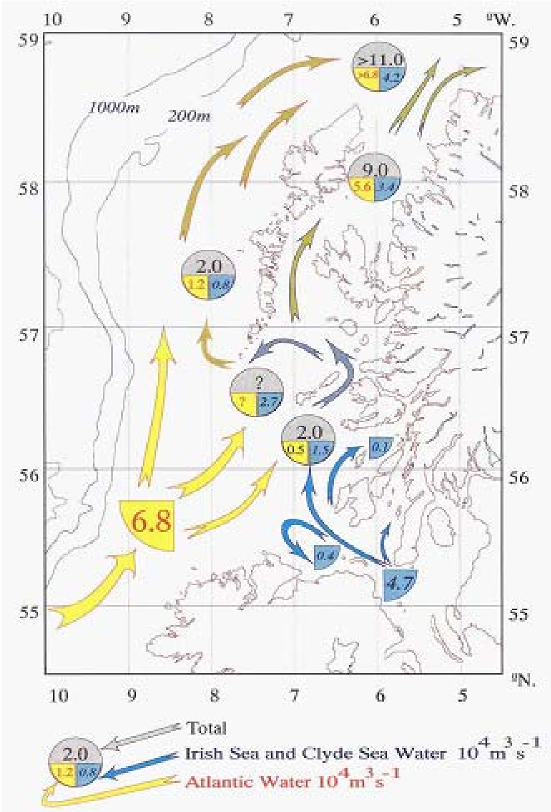
Water in Regional Sea 7 is derived from three sources: oceanic or Atlantic water, Clyde/Irish Sea water and coastal water derived from the land.

Overall circulation patterns (Figure A3d.7) inferred from the distributions of salinity and temperature, and direct water circulation measurements, indicate a net northward transport along the Scottish west coast, both through the Sea of the Hebrides and the Minch and to the west of the Outer Hebrides (the Scottish Coastal Current). On the basis of drifter experiments, Hill *et al*. (1997) described a bifurcation of the northward coastal current in the Sea of the Hebrides, with a proportion of the water mass passing through the Little Minch, and the remainder re-circulating southward toward Barra Head.

Early studies suggested that the Islay Front, between the Scottish and Irish coasts is a seasonally distinctive salinity-controlled front in which temperature plays only a secondary role in controlling the density structure (Simpson *et al*. 1979). Later work (Hill and Simpson 1989) confirmed that two distinct classes of front coexist west of Islay: the type I front (in which the frontal interface extends continuously from the sea surface to the sea bed) forms the boundary of a low salinity coastal current. The other (type II) front which develops in spring and summer marks the transition between mixed and thermally stratified water. The relative locations of the two frontal types changes with season. In winter, only the type I front is present. When thermal stratification commences in early spring a type II front forms to the west of the type I front. As thermal stratification develops farther, in late spring and summer, the type II front advances towards the type I system and eventually crosses it inducing a distortion of the type I interface and bringing about vertical haline stratification. In autumn it appears that the final breakdown of thermal stratification may be inhibited by the vertical salinity (density) gradient associated with the type I front. The Islay Front is also associated with strong residual currents parallel to the front, and enhanced phytoplankton standing crop (Simpson *et al*. 1979).

Through the North Channel and west of mainland Scotland, there is a general northern flood and southern ebb tidal flow, the pattern being complicated by coastal topography, fluvial flow and wind-induced currents. Maximum tidal currents run in the North Channel and south of Islay (more than 4.0m/s between Rathlin Island) and decrease in all directions away from this zone (Figure A3d.7). Velocities within the sea lochs are generally low, attaining about 0.2m/s in the centre of Loch Linnhe and 0.25m/s off the north coast of the Ross of Mull. An exception to this is in the Gulf of Corryvreckan, the narrow channel between the islands of Jura and Scarba, where a tidal race may reach a speed of 4.3m/s. High current velocities are also characteristic of the Sound of Islay (between Islay and Jura), the Firth of Lorne and Sound of Mull.

Figure A3d.7– Shelf circulation pattern and approximate volume fluxes



Source: Courtesy of A. Edwards.

North of Ardnamurchan, maximum tidal currents during mean spring tides are generally between 0.5 and 1m/s. There is an unusual feature in the Sound of Harris: at neap tides in the summer, the south-east going stream runs all day and the north-west going stream runs all night; the effect is reversed at neaps in winter (Ellett 1979).

In the northern Minch between Cape Wrath and the Butt of Lewis, maximum speeds vary from 0.4m/s at spring tides to 0.15m/s at neap tides, these currents flowing approximately north-south. Within the Little Minch between Skye and South Uist the maximum current is 0.5m/s, again in a north-south direction, though values are greater around headlands and over shoaling areas. South of Barra Head on Berneray the maximum surface current during spring tides is 0.75m/s, flowing in an easterly direction.

Throughout the area, the dominance of the Atlantic water mass over Clyde/Irish Sea water and land-derived coastal water limits the differences between summer and winter temperatures. In winter, water on the Hebridean shelf is well-mixed, and relatively warm Atlantic water covers most of the shelf west of the islands. By April, less dense water from the coast spreads westward and – after the onset of surface heating and the development of a thermocline – forms the surface water for much of the outer shelf north of Barra Head. Summer temperatures in the North Channel, at around 12°C, are among the lowest on the west coast of Britain because Ireland obstructs the warm flow of the Gulf Stream.

In winter, temperature values decrease eastwards from about 8.5°C across the outer continental shelf to less than 7.0°C off the northern coast and typically between 8.0°C and 8.4°C in the North Channel. Ellett & Edwards (1983) give values ranging from about 12°C in the southern entrance to the Sea of the Hebrides and the northern entrance to the Minch, to less than 10.5°C in the southern part of the Minch. Throughout the year values are more extreme in the shallow waters near coasts. Similarly, slightly more extreme temperatures may occur within the low-salinity surface layer that can develop in sea lochs, especially near river mouths (Ellett & Edwards 1983).

The mean water temperature in the Tiree Passage is 10.1ºC and the dominant mode of variability in the temperature record is the seasonal cycle, with an amplitude of 3.2ºC. Temperature anomaly time series (deviations from the average monthly values over the last 25 years) from the Tiree Passage and of the full NE Atlantic upper layer show highs in the late 1980s and late 1990s and lows in the early 1980s and mid 1990s. The overall trend on the continental shelf is of warming at a rate of +0.57ºC per decade. In addition, the date of maximum annual temperature has been delayed by 12 days per decade, throughout the time series.

Shelf salinities show only weak seasonality, and no single determining factor has been found for the longitudinal movement of more saline oceanic waters across the shelf. Prolonged periods of high North Atlantic Oscillation index (NAO) were found to coincide with periods of raised salinity of shelf waters (NAO: high values of this index correspond to warm, wet and windy conditions over Scotland).

The irregular coastline results in a diverse range of wave climates, and most of the available data refers to open sea conditions rather than specific sites. The northernmost coasts between Point of Stoer and Cape Wrath are exposed to both northerly and westerly winds, and experience a wave climate only slightly less energetic than that of western coasts of the Western Isles, Orkney and Shetland (Figure A3d.7). The western coasts of the southern islands such as Rum and parts of Skye that are not sheltered by the Western Isles are equally exposed to the prevailing winds and energetic waves. The maximum predicted 50-year wave has a height of over 30m in the north, although significant wave heights in the Minch and Sea of the Hebrides are lower: 75% of the time they are less than 1m and only during 10% of the year do they exceed 2.0m, or at most 2.5m in the extreme north.

A3d.9 FEATURES OF REGIONAL SEA 8

The physical structure of the shelf seas west of the Hebrides is largely determined by a balance between the stratifying influences of solar radiation and fresh water run-off from the land, and the mixing influences of the strong tidally and wind driven flows, themselves shaped by the irregular bathymetry and coastline.

The European Slope Current (ESC, synonymous with the Shelf Edge Current, SEC (see Section A3d.2.1) a feature flowing along the continental slope, is apparently continuous at least from the Goban spur to north of Shetland, a distance of approximately 1600km (Booth & Ellett 1983, Burrows & Thorpe 1999, Souza *et al.* 2001). At the latitude of the Malin Shelf (~56°N) the ESC is a persistent, predominantly barotropic flow of ~20cms$_{-1}$ with greater flow variability in winter and a characteristic salinity of 35.35 (Souza *et al.* 2001). The ESC is constrained to the continental slope, with its velocity core centred approximately above the 800m isobath and the high salinity core consistently displaced closer to the slope, and above the 200-300m isobaths. An explanation of this phenomenon has been given in terms of the differing slope boundary conditions for salinity and momentum (Souza *et al.* 2001). Despite the normally high steadiness, intrusions of the ESC onto the shelf at ~56°N have been observed in the winter months, and there is a suggestion that in winter both mass flux and poleward momentum are directed upslope (Burrows & Thorpe 1999). The shelf edge current exhibits weaker flows in spring and stronger flows in autumn; mean current speeds are estimated to be between 0.05 and 0.2ms^{-1}, with higher speeds where the flow is 'squeezed' by depth contours. The maximum current in summer is at about 200m depth, but in winter flow is much more uniform throughout the water column (IACMST 2005). Measured near-bottom current velocities indicate peak currents over 75cm/s on the upper continental slope west of Shetland (Graham 1990a, Graham 1990b, Strachan & Stevenson 1990). Sediment bedforms observed on the upper slope, such as small barchan-type sand waves, longitudinal sand patches and comet marks (Werner *et al.* 1980), confirm currents in the range 40 to >75 cm/s (Kenyon 1986). Periodic and episodic peak currents are driven by a range of processes (Inall & Sherwin 2006) including internal waves (Huthnance 1983), storm surges (Howarth 2005), gyres and eddies (Dooley & Meinke 1981).

There is a wide range in tidal current strength across the Hebrides shelf. In general, there are near-uniform maximum current amplitudes for a mean spring tide over much of the shelf west of 7.5º W where depths are uniform (Figure A3d.2). Over these parts of the shelf bed friction plays a minor role in determining the tidal currents, and the force balance is primarily between the tidal slope of the surface, inertia and the Coriolis force resulting in highly elliptical tidal currents. Patchy areas to the west and north of the northern Outer Hebrides have more circular M2 tides (rotating anticlockwise). Regions such as these, where tidal ellipses are not rectilinear, experience little or no slack water. Spring-neap modulation of the semi-diurnal tidal currents is strong throughout the region; maximum amplitude of the depth-averaged currents for a mean spring tide indicates extended areas of strongest flows around the headlands of Barra Head and the Butt of Lewis.

Topographic constraints also result in high current velocities in localised areas of the Orkney and Shetland, where tidal harmonics are dominated by the M2 component. Flood streams are generally from west to east in the offshore areas, through the Pentland Firth and between islands in Orkney and Shetland, with the flood stream deflected southwards along the Shetland coastlines. The M2 maximum tidal current amplitude in nearshore waters is 0.04m/s (BODC 1998), although tidal streams reach considerably higher velocities - between 3.5m/s and 4.5m/s – near Muckle Flugga, in Yell Sound, Linga Sound, Bluemull Sound and near Sumburgh Head in Shetland; through the Pentland Firth; and in Hoy Sound in Orkney.

Residual tidal flows through the Pentland Firth and Fair Isle Channel are very low, so that bedflows are dominated by non-tidal components (Johnson *et al*. 1982). Estimated maximum orbital near-bottom currents, generated from wind-waves or internal waves at the shelf edge and shorewards, may have speeds up to 10 fold (or more) higher than the tidal currents (Holmes *et al*., 2003). These orbital currents are important energy sources for mobilising sediment grains into the tidal streams.

During the winter months on the west Hebridean shelf (December to April) the water column is vertically well mixed, and isotherms and isohalines are almost vertical. Temperature and salinity increase offshore and in deeper waters (greater than approximately 100m), and on the outer parts of the shelf the water is of Atlantic origin (S > 35.2‰) and the boundary between coastal and oceanic water is sharp, typically 0.5º C per 10km. This boundary lies approximately two thirds of the distance from Barra to the shelf break, running parallel to the Hebrides and passing close to St Kilda, although there is considerable variability in its shoreward extent. Much of the shelf remains mixed or weakly stratified during the summer with strong thermal stratification restricted largely to sheltered sea lochs on the west coast of the Hebrides and the north coast of mainland Scotland.

A similar pattern is evident west of Orkney, with a strong frontal boundary located close to Cape Wrath in summer, but with greater mixing west of Shetland. However, throughout Regional Sea 8, riverine inputs are relatively small (in terms of catchment area) and temperature and salinity characteristics may be regarded as fully marine.

Along the western coasts of Shetland, Orkney and the Western Isles archipelago, the combination of exposure to prevailing winds and deep, open offshore waters produces a high energy wave regime (Figure A3d.3). Off these coasts significant wave heights exceed 3m for over 10% of the time and 1m for 75% of the time (Draper 1991).

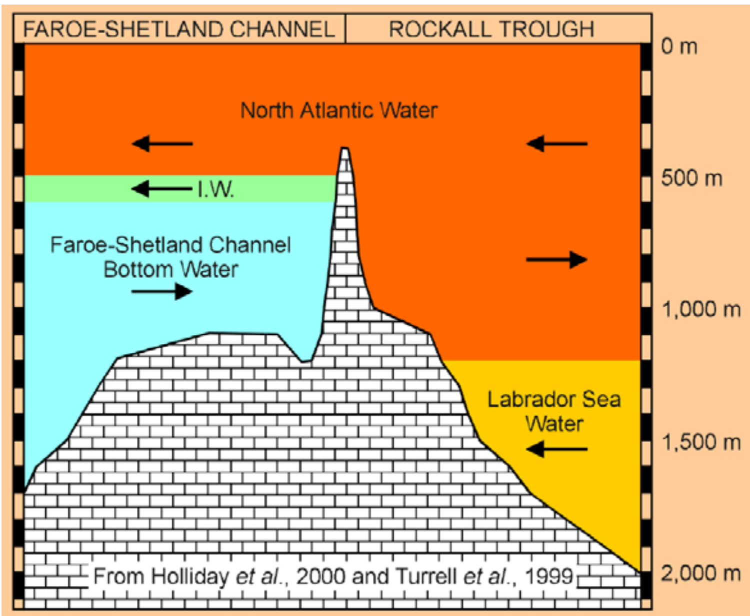
Between 1976 and 1978 the wave climate at a site 15km west of South Uist was investigated in some detail to evaluate the possibilities of wave power along the coasts of the region (see Fortnum (1981) and Stanton (1984) for further information). The results showed that the monthly mean significant wave height at the site varied from about 1.5m in August to about 3.75m in November, with a maximum significant wave height of 9m. Estimated 50 year wave heights in the offshore area west of Shetland are approximately 32m with wave periods of greater than 20 seconds (Grant *et al.* 1995).

A3d.10 FEATURES OF REGIONAL SEA 9

Since the pioneering Porcupine and Lightning studies of 1868-1870 (Wyville Thomson 1874), the Faroe-Shetland Channel has been one of the most studied oceanic regions of the world and two hydrographic sections across the Channel have been surveyed by the Aberdeen Marine Laboratory for over a century (Turrell *et al*. 1999a, 1999b). The Faroe Bank Channel (the continuation of the Faroe-Shetland Channel to the south east) is less well studied, although since the late 1980s and the realisation of the importance of this area for the overflow of cold deep water south, a standard section has been studied regularly by the Faroese Fisheries Laboratory (Hansen and Østerhus 2000).

A series of research programmes and cruises, detailed in SEA 1, have allowed for the study of the long-term monitoring of water exchange between the Atlantic and Nordic seas.

Figure A3d.8– Hydrography of the Faroe-Shetland Channel



Source: Bett 2003

A number of water masses, characterised by their salinity and temperature characteristics, are known to be present in the Faroe-Shetland Channel and studies have shown there to be distinct differences in the distribution of these between the east and west slopes of the

Channel (Dooley & Meincke 1981, Hansen 1985, Saunders 1990, Turrell 1997, Turrell 1999a).

The waters over the Wyville Thomson Ridge and in the upper 500m of the Faroe-Channel and are derived from North Atlantic water which enters the Faroe-Shetland Channel over the Ridge and is concentrated along the eastern side of the Channel, as a slope current close to the edge of the West of Shetland Shelf. It is most intense over the 400m contour (Turrell *et al*. 1999a). This water originates from the Rockall Trough. The Modified North Atlantic Water dominates the surface flow in the centre and along the western slope of the Channel, and represents the northern branch of the North Atlantic Current. As this water flows towards the Faroe Islands from the west it splits and flows into the Faroe Bank and Faroe Bank Channel areas and northwards around the Faroe Plateau in a clockwise direction, entering the Faroe-Shetland Channel from the north-east (Hansen 1985, Saunders 1990). The net flow of these two water masses is to the northeast (Turrell *et al*. 1999a).

The mean velocity of the shelf edge current in the area is approximately 40cm/s towards the northeast, and in the lower water mass 15cm/s towards the southwest (Saunders 1990). The shelf edge current exhibits a seasonal maximum transport in December/January and a minimum in June/July (Gould *et al*. 1985). Measured near-bottom current velocities indicate peak currents over 75cm/s on the upper continental slope west of Shetland (Graham 1990a, 1990b; Strachan & Stevenson 1990). Sediment bedforms observed on the upper slope, such as small barchan-type sand waves, longitudinal sand patches and comet marks (Werner *et al*. 1980), confirm currents in the range 40 to >75 cm/s (Kenyon 1986). Periodic and episodic peak currents are driven by semi-diurnal tides, internal waves (Sherwin 1991), storm surges (Turrell & Henderson 1990), gyres and eddies (Dooley & Meinke 1981).

Internal waves form on the interface between the overlying Atlantic and underlying Norwegian Sea Deep waters, at approximately 500m below the surface. This can result in incursions of cold water at the seabed, accompanied by relatively strong currents (seabed surges) (Grant *et al*. 1995).

Below the Modified North Atlantic Water, Arctic Intermediate/North Icelandic Water originating from north of the Iceland Faroe Ridge occupies water depths of 400-600m on the Faroese side of the Channel (Blindheim 1990). On the Scottish side of the Channel the area occupied by this water is narrow and in slightly shallower depths. A second intermediate water mass is present on the Faroese side of the Channel in the form of Norwegian Sea Intermediate Water which occupies water depths of 600-800m. This water becomes shallower and occupies a reduced depth range towards the Scottish slope, and occasionally does not extend as far as the slope. The net flow of this water mass in the Channel is to the southwest (Turrell *et al*. 1999a).

Below these intermediate waters, at depths of greater than 800m the Channel is filled by cold water originating from the Norwegian Sea, known as Faroe-Shetland Channel Bottom Water. It is believed that most of the transport within this water leaves the Channel through the Faroe Bank Channel and to a lesser extent over the Wyville Thomson Ridge (see below), although some may be recirculated back into the Norwegian Sea (Turrell *et al*. 1999a, Hansen & Østerhus 2000).

The Wyville Thomson Ridge forms the northern most limit of the Rockall Trough and is thought to limit the deep outflow from the Faroe-Shetland Channel towards the Rockall Channel. Knowledge of the Wyville Thomson Ridge overflow was first documented in 1972 (Ellett & Roberts 1973) and subsequently studied by Ellett and co-workers. Ellett (1998) and others (Ellett & Edwards 1978, Zenk 1980, Saunders 1990) found evidence that the Wyville Thomson Ridge overflow can be intermittent both spatially and temporally (Hansen 1985, Hansen & Østerhus 2000). In addition to the steady "base" flow over the Ridge there is evidence of more distinct overflow events which can last for a number of days. During these events currents have been observed to be stronger than normal and temperatures lower (below 3°C), which represents a greater influence of cold water from the Faroe-Shetland Channel Bottom Water. Sherwin & Turrell (2005) and Sherwin *et al*. (2008) have quantified the overflow and concluded that the total flow (including entrained North Atlantic Water) is substantially higher than previously estimated. A significant part of the overflow appears to be channelled through a newly discovered canyon that leads southward down the southern flank of the Faroe Bank into the Ellett gully.

The waters of the northern North Sea / southern Norwegian Sea are influenced by three main water masses. The upper few hundred metres are dominated by the warm, saline water of the Norwegian Atlantic Current. Deeper water depths are influenced by the bottom waters formed in the adjacent Arctic and Greenland Seas (Gammelsrød *et al*. 1992 and Østerhus *et al*. 1996b).

Due to the exposed nature of the Atlantic, the wave climate of the Faroe-Shetland Channel is more severe than that found in the Northern North Sea. The wave conditions are similar throughout the Atlantic area with estimated 50 year wave heights of approximately 32m and wave periods of greater than 20 seconds (Grant et al. 1995).

A3d.11 FEATURES OF REGIONAL SEAS 10 & 11

The Rockall Trough and Atlantic Northwest Approaches are influenced by the oceanic circulation systems of the North Atlantic - principally the North Atlantic Current (NAC) which sweeps eastwards from the western North Atlantic before turning in a more northerly direction and flowing to the west of the Hatton Bank. Smaller southerly branches of the NAC enter the Hatton-Rockall area from the north and circulate over the Rockall Bank and further to the south. A branch of the NAC travels north-eastward across the Rockall Plateau and through the Rockall Trough towards the Faroe-Shetland Channel.

A poleward flowing Shelf Edge Current (SEC) is present along the continental margin and occupies the upper part of the slope, typically above 700m (see above). Near the southern boundary of Regional Sea 10 it makes an excursion across the slope and onto the shelf (Ellett *et al.* 1986, Souza *et al*. 2001) before continuing its path along the slope at the southern end of the Hebrides. The current exhibits some seasonality, with weaker flows in spring and stronger flows in autumn, and mean current speeds are estimated to be between 0.05 and 0.2ms^{-1}, with higher speeds where the flow is 'squeezed' by depth contours. The maximum current in summer was at about 200m depth, but in winter flow was much more uniform throughout the water column (IACMST 2005).

Wintertime mixing of the near-surface layers in the region usually occurs to depths of 500–700m (Ellett & Martin 1973, Meincke 1986; Holliday *et al*. 2000), but there is evidence of deeper mixing, possibly to 1,000m (Ellett *et al*. 1986). This mixing forms relatively homogeneous upper layer waters, identified primarily as a saline Eastern North Atlantic Water (ENAW) entering the region from the south, and occasionally a fresher Western North Atlantic Water (WNAW) from the north west. ENAW forms in the Bay of Biscay (Pollard *et al.* 1996) and is transported northwards by the SEC through the region and beyond (Ellett & Martin 1973, New *et al.* 2001a, b). Less saline WNAW is carried into the area by the main branch of the North Atlantic Current (NAC) but generally turns northwards to the west of Hatton Bank and does not usually enter the Rockall Trough (Schmitz & McCartney 1993, Pollard *et al.* 1996, Holliday *et al*. 2000).

Since the early 1990s there has been a general warming of surface waters in the Rockall Trough. This warming does 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, variations in temperature appear to be 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 Sub Arctic Intermediate Water (Holliday 2003).

Beneath the generally northward flowing surface waters, drifters at a nominal 700m exhibit a more complicated flow pattern. Currents in the northern and western parts of the Iceland Basin are derived from the outflow from the Arctic and flow towards the south west along the Iceland Shelf edge and Reykjanes Ridge (Lavender *et al.* 2005). On the western flank of the Rockall Plateau there is a complementary north-eastward flow of ~0.02ms^{-1}, which appears to cross the gap between the Lousy and Hatton Banks and enter the Rockall Trough. Within the Rockall Trough, at 700m, there is a fairly strong anti-clockwise rotating current (~0.05ms^{-1}). In the north, Norwegian Sea Deep Water (NSDW) is known to flow episodically southwards over the Wyville–Thomson Ridge and into the Rockall Trough (e.g. Sherwin *et al*. 2008). Circulation models (New & Smythe-Wright 2001) and evidence from sediment bedforms within the Rockall Trough (Lonsdale & Hollister 1979) suggest an overall cyclonic flow of deeper water (>1,200m depth), with Labrador Sea Water and North Atlantic Deep Water entering the Rockall Trough from the south. The deep flows then diverge from the slope current and are topographically steered anticlockwise around the Trough, leaving the region immediately to the south of Rockall Bank. These southwestward bottom flows are thought to occur primarily on the lower slopes of the Rockall Bank (New & Smythe-Wright 2001).

During the spring and summer months the water column over much of the oceanic region undergoes thermal stratification, with an upper mixed layer down to approximately 75-100m. The nature and extent of stratification varies both spatially and temporally. Generally, stratification breaks down with the onset of autumn cooling and associated more energetic conditions. This mixing process is reflected in winter temperatures which are fairly constant (9-10°C) through the water column down to about 500-750m, and reach 5-6°C by 1,500m (SAMS 2006). Upwelling occurs along the shelf edge, bringing nutrient rich water to the surface with associated enhanced productivity (IACMST 2005).

Variability in both upper and deep circulation due to eddies has been measured in the Rockall Trough, with eddy activity greatest around the seamounts of the northern Rockall Trough (Dickson *et al.* 1986, Booth 1988). Current observations near the Anton Dohrn seamount revealed very variable directions, with speeds generally in the order of 0.1-0.2ms^{-1} in the upper layers and, about 0.05ms^{-1} near the seabed (Ellett *et al.* 1986). Wind stress levels in the Rockall Trough tend to peak in winter, whilst eddy kinetic energy levels (in the 3 to 28 day band) appear to be at a maximum in spring (Dickson *et al.* 1986). Drifter observations in January 1984 (Booth 1988) demonstrated that the region around the Anton Dohrn seamount is rich in small eddies with periods of between 1 to 3 days. Other drifter observations (Burrows & Thorpe 1999) have shown much larger eddies, with periods in the order of 10 days and speeds up to 0.25ms^{-1}.

Internal waves are periodic oscillations of the water column through disturbances in the vertical density stratification. Essentially, tidal flow across the shelf edge causes the thermocline to depress and this depression propagates away from the shelf edge region as a wave. The NE Atlantic is a prolific area of internal wave generation (Baines 1986), and internal waves have been observed in SAR (Synthetic Aperture Radar) images (New 1988). These images show the generation points at the shelf edge and packets of internal waves propagating away from the source region periodically on every tide. Booth (1981) suggested that strong oscillatory currents found in the deep northern sector of the Rockall Trough were a result of internal tidal motions. Non linear internal waves (solitons) measured during the LOIS Shelf Edge Study (SES) between 56°N-58°N were associated with oscillations in the thermocline of up to 50m and occasional strong currents (up to $0.5ms^{-1}$). In regions where internal waves reflect from the continental slope, periodic mixing of water adjacent to the seabed is often observed (White 1994). Such conditions may cause the generation of nepheloid layers (regions of suspended sediment) in the water adjacent to the slope (Thorpe & White 1988).

Cascades of shelf water down slope generally occur intermittently from late winter to spring, when at temperate latitudes water on the shelf can be colder (denser) than in the ocean. Ellett (1968, cited by SAMS 2006) found evidence of cascading on the western side of the Rockall Bank and estimated that the associated speed was about $0.02ms^{-1}$. Although sufficient conditions for cascading have been observed within the region, there have been few confirmed reports.

Regional Seas 10 and 11 experience some of the harshest metocean conditions in the world. The long Atlantic fetch allows waves of considerable size to develop and these cross the area, particularly during winter months and the region is exposed to the full force of storms generated in the Atlantic Ocean. The largest wave recorded in the Rockall Trough to date was measured at 29.1m in February 2000 (Holliday *et al.* 2006). The region also experiences exceptionally high interannual variability, and monthly averaged significant wave heights can vary by as much as a factor of two between consecutive years (Woolf *et al.* 2002). Much of this variability can be attributed to changes in the North Atlantic Oscillation Index (IACMST 2005). For example, a unit change in the NAO will induce a 0.42m increase in the mean winter wave height, and a 1.28m change in the 100 year return value (Woolf *et al*. 2002).

A3d.12 AMBIENT NOISE

Ambient noise is made up of contributions from many sources, both natural and anthropogenic. These sources add together in a complex manner resulting in significant spatial and temporal variations in the noise field. In recent years there has been an increasing awareness that offshore activities have contributed to significant increases in the levels of underwater ambient noise.

For previous SEAs (6 & 7) QinetiQ were commissioned by the DTI to provide information on background ambient noise levels, and to identify the main sources of noise. Much of the subject areas (Irish Sea and west of Scotland) are relatively shallow-water and many of the consideration in relation to sources and transmission of ambient noise made by the SEA reports (Harland *et al*. 2005, 2006) are of more relevance to coastal than offshore locations.

The wide range of ambient noise sources include natural physical sources (e.g. wind, precipitation, sediment transport and shore/surf noise); biological noise (e.g. fish and crustacean species) and anthropogenic sources such as commercial shipping, aggregate extraction, industrial sources, military sources, fishing and aircraft.

Ambient noise is generally made up of three constituent types – wideband continuous noise, tonals and impulsive noise. The latter is transient in nature and is usually of wide bandwidth and short duration. It is best characterised by quoting the peak amplitude and repetition rate. Continuous wideband noise is normally characterised as a spectrum level, which is the level in a 1Hz bandwidth. This level is usually given as intensity in decibels (dB) relative to a reference level of 1 micro Pascal (µPa). Tonals are very narrowband signals and are usually characterised as amplitude in dB re 1µPa and frequency. Ambient noise covers the whole acoustic spectrum from below 1Hz, to well over 100kHz. Above this frequency the ambient noise level drops below thermal noise levels.

In deep water the levels of ambient noise are now well defined and the contributions from various sources well understood and categorised according to dominant source and frequency (Urick 1983). In contrast, comparatively shallow water areas (e.g. parts of the Irish Sea and the southern North Sea) were not well studied until recently when information was required to support renewable energy developments in coastal waters (Nedwell *et al.* 2003). The same authors noted that ambient noise levels in sites utilised for offshore wind farm developments (shallow water shoals) were toward the upper bound of deep water ambient noise levels, due to contributions from natural sources such as surface noise (waves) and anthropogenic sources such as shipping. Propagation losses through the seabed can be significant in shallow coastal waters, but noise from high intensity events such as pile driving can be detectable above background underwater noise for tens of kilometres (Nedwell *et al*. 2007).

In addition to the variety of ambient noise sources and characteristics, there are additional effects which will modify the level and spectral content of the ambient sound field. The effects of density variations on acoustic propagation, losses at the seabed and water surface and multi-path effects are discussed by Harland *et al*. (2005).

Under conditions of low wind speeds and with no precipitation noise, shipping noise is likely to dominate across large parts of the UK continental shelf. Shipping noise will be important in proximity to major port developments. In some offshore areas, ambient noise is likely to be dominated by industrial noise from production facilities (notably where turbines are used for gas compression). Operational noise characteristics associated with oil & gas, and wind farm developments are considered in Section 5.

A3d.13 EVOLUTION OF THE BASELINE AND ENVIRONMENTAL ISSUES

Recent assessments of observed and predicted change, in relation to specific aspects of the water environment at a UK-wide scale, are summarised from MCCIP (2007) and supporting scientific assessments below:

A3d.13.1 Sea surface temperature

The following information is from Holliday *et al*. (2007). Sea surface temperatures (SST) in the north east Atlantic and UK coastal waters have been rising since the 1980s, most rapidly in the southern North Sea and the English Channel. Despite a relatively cold winter in UK waters in 2005/2006, anomalously rapid warming in the spring and early summer meant that 2006 became the second warmest year in UK coastal waters since 1870.

The temperature of the upper ocean (0-800m) to the west and north of the UK has been generally increasing since the 1970s. A significant period of warming occurred from 1995 to 2003. The decadal-scale pattern of temperature around the UK reflects the mean conditions of the North Atlantic which has evolved from a maximum in the early 1960s and a minimum in the 1980s and 1990s.

West of the UK the water of the deep ocean (>1000m) comes from the Labrador Sea and has cooled since 1975. North of the UK, the deep water (800m) flows from the Nordic Seas and shows no long-term trend since 1950.

In the northern North Sea the temperature is most strongly influenced by inflowing North Atlantic water, showing similar decadal variations and a general warming since the mid 1980s. In the southern North Sea, atmospheric forcing is the dominant influence, with ocean temperatures being generally cool from 1970 to 1987 when a "switch" to warm conditions occurred.

The upper 1500m of the North Atlantic has warmed since 1999 and remains anomalously warm up to the end of 2006, especially in the zone between 50-70°N.

A3d.13.2 Thermal stratification

The following information is from Sharples and Dyce (2007).

Freshwater Stratification: As stratification of the regions of freshwater influence in Liverpool Bay and the southern North Sea depends on the balance between the rate of supply of the estuarine water and the strength of the mixing processes, changes in winds and rainfall will modify this balance.

Onset of Thermal Stratification and the Spring Bloom: Away from sources of freshwater, large areas of the UK shelf seas stratify in response to atmospheric warming in spring and summer (e.g. the Celtic Sea, the North Sea north of Dogger Bank, the Malin Sea). There is evidence of a recent trend to earlier stratification largely in response to warming air temperatures. Our understanding of how shallow seas respond to meteorology suggest that stratification and the associated spring bloom will, on average, occur earlier in a warmer climate.

A3d.13.3 North Atlantic circulation patterns

The following information is from Cunningham (2007). The meridional overturning circulation (MOC) is part of a global ocean circulation that redistributes heat from Equatorial to Polar Regions. In the Atlantic the MOC carries heat northward which is released to the atmosphere and maintains UK temperatures between 3-5°C higher than elsewhere at similar latitudes. However, the present strength and structure of the MOC may not continue: climate models suggest that increasing atmospheric greenhouse gas could lead to an abrupt rearrangement of the MOC and climate models and palaeoclimate records indicate that the MOC has undergone large and rapid changes in the past 20,000 years. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change suggests that there is less than 10% chance of abrupt changes during the 21st Century, but that there is greater than 90% chance that the MOC will slow by 25%. Recent observational evidence suggests that since the early 1990s the MOC has slowed by up to 30%, with a significant adjustment of ocean water masses. However, the interpretation of a 30% slowing is controversial because of a lack of understanding of the natural variability of the MOC, and possibly conflicting evidence of warmer North Atlantic sea surface temperatures. There is a broad scientific consensus that continuous observations of the strength and structure of the MOC are required. A UK/US consortium installed a continuous monitoring system in 2004. First results show that the array provides continuous observations of MOC strength and that the error of the annual mean strength is 8%. If the circulation passes through a bifurcation, or if the overturning reduces by 25% as coupled climate models suggest it might under increasing CO_2 concentrations, it should be possible to identify the change relative to the 2004-05 average.

A3d.13.4 North Sea Circulation

Holliday & Reid. (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 the Rockall Trough. However, 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, 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, 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).

A3d.13.5 Wave climate

Woolf and Coll (2007) reported strong evidence for increased wave heights in western and northern UK territorial waters and for increased occurrence of strong winds over the UK from the 1960s to the present. It is unclear whether recent behaviour is driven by "global climate change" or is simply natural variation and whether substantial changes in storminess are likely in the 21st century. Bacon & Carter (1991) inferred an increase in mean wave height of about 2% per year "over the whole of the North Atlantic in recent years, possibly since 1950" from observational data notably from Seven Stones Light Vessel (1962- 1986). Recent analyses of a more extensive data set confirm a significant upward trend in wave heights in the North Atlantic, but only for the last 50 years and embedded within a pattern of multi-decadal variability over more than a century (Gulev & Hasse 1999, Gulev & Grigorieva, 2004). There have also been significantly more severe storms over the UK since the 1950s (Alexander *et al.* 2005). However, trends in winds around the UK are much weaker than for wave heights. Most of the increase in wave heights is attributed to "swell" responding to changes in the persistence of westerly winds over the North Atlantic rather than locally generated waves.

Changes in winds and waves can be better understood by considering their relationship to atmospheric pressure gradients (Bacon & Carter 1993) and particularly to large-scale atmospheric variability such as the North Atlantic Oscillation (NAO). The characteristics of fluctuations in the westerly winds in the temperate northern hemisphere may also be described as an 'annular mode', the Northern Annular Mode (NAM) (Solomon *et al*. 2007). Thus the increased mid-latitude westerlies in the North Atlantic can largely be viewed as reflecting either NAO or NAM changes (Solomon *et al*. 2007).

Wave heights in the North-East Atlantic and northern North Sea are known (from analysis of *in situ* data, satellite data and model reconstructions) to respond strongly and systematically to the NAO (e.g. Woolf *et al*. 2002 and 2003). Other parameters - such as cyclone activity (Gulev *et al*. 2001) and the number of "gale days" at coastal sites in Scotland - show a weaker, but still significant response to NAO. Thus, many of the changes over the last 50 years can be understood in terms of the behaviour of the NAO. The recent strong trend in the NAO (towards stormier conditions) is apparently unique in its history, but it is controversial whether this is a response to greenhouse gas forcing (Osborn 2004). Many Global Climate Models suggest a general trend towards the stormier tendency of NAO/NAM in the 21st century (e.g. Terray *et al*. 2004; Miller *et al*., 2006). However, alternative analyses suggest different and mostly weaker changes in winds and storminess (e.g. Hulme *et al*. 2002; Barnett *et al*. 2006). Typically, climate models predict a decrease in the total number of extra-tropical cyclones but an increase in the number of intense events (Lambert

& Fyfe 2006). Either a strengthening of the storm track or an increase in intense cyclones will result in a deterioration of wave conditions (Wolf & Woolf 2006). This is a likely outcome in the wintertime in western and northern UK waters (Tsimplis *et al*. 2005) but there can be only low confidence in this prediction.

A3d.13.6 pH

The following information is from Turley (2007). The uptake of anthropogenic carbon since 1750 has led to the oceans becoming more acidic with an average decrease in pH of 0.1 units. Surface ocean and UK coastal water pH will continue to rapidly decline in the future as they take up more atmospheric CO_2.

Nearly half of the CO_2 derived from burning fossil fuel has already been absorbed by the surfaces of our seas and oceans, and more will be absorbed in the future as we continue to increase our CO_2 emissions to the atmosphere. The ocean uptake of CO_2 is effectively buffering even more serious climate change than that predicted by clear evidence-based scientific consensus. Continued acidification will reduce the ability of the ocean to take up CO_2 from the atmosphere, which will have feedbacks to future climate change, further accelerating the accumulation of CO_2 in the atmosphere.

A3d.13.7 Sea level

The following information is from Woodworth and Horsburgh (2007). Global-average sea level rose during the 20th century at an average rate of 1-2 mm/year, with some consensus on the larger value by the research community. The rate was larger (approximately 3 mm/year) during the 1990s. UK sea level records are consistent with these values but with smaller trends observed in Scotland (where the land is uplifting) than in the south of the UK. Extreme sea levels are also known to have increased, both on global-average and UK bases, following to some extent the rise in mean levels but also subject to long term changes in meteorological forcings.

A3d.13.8 Eutrophication

Phytoplankton growth is regulated by light and the availability of nutrient forms of nitrogen and phosphorus and to a lesser extent silicate and carbon. Excessive plant growth in response to an increased supply of nutrients is termed eutrophication and measures have been taken to reduce inputs of nutrients to avoid this occurring (OSPAR 2000c, DEFRA 2004a). Common assessment procedures have been proposed by OSPAR to guide decisions on where such measures are required. These set normal and elevated levels for dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), and a guideline that states chlorophyll concentrations should be no more than 50% higher than historical offshore background for the area concerned.

The common assessment procedures criteria for DIN and DIP relate to winter concentrations and in the northern North Sea concentrations of both DIN and DIP and of chlorophyll are normally below the levels at which eutrophication is regarded as likely to occur, while nutrient concentrations over most of the northern North Sea are considered typical of the background for the North Atlantic. This situation is largely a reflection of the fact that inputs of nutrients from land are generally low and the fact that there is active tidal mixing and water movement. Thus for the northern North Sea as a whole nutrients do not present a cause for concern. Minor problems do arise in a few restricted localities - the Ythan estuary on the Scottish coast north of Aberdeen, around Lindisfarne on the north-east coast of

England and in an area of the Tees estuary known as Seal Sands, where problems are caused by accelerated growth of benthic macroalgae. Both the Lindisfarne and Ythan problems are believed to be attributable to run off from agricultural land; in the Tees estuary a combination of industrial sources and urban sewage discharges, plus the use of fertilisers in agriculture inland is involved.

The Southern Nutrients Study (SONUS) was initiated in 1994 to determine the nutrient budget of Southampton Water and to establish fluxes to the English Channel. The amounts of nutrients entering this Natural Area since the mid-1980s have been considerably reduced (Crumpton & Goodwin 1996).

In Regional Sea 3, sheltered areas such as Langstone, Chichester and Portsmouth Harbours and Pagham Harbour periodically experience excessive macroalgal growth on mudflats. These sites have been designated as Sensitive Areas under the Urban Waste Water Treatment Directive, and therefore require nutrient-stripping from significant wastewater discharges where they serve populations in excess of 10,000.

In Regional Sea 6 DIP and silicate are considered to be enriched in both coastal and more offshore waters, and DIN in coastal waters, in relation to Celtic Sea shelf break waters. Maximal values occur in near shore eastern Irish Sea waters, and this has been attributed to anthropogenic enrichment (Gowen *et a*l. 2008). However, the lack of oxygen depletion, lack of trends in *Phaeocystis* blooms and toxic microalgal occurrences, and absence of changes in the dominant life form of pelagic primary producers, was considered as evidence of a lack of undesirable disturbance thus arguing against anthropogenic eutrophication, in the Irish Sea. Recent levels of phosphates in the Northern Irish Sea are reduced in comparison to maxima seen in the 1970s to early 1990s; significant changes at a Cumbrian phosphate processing plant being the likely main reason, although cessation of sewage sludge dumping and reduced use of phosphates in detergents are also likely contributing factors (Kennington et al. 1997; Government Laboratory (Isle of Man) 2008).

In Regional Sea 7 the concentrations of both DIN and DIP were found to be below the criteria set for Scottish waters. At a very local level mariculture activities may result in increased nutrient concentrations due to fish excretion and decomposition of unused fish food. In recent years there have been more numerous cases of shellfish being contaminated by toxins of algal origin. Blooms of toxin forming phytoplankton are considered to be a possible manifestation of eutrophication, but in Regional Sea 7 the concentrations of DIN and DIP are not high enough to be regarded as the primary cause of shellfish contamination.