Appendix 1D: Water Environment

A1d.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
- Density stratification (influenced principally by temperature and salinity) and frontal zones between different water masses
- Tidal flows
- Tidal range
- Overall patterns of temperature and salinity
- Wave climate
- Internal waves
- Water Framework Directive ecological status of coastal and estuarine water bodies
- Eutrophication
- Ambient noise

Recent assessments of changes in hydrographic conditions are summarised, based mainly on reports by Defra (2010a, b) and MCCIP (2013) but incorporating a range of other grey and peer reviewed literature sources. 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), northern hemisphere and globally. There are varying degrees of confidence in the interpretation of observed data and prediction of future trends.

A1d.2 UK context

There have been a number of information gathering and assessment initiatives which provide significant information on the current state of the UK and neighbouring seas, and the activities which affect them. These include both UK wide overview programmes and longer term specific monitoring and measuring studies. In addition, a significant number of individual academic studies have been undertaken, focused on UK waters.

The OSPAR Quality Status Report (QSR) published in September 2010 evaluated the implementation of the OSPAR strategies and their effectiveness in improving the quality of the marine environment. Key aspects of the QSR cover biodiversity, eutrophication, hazardous substances, offshore oil and gas industry and radioactive substances (OSPAR 2010a). Similarly Charting Progress 2 (Defra 2010) provided an updated assessment of the state of UK seas since Charting Progress was published in 2005. Supporting technical reports on healthy and biologically diverse seas, ocean processes, clean and safe seas, and productive seas (Defra 2010b, c, d, e) provide relevant information on the current baseline and issues affecting the water environment.

The EU Marine Strategy Framework Directive (MSFD) establishes a framework within which Member States shall take the necessary measures to achieve or maintain Good Environmental Status (GES) in the marine environment by 2020 at the latest. In the UK the Marine Strategy Regulations 2010 transposes the Directive into UK law and requires the development of the five elements of the marine strategy: (1) the assessment of marine waters; (2) the determination of the characteristics of good environmental status for those waters; (3) the establishment of environmental targets and indicators; (4) the establishment of a monitoring programme, and (5) the publication of a programme of measures. Qualitative descriptors for determining good environmental status are listed in Annex I of the MSFD and those of relevance to the water environment include:

- Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters.
- Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems.
- Properties and quantities of marine litter do not cause harm to the coastal and marine environment.
- Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.

The UK produced Part One of the Marine Strategy in 2012, a publication which contained information on the first three elements of the MSFD. Defra, the Scottish Government, the Northern Ireland Executive and the Welsh Government conducted consultation on the UK implementation of the MSFD in 2012 in relation to the current state of the UK seas, GES characteristics, targets and objectives. Part Two of the Marine Strategy was published in 2014 and focused on a co-ordinated monitoring programme for the ongoing assessment of GES. Part three, published in 2015, focused on a programme of measures that will contribute to the achievement and maintenance of GES. The MSFD in the UK compliments other key European and UK Directives such as EC Habitats Directive and EC Birds Directive, to provide an overarching framework which will allow the fulfilment of international commitments of GES.

The Marine Policy Statement (MPS) was published in 2011 and underpins marine spatial planning as part of the Marine and Coastal Access Act 2009. It outlined the UK Administrations' vision for the UK marine area, with water quality and resources, and noise identified as high level considerations for marine plan authorities (e.g. Marine Management Organisation). The MPS indicated that marine plan authorities must contribute to or align with delivery of the policies and objectives of relevant River Basin Management Plans (RBMPs, see below and Section A1d.2.8) and the MSFD.

RBMPs were finalised for all UK River Basin Districts (RBD) in 2009, with updates provided in 2015. These plans describe the RBDs, the pressures that the water environment faces and the measures that will be taken to protect and improve rivers, lakes, estuaries, coastal waters (out to 3nm in Scotland and Solway Tweed RBD and 1nm in rest of UK) and groundwater. The Water Framework Directive sets a target of aiming to achieve at least 'good ecological status' in all water bodies by 2015. However, provided that certain conditions are satisfied, in some cases the achievement of good status may be delayed until 2021 or 2027.

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 & Portmann (2006) carried out a review of monitoring of the marine environment by organisations based in the UK. One conclusion of the report was that the existing marine monitoring sites as a representative of the UK environment were ‘unbalanced and inappropriate’, leading to the establishment of a network of marine observatories established partly through the Oceans 2025 NERC initiative. Whilst the main focus of the review initially was measurements related particularly to the physical marine environment, 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 Science Coordination Committee (MSCC). The MSCC is a partnership of government departments, devolved administrations, environment agencies and research bodies involved in funding and providing marine science in the UK. It oversees working groups including the Marine Assessment and Reporting Group (MARG), Marine Environmental Data and Information Network (MEDIN), the UK Integrated Marine Observing Group (UK-IMON) and the UK Marine Monitoring and Assessment Strategy Evidence Groups (UKMMAS), which has an ocean processes evidence group.

MEDIN (http://www.oceannet.org), which combines the Marine Data and Information Partnership (MDIP), and the Marine Environmental Data Action Group (MEDAG), aims to coordinate accessibility and availability, providing online search interfaces for UK marine environmental data. Available resources include wave, current, sea level and tidal data submitted by over 100 UK organisations, marine monitoring programmes and research cruises.

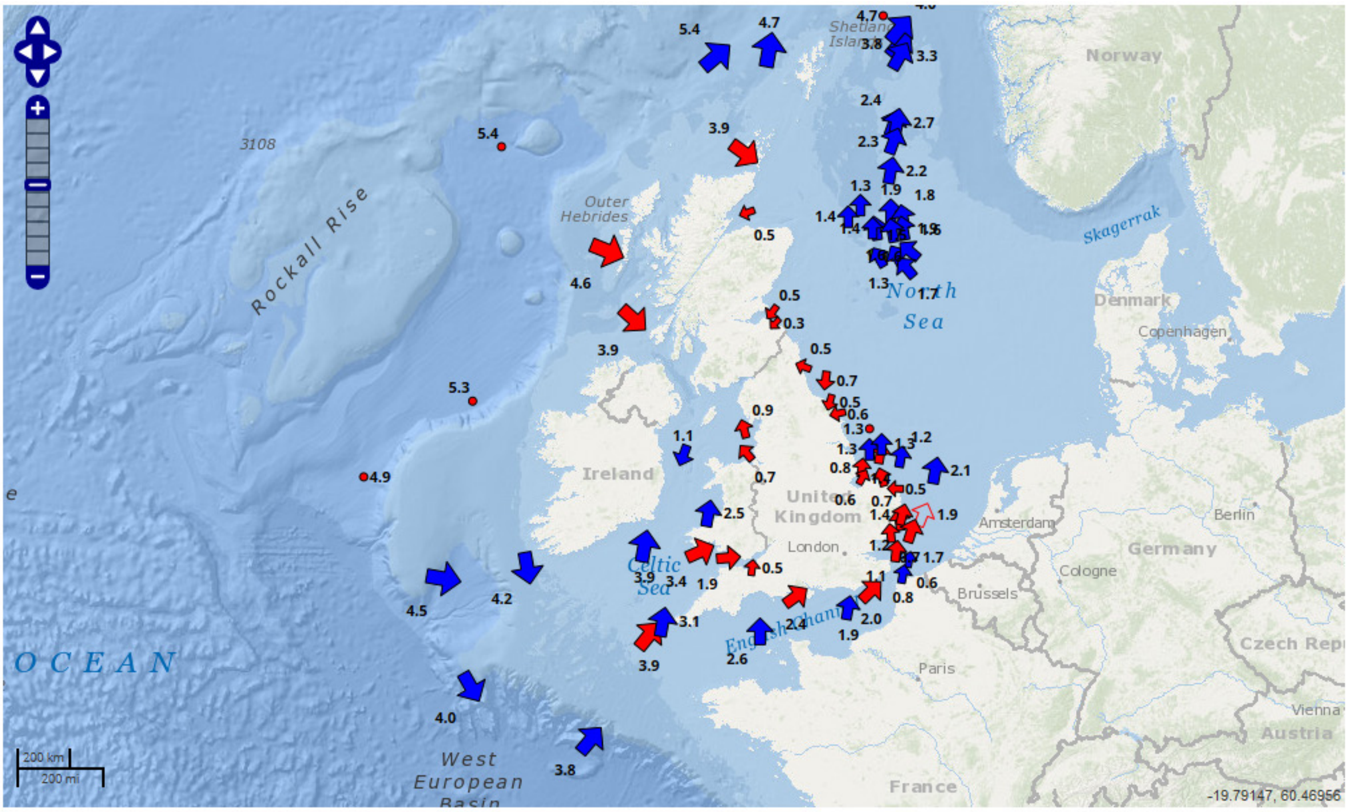
The UK-IMON draws together existing UK marine observing programmes and observatories, including information within MEDIN, Cefas’ SmartBuoy and WaveNet programes, longer term monitoring initiatives in the Tiree passage, Porcupine Abyssal Plain (PAP), Rockall Trough (Ellett Line), Liverpool Bay, Western Shelf and Western English Channel, and wider UK programmes and EU data sources (e.g. Global Monitoring for Environmental Security (GMES) and European Marine Ecosystem Observatory (EMECO) Datatool). Figure A1d.1 below provides a snapshot from the WaveNet website showing significant wave height around the UK as recorded at monitoring stations / buoys. In addition the National Network of Regional Coastal Monitoring Programmes for England can be accessed through www.channelcoast.org.

There are a number of long term data sets covering UK waters, with examples listed by Clark *et al.* (2001), Defra (2010) and MCCIP (2013). These include the MAFF Sea Surface Temperature and Salinity Data Set (ship routes to and from the UK (1963 to 1990) and continued by CEFAS to present day); 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).

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, Western Channel Observatory). 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 60 years, and plankton since the 1990s (Government Laboratory (Isle of Man) 2015). 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 Scottish Association of Marine Science (SAMS).

Figure A1d.1: Significant wave height (m) on 3rd December 2015 as recorded at WaveNet sites around the UK



Map Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors.
Data last loaded: 15:23:27 GMT+0000 (GMT Standard Time) Thu Dec 03 2015

Notes: Red arrow = Wave direction; Blue arrow = Wind direction; Red circle = No height or direction recorded in past 36 hours
Source: http://wavenet.cefas.co.uk/Map

Since the pioneering Porcupine and Lightning studies of 1868-1870 (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 2010). 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 height and period (but not direction). 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.

A1d.2.1 Water masses and circulation

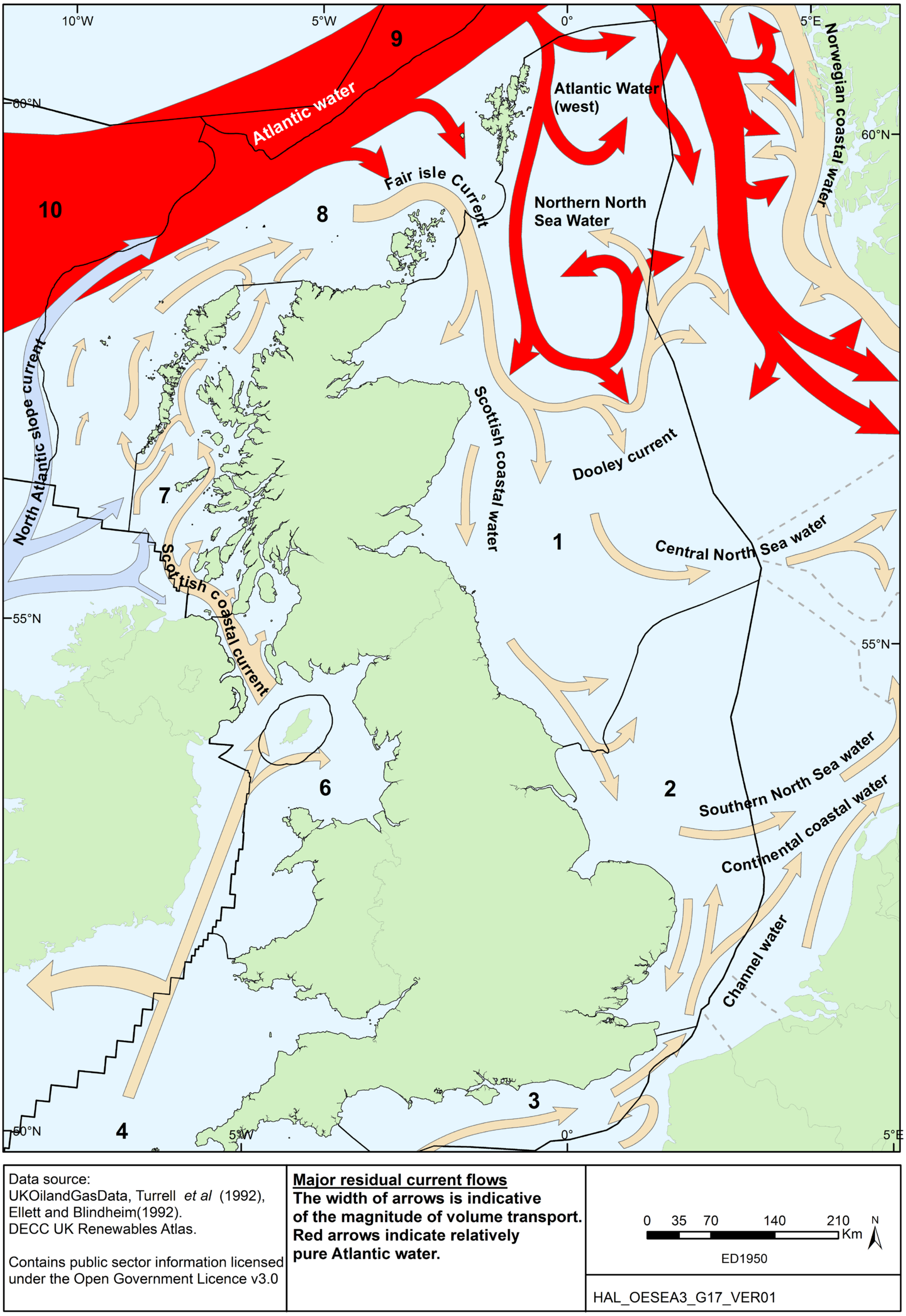
The North Atlantic Current (NAC) is an important component of the global climate system, bringing warm subtropical water to northwest Europe and influencing the climate of the UK and its surrounding seas. The western continental shelf edge and shelf slope of the UK are influenced by two main oceanic circulation systems of the North Atlantic: the sub-polar and sub-tropical gyres. The main branch of the NAC sweeps eastwards from the western North Atlantic before turning in a more northerly direction and flowing to the west of the Hatton Bank (Pollard *et al.* 2004). 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 (Pollard *et al.* 2004).

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 (Turrell *et al.* 1996, Nauw *et al*. 2015). Sources and circulation of water in the North Sea as a whole were summarised by SEA2, which identified (after Turrell 1992, see Figure A1d.2) 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, around Shetland and between Orkney and Shetland (Winther & Johannessen 2006). Most of this water however recirculates around the northern and eastern North Sea and exits via the surface Norwegian Coastal Current back into the North Atlantic. Only a small percentage Atlantic-origin inflow flows southwards along the coast of Scotland and England (Howarth 2001) and less than 10% of the inflow to the North Sea enters by the English Channel.

The generalised pattern of water movement in the North Sea is forced by a combination of tides (see Section A1d.2.4), wind patterns, density gradients (caused by freshwater input) and pressure gradients (Howarth 2001). They may also 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 2000, Nauw *et al.* 2015). Storm events may also generate nearbed, wave-induced currents sufficient to cause sediment mobilisation. Modelling work on the seasonal variability of different components of forcing shows an increase in the wind element during the autumn and winter seasons in the south-west North Sea region, increasing from 0% forcing in spring and summer to 52 and 66% in autumn and winter (Holt & Proctor 2008). This is reflected in the significant wave heights measured throughout the year. Tidal forcing remains a consistent component throughout the year, with density (related to stratification) differences driving a larger component of the flux in spring and summer (75 and 82% compared to 43-44% for autumn and winter). This is however depth averaged and it can be expected that density forcing plays a lesser role in the shallower nearshore regions away from significant freshwater inputs.

Figure A1d.2: Major water masses and residual circulation in the North Sea



Data source:
UKOilandGasData, Turrell *et al* (1992),
Ellett and Blindheim(1992).
DECC UK Renewables Atlas.

Major residual current flows
The width of arrows is indicative of the magnitude of volume transport. Red arrows indicate relatively pure Atlantic water.

HAL_OESEA3_G17_VER01

The tidal movement in the Irish Sea and English Channel are both from a southerly direction, with a generalised decrease in tidal amplitude with distance (see Figure A1d.12) caused by bottom friction.

A1d.2.2 Stratification and frontal zones

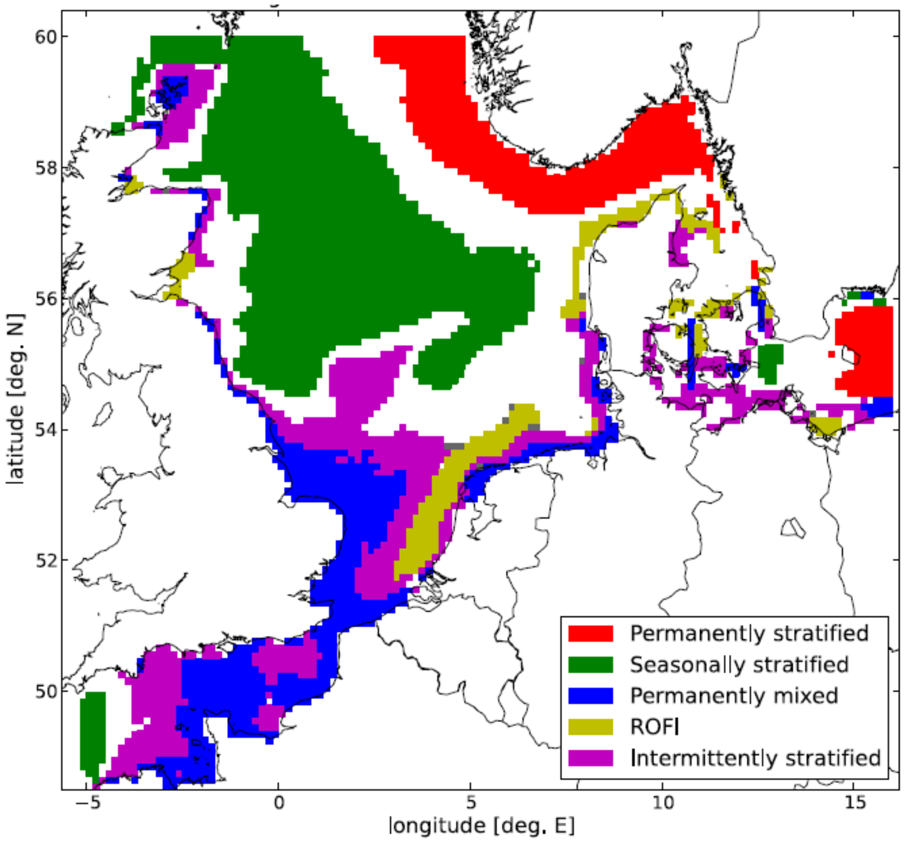
Fronts or frontal zones mark boundaries between water masses, including tidally-mixed and stratified areas, and are numerous on the European continental shelf. Tidal mixing fronts normally form in summer months around the UK, when stratification occurs away from the coast due to more settled weather. Salinity fronts are observed all year round and occur where freshwater runoff occurs (e.g. mouths of estuaries and sea lochs), or where there is greater influence of saline ocean waters. Persistent localised fronts can also occur around topographical features, such as islands, banks, deeps and channels, due to their interaction with currents. Internal waves and eddies are also persistent features in these areas. Around the UK, the Flamborough and Islay Fronts have been extensively 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 2010) although the Kattegat, Skagerrak and Norwegian Trench region of the North Sea have stable salinity stratification all year. Further discussion is provided in Section A1d.2.5.

The UKSeaMap project (Connor *et al.* 2007) 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 exceeded 0.5ºC, divided by the number of days in the 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 (Figure A1d.4).

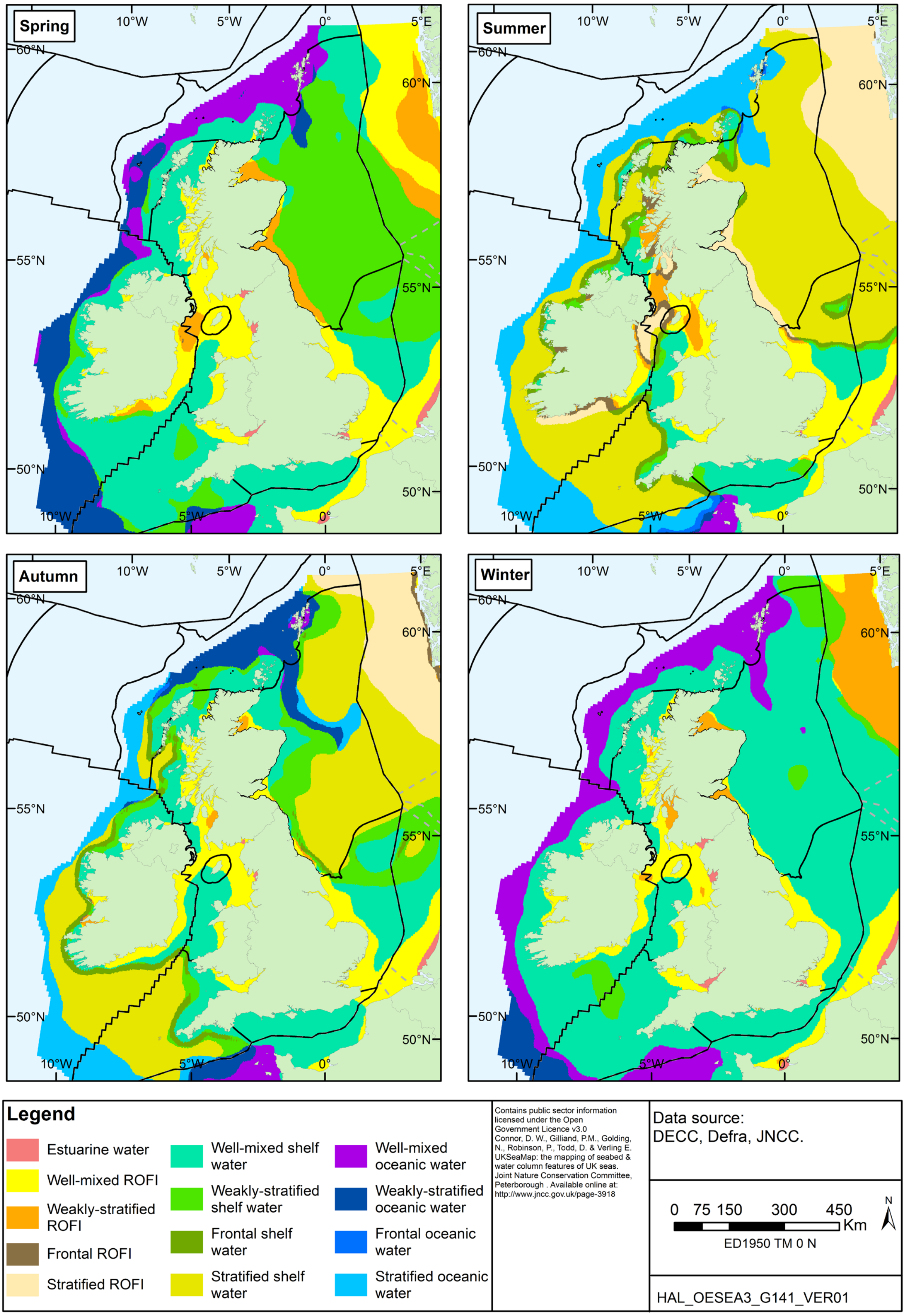
Van Leeuwen *et al.* (2015) identified five regimes using an applied ecosystem model: permanently stratified, seasonally stratified, intermittently stratified, permanently mixed, and Region Of Freshwater Influence (ROFI). 29% of the North Sea did not fall under a specific regime category due to high interannual variability, but overall the regimes were found to be remarkably stable in this model (Figure A1d.3).

Figure A1d.3: Regions of dominant stratification in the North Sea 1958-2008



Notes: Results of modelled, annual regions in the North Sea based on density stratification, showing regimes which occur for most years. Transparent areas indicate where the dominant regime occurs for less than 50% of the time (less visible due to minimal occurrence).
Source: van Leeuwen et al. (2015)

Figure A1d.4: Seasonal water mass and water column structure in UK waters



Contains public sector information licensed under the Open Government Licence v3.0
Connor, D. W., Gilliand, P.M., Golding, N., Robinson, P., Todd, D. & Verling E. UKSeaMap: the mapping of seabed & water column features of UK seas. Joint Nature Conservation Committee, Peterborough . Available online at: http://www.jncc.gov.uk/page-3918

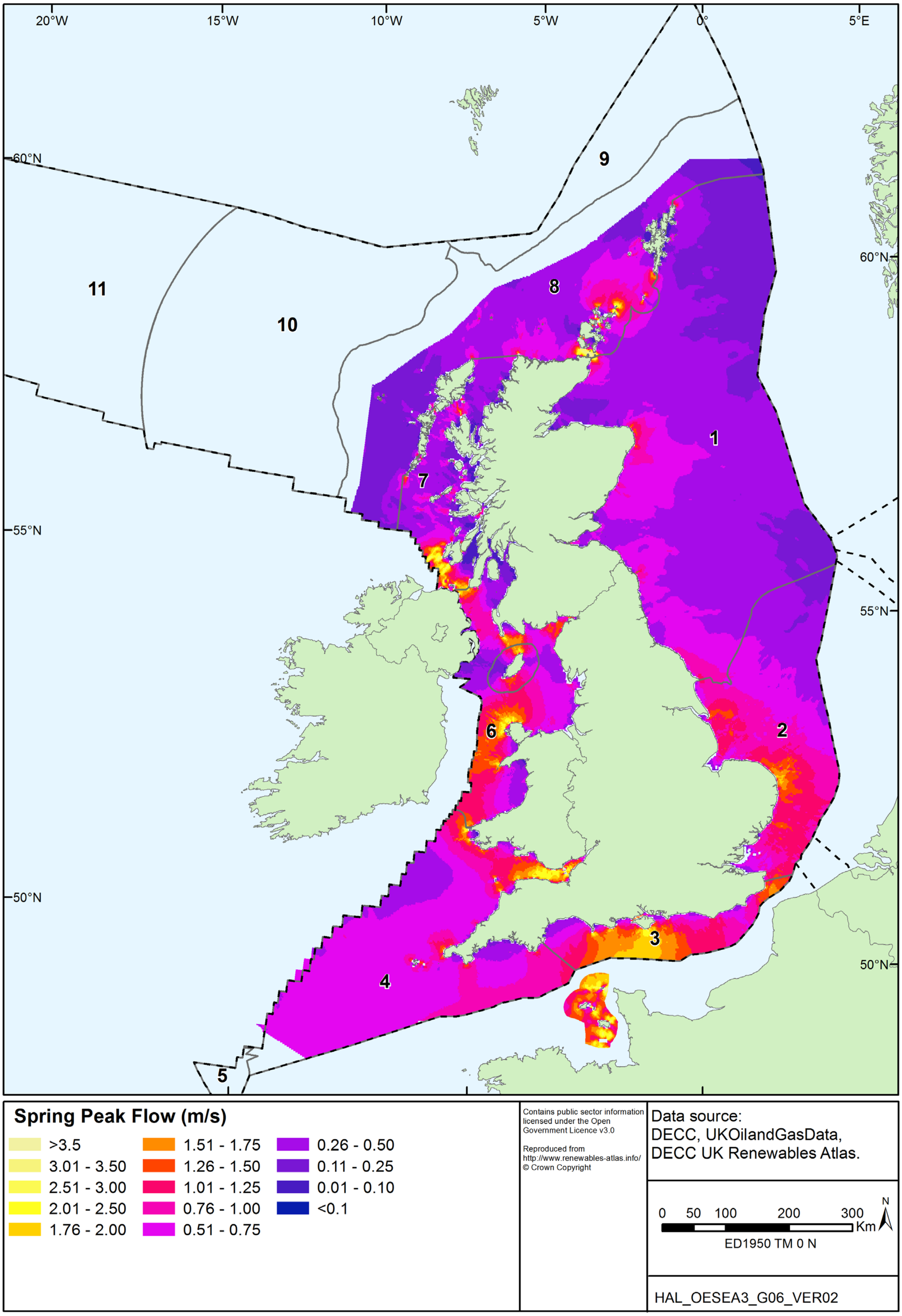
Data source: DECC, Defra, JNCC.

Typically, 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). 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 & Griffiths 1978, Becker 1990). A persistent narrow (10-15km) near-surface flow between the Firth of Forth and the Dogger bank has also 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). Similarly, during spring and summer a complex patchwork of mixed and stratified areas develop within the Irish Sea determined primarily by thermal inputs and tidal mixing (Neil *et al.* 2012).

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).

Figure A1d.5: Peak flow for mean spring tide



A1d.2.3 Coastal tidal flows

Bathymetry plays a significant role in modifying coastal tidal and residual currents, especially in the North Sea (Nauw *et al.* 2015). 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, Renewables Atlas 2011).

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. A near surface coastal current (10-15km wide) flows southwards, following the 40m depth contour, from the Firth of Forth to the Dogger Bank (Hill *et al.* 2008).

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 A1d.5). 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).

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 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.

A1d.2.4 Tidal range

Details of the mean spring tidal range around the UK are presented in Figure A1d.6. It shows that the areas with the greatest tidal range are located within the wider Severn Estuary and around the Channel Islands. The highest astronomical tide recorded at the port of Avonmouth, within the Severn Estuary, in 2015 measured 14.65m (National Tidal and Sea Level Facility). Tidal ranges greater than 6m also occur in The Wash, eastern English Channel and wider Liverpool Bay and Solway Firth. Table A1d.1 details all estuaries within England and Wales with tidal ranges >6m.

Conversely, the areas where tidal range is at a minimum, called amphidromic points or tidal nodes (shown as lines in Figure A1d.7), occur off the south coast of England; between Islay, the Mull of Kintyre and the Northern Irish coast; the south-western Irish Sea; the centre of the North Sea offshore Denmark; southern North Sea, offshore The Netherlands; and the south-western coast of Norway. The general tidal flow pattern of the North Sea (see Section A1.d.2.1) is influenced by these points, with the tidal wave entering the northern North Sea and travelling southwards down the UK coastline before travelling around the amphidromic points offshore The Netherland and Denmark and leaving the North Sea along the Norwegian coast (Nauw *et al*. 2015). Other than in these areas tidal range decreases with distance from the coast.

Table A1d.1: Estuaries with a tidal range of 6m or above in England and Wales

Estuary	Regional Sea	Tidal range (m)
Severn Estuary	4	12.3
Bridgwater Bay	4	11.1
Thaw Estuary	4	10.5
Blue Anchor Bay	4	9.7
Ogmore Estuary	4	8.9
Mersey Estuary	6	8.9
Afan Estuary	4	8.6
Neath Estuary	4	8.6
Tawe & Swansea Bay	4	8.6
Morecambe Bay	6	8.4
Inner Solway Firth	6	8.4
Duddon Estuary	6	8.1
Alt Estuary	6	8
Ribble Estuary	6	7.9
Esk Estuary	6	7.7
Dee & N. Wirral	6	7.6
Carmarthen Bay	4	7.5
Taw-Torridge Estuary	4	7.3
Loughor Estuary	4	7.1
Conwy Estuary	6	7.1
Traeth Lafan	6	6.9
Clwyd Estuary	6	6.7
Dee Estuary	6	6.7
The Wash	2	6.5
Inner Thames Estuary	2	6.5
Cuckmere Estuary	3	6.5
Gannel Estuary	4	6.4
Traeth Dulas	6	6.4
Traeth Coch	6	6.4
Milford Haven	6	6.3
Ouse Estuary	3	6.1
Humber Estuary	2	6

Source: The Estuary Guide website - http://www.estuary-guide.net/

Figure A1d.6: Mean spring tidal range around the UK

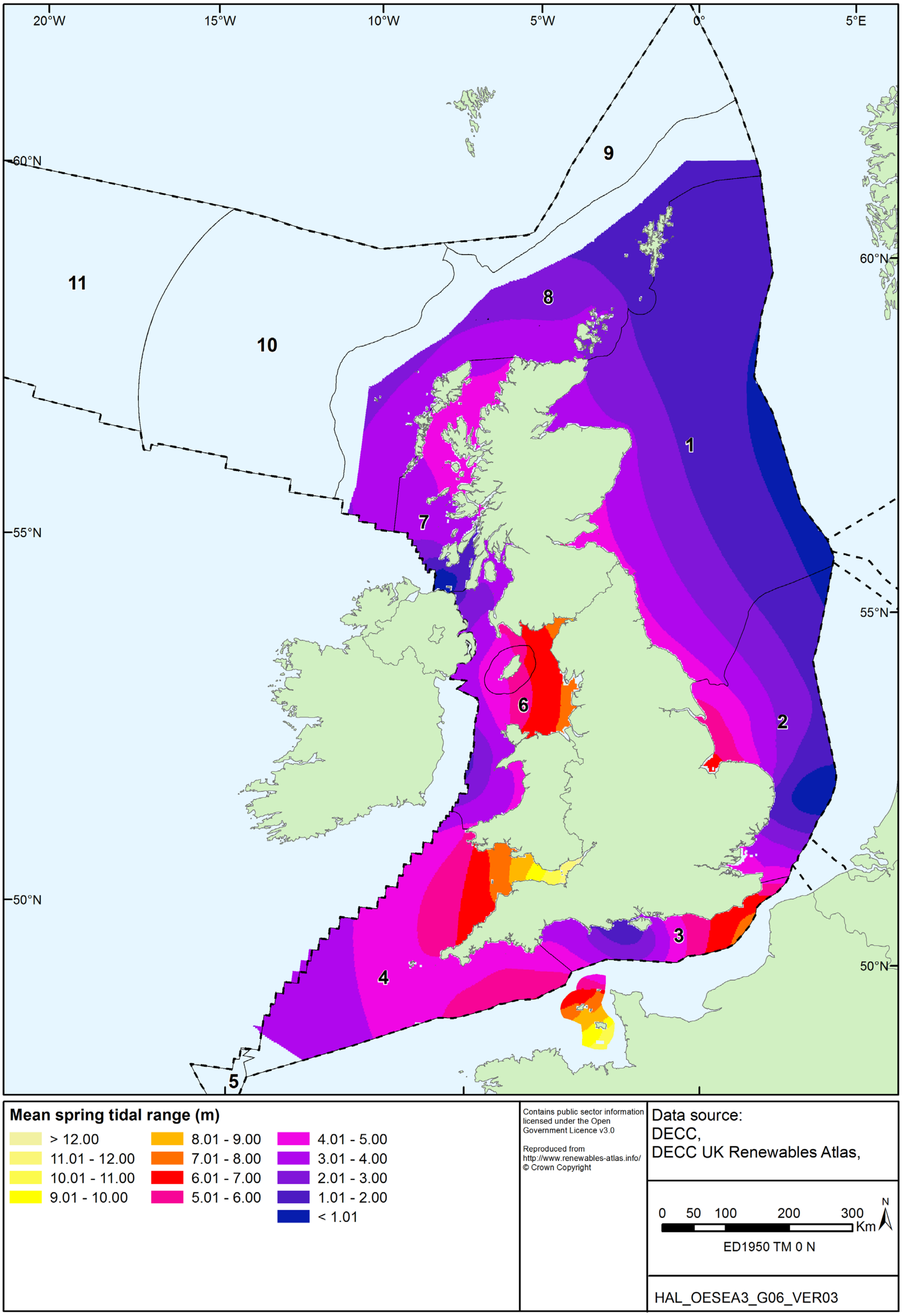
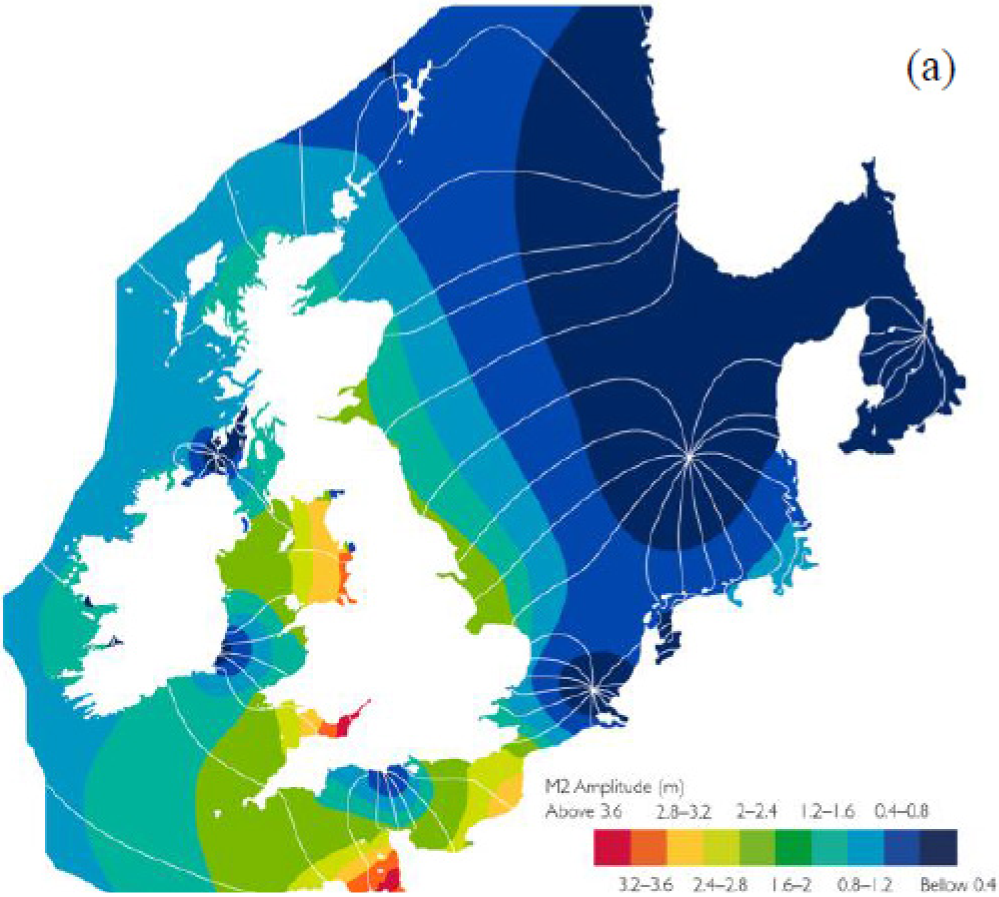


Figure A1d.7: Modelled M2 (lunar semi-diurnal) tidal co-amplitude (colours) and co-range (lines)



Source: Luxford et al. (2014)

A1d.2.5 Temperature and salinity

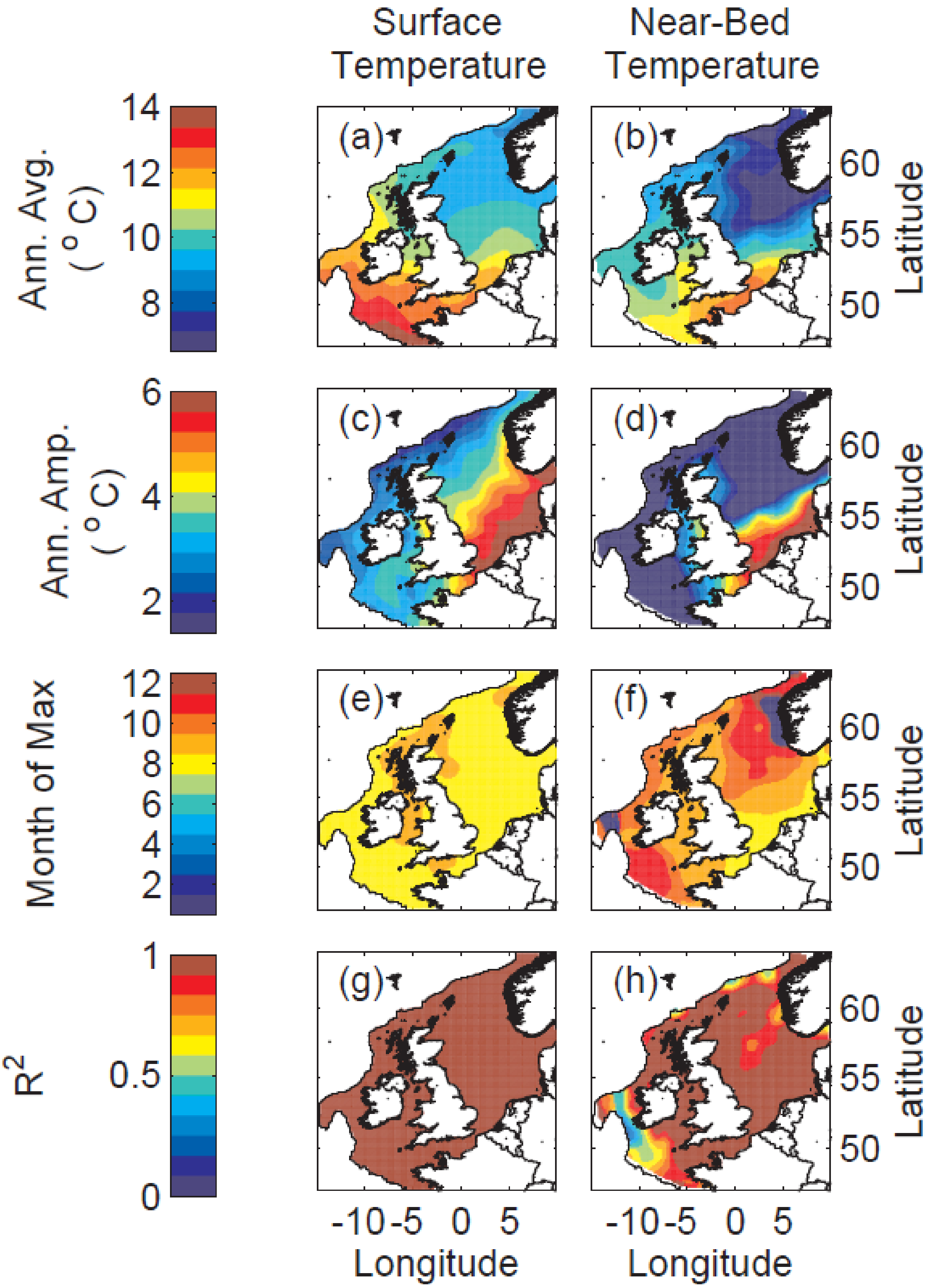
Sea surface temperature and salinity values in the northern North Sea are to a large extent influenced by the flow of oceanic Atlantic waters into the North Sea through the Fair Isle Channel (Turrell 1992). Oceanic inflow combines with less saline coastal waters to make up a southern flow down the Scottish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

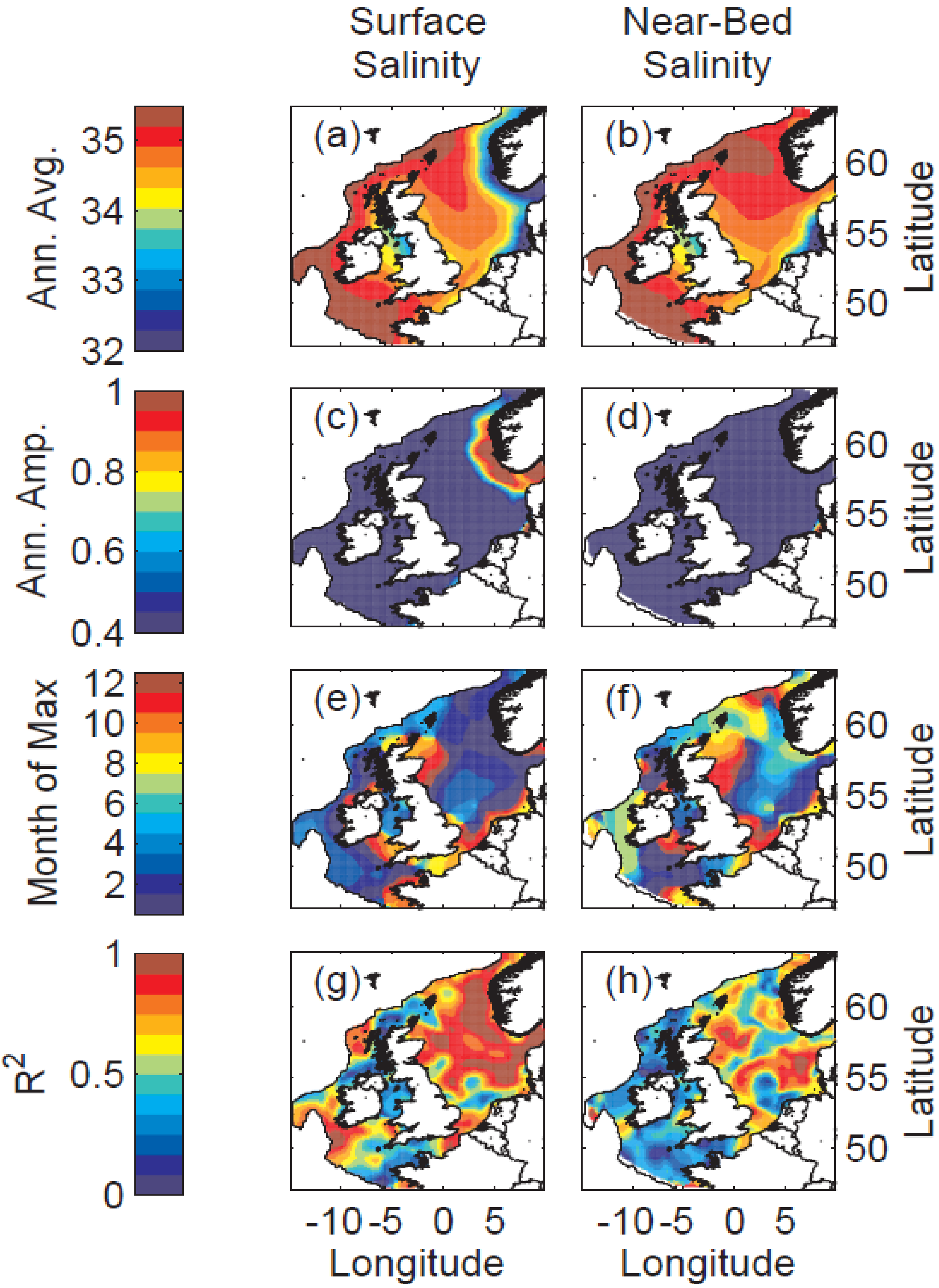
An improved dataset of near surface and bottom temperature and salinity on the north-west European continental shelf by Berx & Hughes (2009) for the years 1971-2000 is shown in Figures A1d.8 and A1d.9. The average temperature for the area (Figure A1d.8a) shows a decrease with increasing latitude and an influence of water from the North Atlantic entering the North Sea from the north. The greatest seasonal variations in temperature occur in the shallow southern part of the North Sea and German Bight where the water column remains well mixed throughout the year. In comparison the northern part of the North Sea has a low annual amplitude especially in near bed temperatures due to the development of seasonal stratification which blocks the mixing of warmer surface waters to depth.

Figure A1d.8: Surface and near-bed temperature for the NW European continental shelf for the period 1971-2000 showing (a, b) annual mean temperature (^{o}C), (c,d) annual seasonal cycle amplitude (^{o}C), (e, f) phase (expressed as month of maximum) and (g, h) R^2 of the HAMELS analysis



Source: Berx & Hughes (2009)

Figure A1d.9: Surface and near-bed salinity for the NW European continental shelf for the period 1971-2000 showing (a, b) annual mean salinity (‰); (c,d) annual seasonal cycle amplitude (‰); (e, f) phase (expressed as month of maximum); and (g, h) R^2 of the HAMELS analysis



Source: Berx & Hughes (2009)

This seasonal stratification is also evident in Figures A1d.8e and f which show that in surface waters the month of maximum temperature is uniformly late August / early September but in near bed waters it occurs during October in areas with seasonal stratification. This is because it is only when the thermocline breaks down that warmer surface waters can be mixed to depth.

The salinity data (Figure A1d.9) clearly shows the influence of the North Atlantic Current, with increased salinity to the west of the area. Density stratification due to large freshwater inputs can be seen in the Baltic, Dutch coastal region, Liverpool Bay and Clyde Sea. Berx & Hughes (2009) state that a clear seasonal signal can only be identified in the Baltic outflow, with all the other areas falling below the 95% confidence boundaries.

A1d.2.6 Wave climate

In British waters, the Western Isles experience the highest wave heights (long term mean significant wave height (Hs) of 3.0m (Figure A1d.10). Significant wave heights can, however, exceed 10-15m in these areas during annual storm events (WaveNet website - https://www.cefas.co.uk/cefas-data-hub/wavenet/). The east coast of Shetland, Orkney and the Scottish 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 north-east 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. Mean significant wave heights for the more sheltered central and southern North Sea, Irish Sea, English Channel and inshore waters are low at generally <1.5m. The maximum significant wave height recorded at the Goodwin Sands Waverider in the southern North Sea over the period 2008-2014 was 2.37-3.69m, with the monthly average for 2014 ranging from 0.46m in June and September to 1.17m in February (Channel Coastal Observatory 2015).

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 November and March. Again more sheltered areas have the smallest seasonal variability in significant wave height, with the Atlantic Ocean area showing the largest variability (Woolf *et al.* 2002). 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), with seasonal variation at the Portleven Waverider buoy, Cornwall, recorded in 2014 as 2.8m (for monthly averages) (Channel Coastal Observatory 2015). In addition, interannual variability is very high, with a strong linear dependence on the North Atlantic Oscillation (NAO) index shown by Woolf *et al.* (2002).

A1d.2.7 Coastal and estuarine water bodies

River Basin Management Plans (RBMP) were published by the relevant devolved national authority (SEPA, EA, NRW and DOE) in 2009 for all UK River Basin Districts (RBD) under the Water Framework Directive (WFD). One of the primary objectives of the WFD is to achieve ‘good ecological status’ for all surface waters, including coastal and transitional (estuarine) water bodies. Additional objectives include; preventing the deterioration of the status of the water body, achieving standards and objectives for protected areas and cessation of discharges, emissions and loses of hazardous substances into surface waters. The initial plans covering the period 2009-2015 were updated in 2015, assessing the progress made against the first plans and revised measured required to meet targets by the next review period in 2021. The WFD classification scheme for water quality includes five status classes: high, good, moderate, poor and bad. Annex V of the WFD provides a general definition of good status for rivers, lakes, transitional waters and coastal waters: “The values of the biological quality elements for the surface water body type show low levels of distortion resulting from human activity, but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions.” More specific definitions including of chemical and biological quality elements are also detailed in Annex V. The current status of relevant RBDs is described below in Table A1d.2.

Table A1d.2: Current extent and status of estuarine and coastal water bodies

River Basin District	Number of water bodies in the RBD		Percentage of water bodies at good or better overall status (2015)	
	Estuarine	Coastal	Estuarine	Coastal
Scotland	49	457	85%	97%
Solway Tweed	11[1]	8[1]	91%[1]	88%[1]
Northumbria	7	7	14%	57%
Humber	7	2	29%	0%
Anglian	18	13	11%	15%
Thames	10	1	50%	0%
South East	23	11	22%	36%
South West	23	23	17%	61%
Severn	6	0	0%	-
Western Wales	28	23	25%	39%
Dee	1	0	0%	-
North West	11	5	27%	60%
North Western IRBD	2	1	0%	100%
Neagh-Bann IRBD	2	3	0%	33%
North Eastern IRBD	2	15	0%	47%

[1] Data from 2009 River Basin District management plan [update was due Dec 2015]
Sources:
UK Government website - https://www.gov.uk/government/collections/river-basin-management-plans
Natural Resources Wales website - http://waterwatchwales.naturalresourceswales.gov.uk/en/
Scottish Government website - http://www.environment.scotland.gov.uk/get-informed/water/
Northern Ireland Department of the Environment website - https://www.doeni.gov.uk/topics/water/river-basin-management

Flood Risk Management Plans (FRMP) are published by the Environment Agency for England and Natural Resources Wales for Wales covering all areas where there is a significant risk of flooding from main rivers, the sea and reservoirs. The initial plans were published in December 2015 by RBD.

A1d.2.8 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 have arisen in a few restricted localities - the Ythan estuary on the Scottish coast north of Aberdeen, Firth of Clyde, 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 (Defra 2010, Scottish Government 2011). 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.

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 (dissolved inorganic nitrogen) and DON (dissolved organic nitrogen) 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 through riverine inputs (Gowen *et al.* 2008, Yamashita *et al.* 2011, Moschonas *et al.* 2015). 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.

A1d.2.9 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. The subject areas (Irish Sea and west of Scotland) are largely 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 (Hildebrand 2009). 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, Bailey *et al.* 2010).

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 5.3 of the Environmental Report.

Underwater noise is part of Descriptor 11 of the MSFD aiming for Good Environmental Status (GES) by 2020. A monitoring strategy for the North Sea (JOMOPAN) has been set up to develop a structure for a joint monitoring programme for ambient noise in the North Sea (Indicator 11.2.1 of the MSFD). The project also aims to provide tools necessary for managers, planners and other stakeholders to assess the effect of ambient noise on the environmental status of the North Sea and to co-ordinate activities in a trans-national manner. In the proposal it was suggested that there was no clear benefit monitoring outside the range of 10Hz to 1kHz, suggesting (based on a modelled sound map) that in the North Sea the contribution of shipping noise above 1kHz would be small compared to natural sources (Snoek *et al.* 2015).

A1d.3 Features of Regional Sea 1

In Regional Sea 1 a shallow and narrow shelf platform (~10km wide and <30m deep) extends from the Firth of Forth down to Flamborough Head, with the seabed shelving smoothly eastwards away from the coast to depths of >70m and up to 110m in the Farn Deeps. The nearshore region is dominated by the southwards flowing coastal current, which flows at a velocity of ~0.6 m/s during spring tides and 0.3 m/s at neap tides (BERR 2008).

One site within Regional Sea 1 (Stonehaven) has been sampled since 1999 with data collected on water temperature, salinity, nutrients and phytoplankton. Three coastal stations in Regional Sea 1, at Blyth, Redcar and Scarborough, are part of the long term Cefas coastal temperature network recording water temperature. As part of the SmartBuoy and Wavenet programmes, eight nearshore stations record sea temperature and wave characteristics such as significant height, and seventeen offshore stations (primarily associated with oil and gas installations) record wave and wind characteristics. A number of these stations provide long term data sets from the 1970's to present day, for example Forties (1974-present), Frigg (1979-present) and Ekofisk (1980-present).

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. The Tay has the largest mean annual flow of all British rivers (164m^3/s; Gilvear *et al.* 2002), with salinity measurements increasing offshore away from this freshwater input (Berx & Hughes 2009). Sand waves to the west of the Newcombe shoal are also 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 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, 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 1.5m/s), 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.

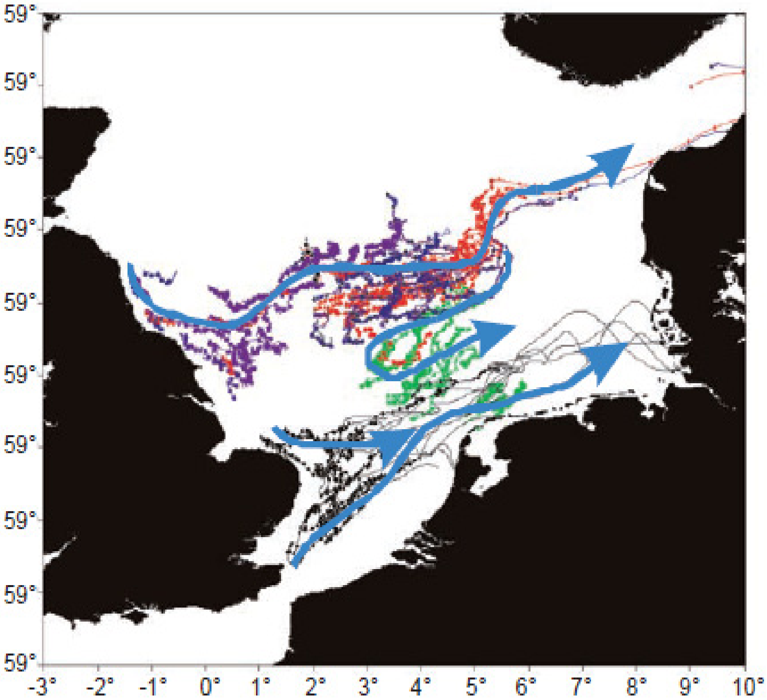
A1d.4 Features of Regional Sea 2

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.

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 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). 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.

In general, maximum velocities are below 1.0m/s in the nearshore region, except in the vicinity of major headlands (Flamborough Head, Spurn Point and South Foreland) where peak velocities may reach 2.0m/s. A Defra funded project (AE1225) utilising drifters in the region shows the position of organised summer flows (0.15m/s) north of the Flamborough Front away from the English coastline along the northern edge of Dogger Bank and northeast into the Skaggerak (Figure A1d.12). This figure also shows associated flows (~0.1 m/s) south-west along the southern edge of Dogger Bank and anticlockwise around the edge of the stratified region at the southern end of the Oyster Grounds (Fernand 2006).

Figure A1d.12: Drifter tracks in the central and southern North Sea with arrows showing main flow pathways



Source: Cefas (2006)

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.

In winter, the waters in the north of Regional Sea 2 are some of the coldest areas of the UK (Jones *et al*. 2004); 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. A series of 9 measurements points for temperature and salinity along the ferry route from Harwich to Rotterdam have been taken on a weekly basis since 1970 (Cefas website). These provide a transect across the southern North Sea and show slightly reduced seasonality in temperatures in the deeper water at the centre of the transect as opposed to the shallower coastal ends.

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.

A1d.5 Features of Regional Sea 3

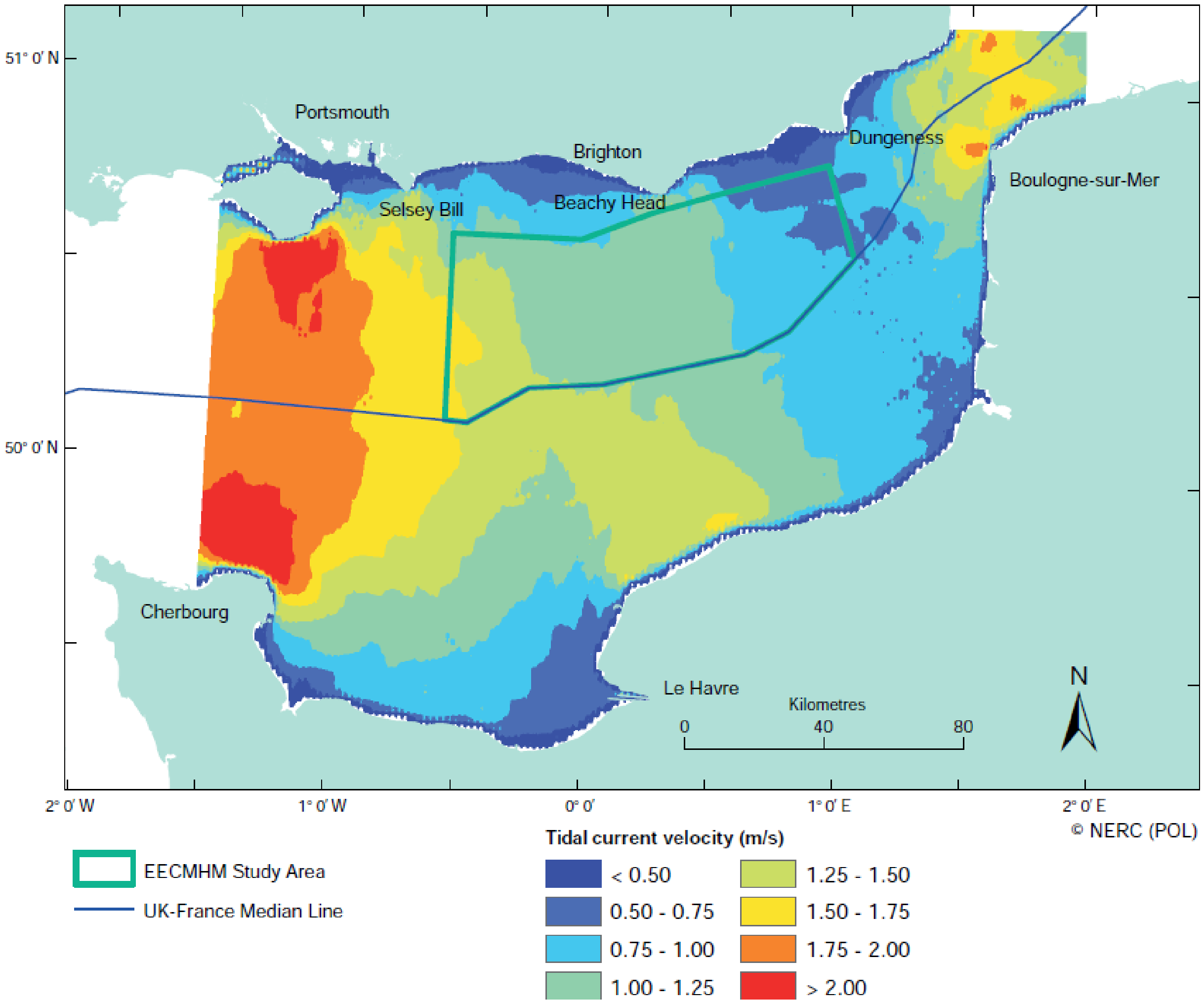
Regional Sea 3 is characterised by a reasonably well-defined transition between two marine provinces, centred on the Solent. The Eastern Channel is largely influenced by cool Boreal water (which dominates the North Sea system), whereas the western part of the Channel is influenced by relatively warmer Lusitanian water, which comes in part from the North Atlantic Current 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 (Howarth 2001).

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 ^{125}Sb, ^{137}Cs, ^{134}Cs and ^{99}Tc 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 (^{125}Sb and ^{99}Tc) 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 generally 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 (Figure A1d.13). Stronger tidal currents in the western-central Channel occur off Portland Bill, where they may reach over 3.5m/s, and off the French coast where extreme current velocities of 4.6m/s have been recorded (James *et al.* 2007). 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 (Figure A1d.13). The eastern English Channel is also exposed to swell from the Atlantic Ocean. Two light vessels moored within the Channel and 2 Wavenet sites at Hastings and Poole Bay have recorded water temperature and wave conditions since 2003 (2002 for the Hastings Wavenet site) (Cefas website).

Figure A1d.13: Maximum amplitude of depth averaged mean spring tidal current



Source: James et al. (2007)

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 6.5°C and 8°C. In August, surface water temperatures in the central English Channel are on average 16-16.5°C (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.

A1d.6 Features of Regional Sea 4 & 5

The body of water present within Regional Seas 4 and 5 is predominantly Atlantic in origin. The driving force behind water movements in these regions is the North Atlantic Circulation (NAC). The NAC divides to the south-west of Ireland, with one mass of water moving north-eastwards 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 south-western peninsula and beyond.

Research into the physical oceanography of the western English Channel has been undertaken since 1888, with a significant number of research cruises undertaken by marine laboratories in Plymouth. In addition, multiple light vessels, Wavenet and Waverider buoys currently record daily water temperature, salinity and wave conditions in the Regional Seas 4 and 5. 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 north-westerly 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 were 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 0.1-1.0m/s. Current speed maxima during mean neap tides are approximately 40-50% of these values (Lee & Ramster 1981). Satellite tracked drifters (Cefas 2006) show that from early summer to autumn there is a continuous oceanic pathway driven by geostrophic currents from NW France, over the western English Channel, south along the Cornish coast, around the Lizard Peninsular, up the north Cornish and Devon coasts, across the St Georges Channel and then around the south-west and west coast of Ireland (Figure A1d.14). These flows occur at the boundaries of stratified regions, inhibiting lateral transport between stratified and non-stratified areas.

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 Cotentin 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 slow, between 0.75 and 1.25m/s. A significant northerly coastal current exists between the Scilly Isles and Lundy Island (Pingree *et al.* 1999), with an additional localised clockwise circulation measured around the Scilly Isles (Southward *et al.* 2005).

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 (Polton *et al*. 2002).

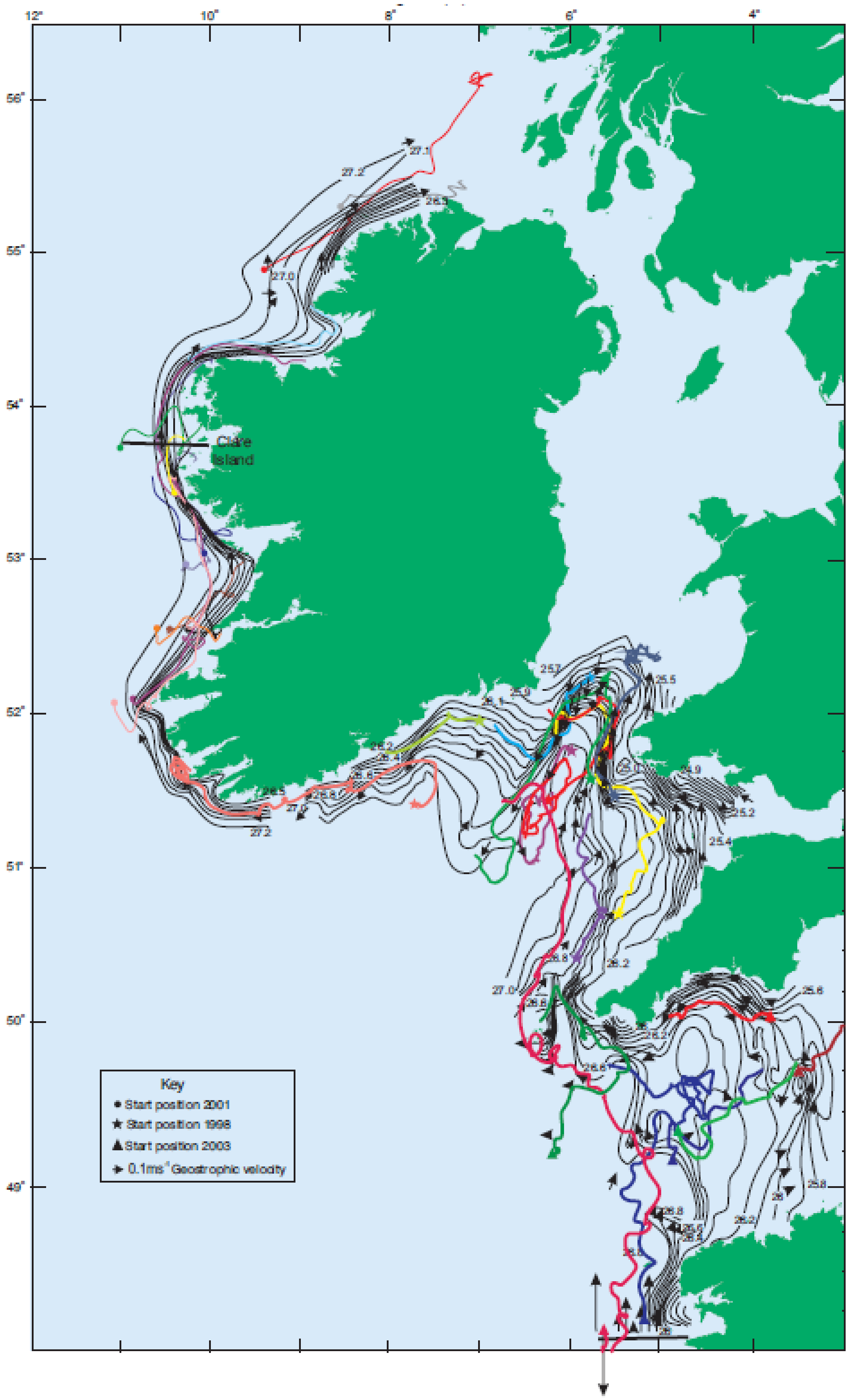
The tidal range for the eastern part of Regional Sea 4 (i.e. the central Channel) is not particularly large; around 3.0-4.0m mean spring in Lyme Bay. Tidal range increases progressively offshore into the English Channel and is particularly high near the Channel Islands. On the northern side of the south-western 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 south-western 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 0.5-1ºC 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). The Western Channel Observatory (http://www.westernchannelobservatory.org.uk) is an oceanographic time-series and marine biodiversity reference site which combines historical data with present day monitoring and measuring, satellite data and modelling. The observatory operates two scientific buoys which provide hourly measurements including SST, salinity and turbidity. Measurements, including temperature and salinity, are also taken weekly at a coastal station and fortnightly at an open shelf station (25nm south-west of Plymouth) using the research vessels of the Plymouth Marine Laboratory and the Marine Biological Association. One station, E1, has a record of temperature and salinity dating from 1903, one of the longest offshore records in the world. Sea surface measurements in Plymouth Sound (approx 50º22'N 04º08'W) were taken by city authorities between 1898-1989 (Cooper 1958) and by a local resident (1967-2003).

Figure A1d.14: Northwards transport from Brittany to Scotland showing Argos drifters tracks overlain on bottom density contours.



Source: Cefas (2006)

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), as well as a good correlation between the strength of the North Atlantic Oscillation and sea surface temperatures in the English Channel.

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.* 1996). 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.

A1d.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 60 years, and plankton since the 1990s (Government Laboratory (Isle of Man) 2015). 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). In addition, the Coastal Observatory in Liverpool Bay integrates measurements from SmartBuoys, instrumented ferries running from the UK to Ireland, drifters, tidal gauges, survey cruises, satellite and radar data, riverine inputs and met stations for the Irish Sea.

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, where for example it causes a band of low salinity water in the coastal region (<50m water depth) close to the Irish coast (Hill *et al.* 1996). The Irish Sea receives freshwater run-off from a large area of land, approximately 43,000km^2 (Bowden 1980) 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 results in seasonal stratification. However, stratification is a highly dynamic process and in some areas (e.g. east of Isle of Man) is only likely to develop during hot, calm conditions and can easily be mixed away by storms or spring tides.

Long time-series of satellite imagery data has been used to automatically detect thermal ocean fronts. The resulting maps showed considerable and consistent seasonal variation in the occurrence, location and frequency of fronts in the Irish Sea. The front maps agreed closely with in situ and modelled analyses of persistent frontal locations in this region (marked 1-4 in Figure A1d.15), and also identified many additional, variable frontal zones.

Four main, persistent frontal areas are identified in Regional Sea 6 (positions shown in Figure A1d.15):

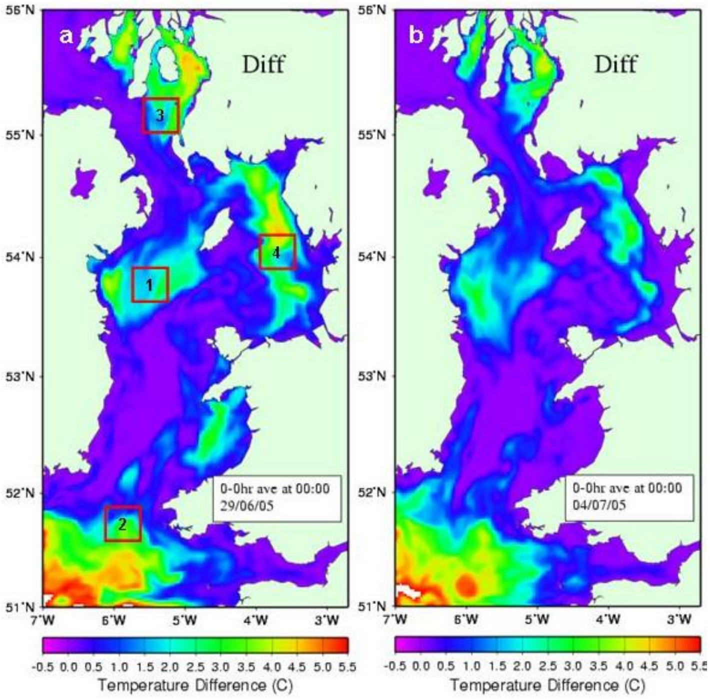
1. In the western Irish Sea a combination of deeper water (>100m water depth) and slower tidal currents allows stratification to form in spring and summer when tidal energy is insufficient to maintain mixing against the increase in surface buoyancy through solar heating (Young & Holt 2007). The maximum surface to bed temperature difference is around 5ºC during stratification. 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 (Young & Holt 2007). 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, although there is significant transport across the boundary (St Georges Channel; Figure A1d.14)

3. A front separates the stratified regime of the Clyde Sea from the well mixed waters of the North Channel. Significant inputs from the River Clyde and other freshwater sources (60-700 m^3/s) promote haline stratification throughout the year. The outflow of surface water over the sill into the North Channel is up to 1.5‰ less than the inflow water (McIntyre *et al.* 2012), maintaining the stable stratification which is not affected by weak tidal stirring. During the summer, this stratification is reinforced by strong thermal stratification.

4. Differences between saline oceanic inflows and freshwater input also causes 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. In Liverpool Bay freshwater inputs continually replace the stratification that tidal mixing reduces, with 65% of tidal cycles showing a switch between a vertically mixed water column and a stratified one (Polton *et al.* 2011).

Figure A1d.15: Seasonal 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/)

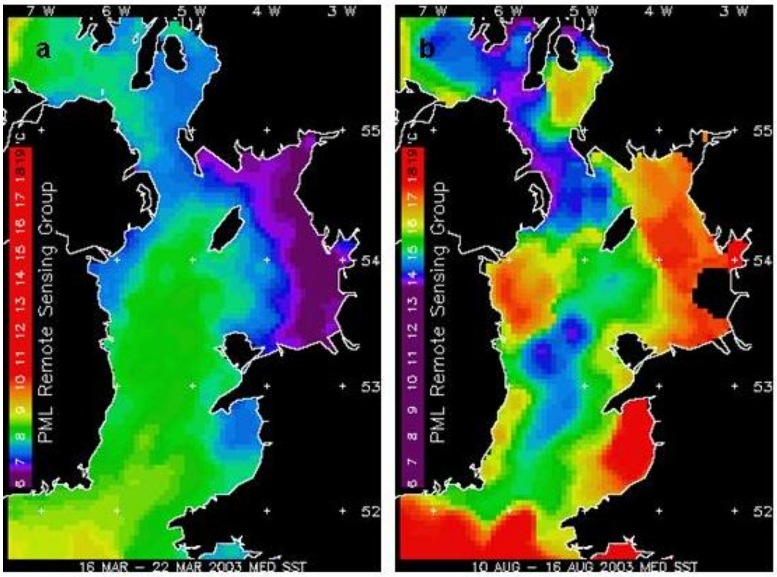
A strong north flowing jet current has been observed in the eastern St George's Channel in summer (Horsburgh *et al*. 1998). This jet current is density driven and associated with the Celtic Sea tidal-mixing front which forms between May and October. Peak velocities observed for this current were up to 0.28m/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. Brown *et al.* (2003) also identified these flows, with velocities of 0.25 m/s recorded.

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 on the Irish coast of 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 (Figure A1d.16). 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.

Figure A1d.16: 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/

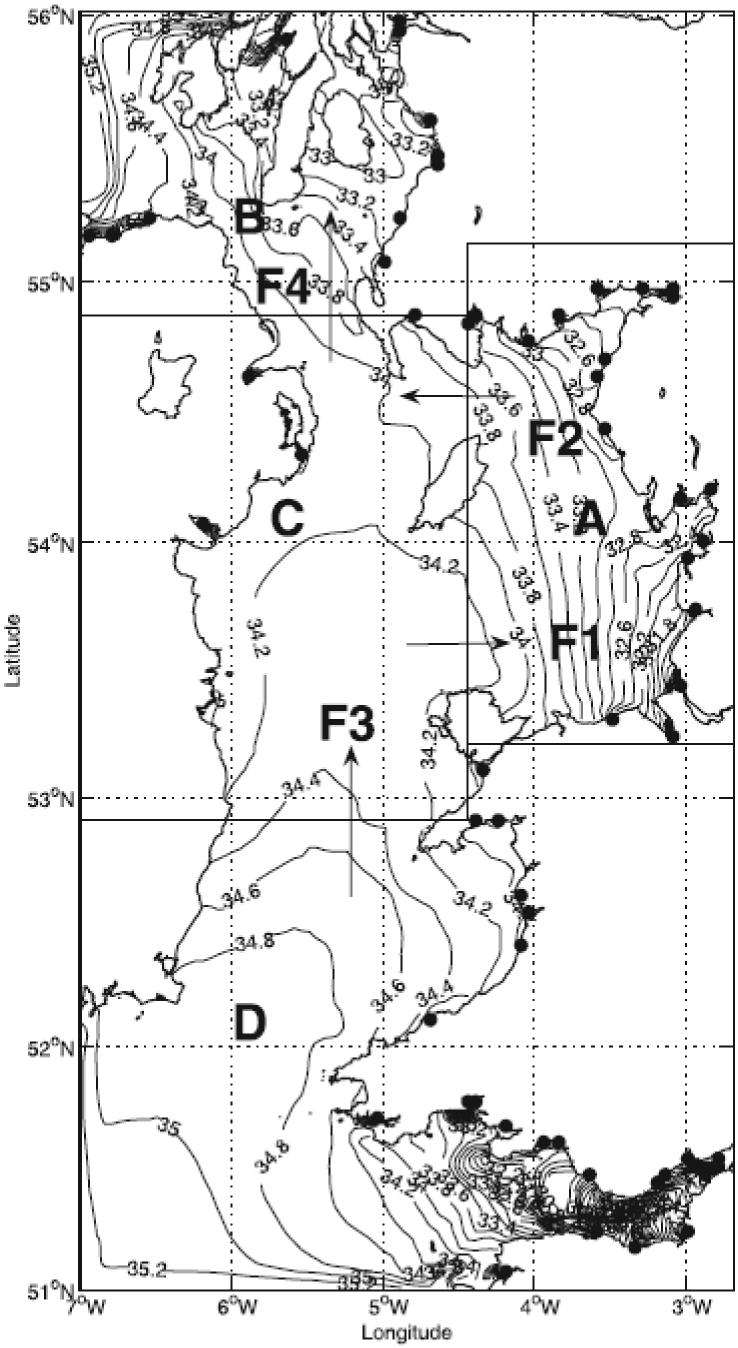
The long term temperature record shows a large degree of variability in the seasonal cycle, although a general increasing trend is apparent, indicating a rise of around 0.6ºC over the last 70-100 years, and particularly an increase in winter temperatures since 1990.

The annual mean salinity decreases from south (34.9‰) to north (34‰) and from the central channel of the Irish Sea (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 (Figure A1d.17). 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 Cleveleys Waverider buoy recorded wave heights of up to 4.7m during storms in 2014, with all storm waves originating from a westerly or northwesterly direction (Channel Coastal Observatory 2015).

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, with monthly averages in 2014 between 0.31m in September and 1.12m in February at the Morecambe Bay Waverider site (Channel Coastal Observatory 2015). 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 A1d.17: Salinity (‰) of the Irish Sea derived from ICES data for December – March 1960-2000



Source: Young & Holt (2007)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 Scottish Association for Marine Science (SAMS), which also records temperature and salinity. 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 Marine Scotland 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), the Blackstones Wavenet site (56º 03.72'N, 007º 0.41'W, 97m water depth) and the Atlas of UK marine renewable energy resources (ABPmer *et al.* 2008), supplemented by the relevant JNCC Coastal Directories (Barne *et al.* 1997a, b).

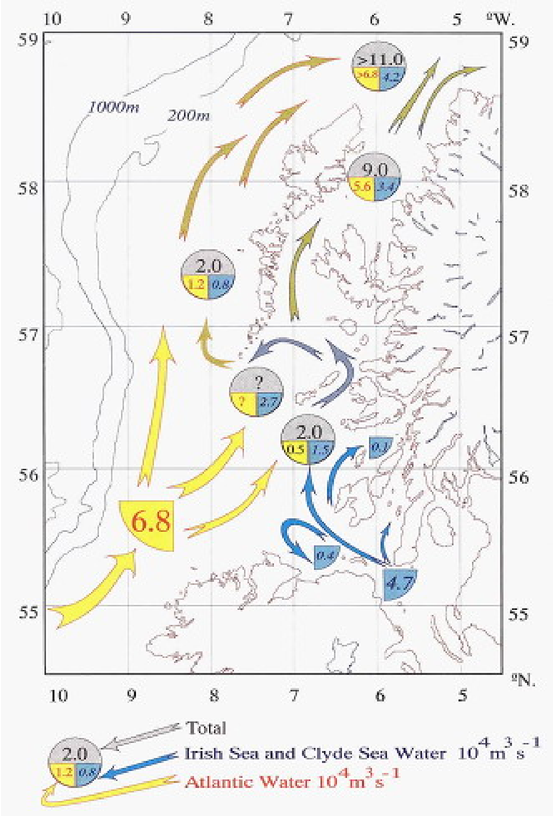
Water in Regional Sea 7 is derived from three sources: oceanic or Atlantic water, Clyde/Irish Sea water and coastal water derived from the land.

Overall circulation patterns (Figure A1d.18) 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. This has been corroborated by other studies, e.g. Craig (1959), Simpson and Hill (1986).

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 & 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 further, 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). A thermal front also forms in spring and summer south-west of Tiree (the Tiree Front), related to the boundary between the well mixed shallow shelf area and deeper water (Miller *et al.* 2015).

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 A1d.18). 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 A1d.18: 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.

A number of topographical depressions, including troughs, channels, valleys and canyons generally formed by glacial activity at lower sea levels are found within Regional Sea 7. In general these features have increased seasonal stratification, due to weaker tidal and residual currents, although in some cases sloping bathymetry or the generation of density driven currents may enhance internal mixing. An example is Muck deep, which has been shown to have an internal tide which intensified near-bottom currents and may contribute to density driven cross-shelf circulation (e.g. Ellet & Edwards 1983).

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 (Inall & Griffiths 2003). 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 A1d.10). 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 Blackstones waverider buoy, situated between Tiree and the north coast of Ireland, recorded peak significant wave heights of 13.5m over the period December 2014 to December 2015, with all waves >10m coming from a westerly to north west-west direction (Cefas website - https://www.cefas.co.uk/cefas-data-hub/wavenet/). 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.

A1d.8 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 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 ~0.2m/s 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 0.2m/s, 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 0.75m/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 0.4 to >0.75 m/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 7.5ºW where depths are uniform (Figure A1d.5). 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 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 coastline. 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 0.5ºC 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. Seasonal fronts have also been identified in the Fair Isle region between Orkney and Shetland, with the strong tidal currents in the region separating stratified and well mixed waters. Strength of seasonal stratification correlates with the variability in the fronts, with them being more prominent in spring and summer, although still evident for parts of autumn and winter (Miller *et al.* 2015). 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 A1d.10). Off these coasts significant wave heights exceed 3m for over 10% of the time and 1m for 75% of the time (Draper 1991). The West of Hebrides waverider buoy (57º17.53'N, 007º54.86'W, 100m water depth) shows peak significant wave heights of >15m over the period December 2014 to December 2015 (Cefas website). 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 indicated 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).

A1d.9 Features of Regional Sea 9

Since the pioneering Porcupine and Lightning studies of 1868-1870 (Murray 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 (part of Marine Scotland) 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 & Østerhus 2000).

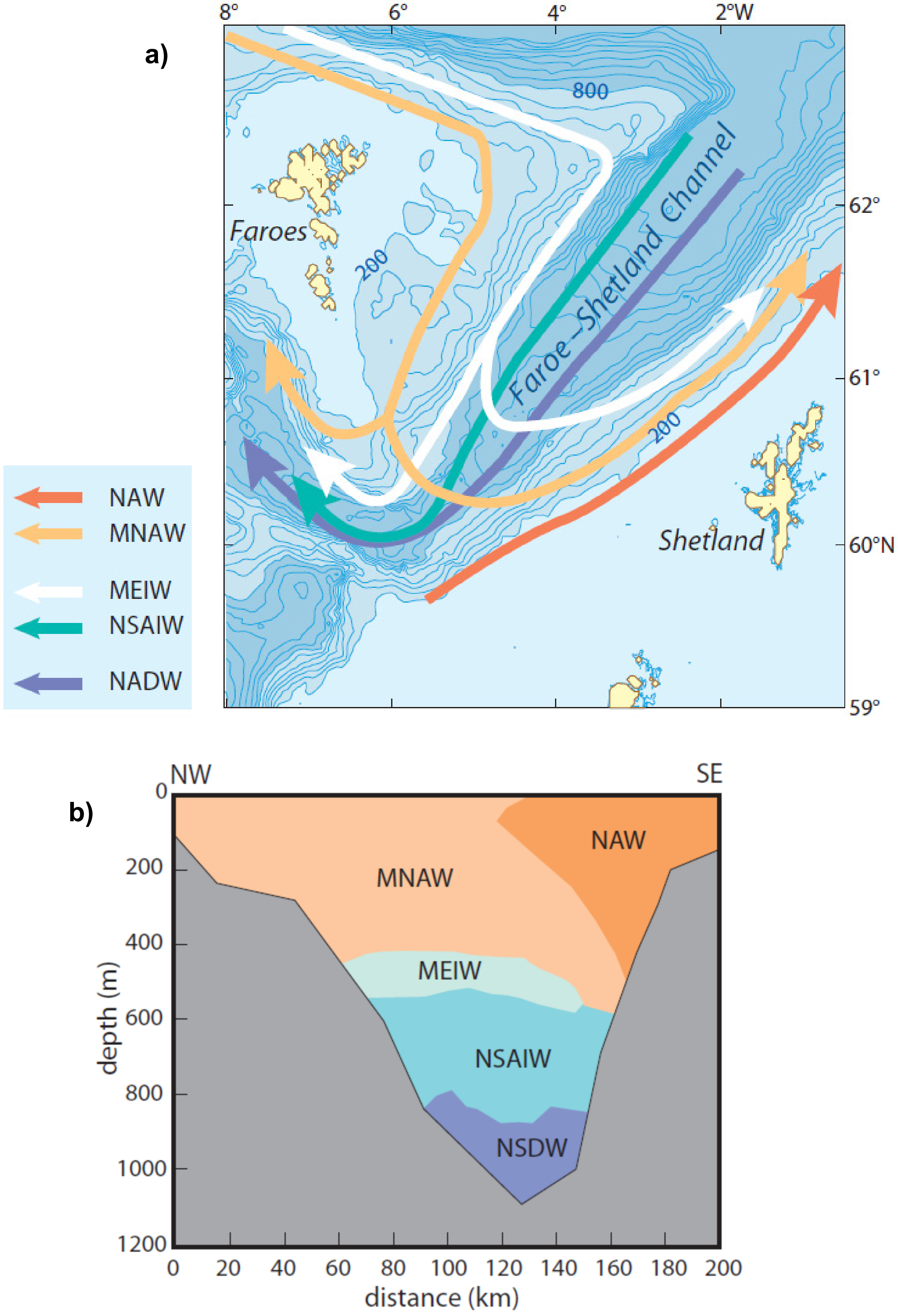
A series of research programmes and cruises, detailed in SEA 1 and added to by more recent studies including modelling and satellite imagery, have allowed for the study of the long-term monitoring of water exchange between the Atlantic and Nordic seas. Observations have been focused on two hydrographic sections across the Faroe-Shetland Channel: the Nolso-Flugga and Fair Isle-Munken sections (McKenna *et al.* 2016).

The Faroe-Shetland Channel is one of three main pathways of North Atlantic water into the Nordic Seas, where it cools to form North Atlantic Deep Water, a process which drives global Meridional Overturning Circulation. As a result through the channel poleward flowing Atlantic water flows above southward-flowing water from the Nordic Seas. A number of water masses (Figure A1d.19a and b), characterised by their salinity, temperature and nutrient 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 (e.g. Dooley & Meincke 1981, Hansen 1985, Saunders 1990, Turrell *et al.* 1999a, Souza *et al*. 2001, Hughes & Turrell 2004, McKenna *et al.* 2016).

The waters over the Wyville Thomson Ridge and in the upper 500m of the Faroe-Shetland Channel are derived from North Atlantic Water (NAW) 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) and contributes 2.7Sv (1SV = $1x10^6$ m^3/s) of warm, saline North Atlantic to the Nordic Seas (Berx *et al.* 2013), as opposed to 3.8Sv over the Iceland-Faroe Ridge and 0.8Sv through the Denmark Strait (Østerhus *et al* 2005). Research has, however, shown this volume flux to vary significantly on a seasonal and annual basis (Berx 2012).

The mean velocity of the shelf edge current in the area is approximately 0.40m/s towards the northeast, and in the lower water mass 0.15m/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 0.75m/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 0.4 to >0.75 m/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).

Figure A1d.19: Hydrography of the Faroe-Shetland Channel showing a) representation of the paths of the main water masses, b) schematic section across the channel showing generalised distribution of water masses.



Notes: NAW = North Atlantic Water; MNAW = Modified North Atlantic Water; MEIW = Modified East Icelandic Water; NSAIW = Norwegian Sea Intermediate Water; NSDW = Norwegian Sea Deep Water, a major component of NADW = North Atlantic Deep Water
Source: Berx (2012)

Temperature induced stratification only occurs in summer over the upper 200m on the west Shetland shelf (Hall *et al.* 2011). There is, however, permanent stratification at ~550-650m water depth along the west Shetland slope associated with the pycnocline separating overlying Atlantic and underlying Norwegian Sea waters. Internal waves form at this interface and result in incursions of cold water at the seabed, accompanied by relatively strong currents (seabed surges) (Grant *et al.* 1995). Studies have also shown the presence of a semidiurnal internal tide as well as non-linear internal waves (Hall *et al.* 2011), which all promote mixing between the different water masses.

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 south-west (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, Norwegian Sea Deep 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). The main pathway for this south-west trending transport through the channel is a fast, narrow current on the Shetland slope, whereas over the rest of the deep parts of the channel to the west topographically generated eddies force some of the water to recirculate within the channel. Most of this recirculated water is subject to lateral and diapycnal mixing before joining the slope current or flowing over the Wyville Tomson Ridge (Broadbridge & Toumi 2015). However 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 3ºC), 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 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.* 1996).

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).

A1d.10 Features of Regional Sea 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.

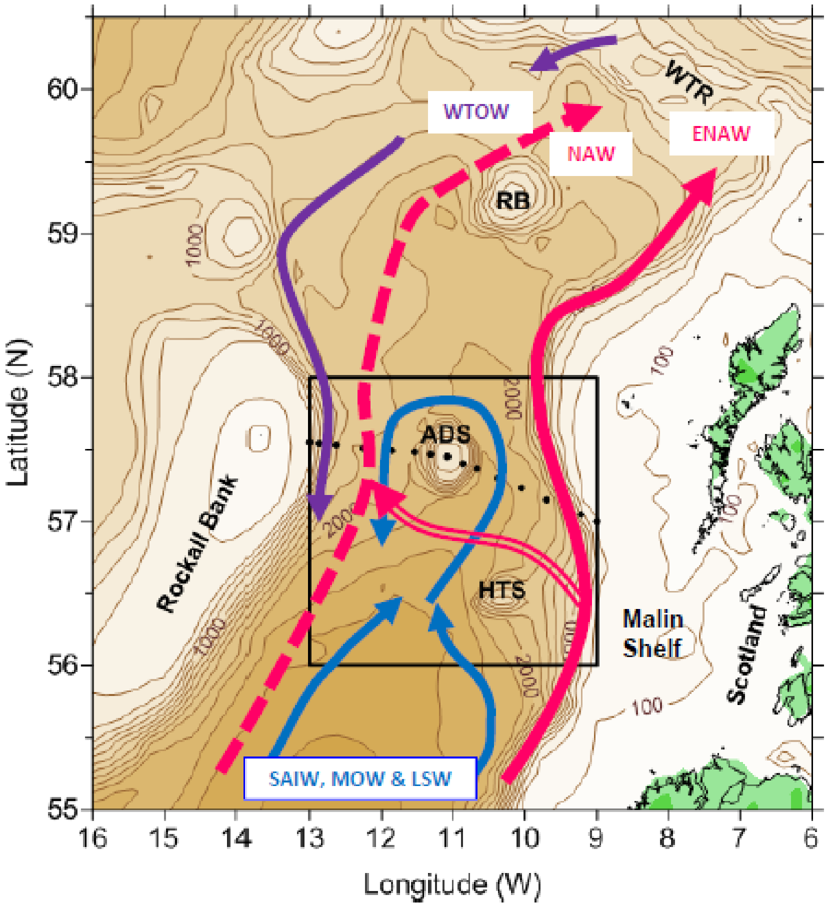
A poleward flowing Shelf Edge Current (SEC) is present along the continental margin and occupies the upper part of the slope, typically above 700m (see above). Near the southern boundary of Regional Sea 10 it makes an excursion across the slope and onto the shelf (Ellett *et al.* 1986, Souza *et al.* 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 0.2m/s, 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).

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 (Figure A1d.20), 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 ~0.02m/s, 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 (~0.05m/s), with additional eddies and large scale circulation cells in the order of 100km wide and 1,000m deep (Sherwin *et al.* 2015). In the north, Norwegian Sea Deep Water (NSDW) is known to flow episodically southwards over the Wyville–Thomson Ridge and into the Rockall Trough at a depth of 600-1,200m (e.g. Sherwin *et al.* 2008, Johnson *et al.* 2010). 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 (Figure A1d.20). 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 south-westward bottom flows are thought to occur primarily on the lower slopes of the Rockall Bank (New & Smythe-Wright 2001).

Figure A1d.20: Rockall Trough area showing bathymetry and major currents



Notes: WTR = Wyville Thomson Ridge, RB = Rosemary Bank, ADS = Anton Dohrn Seamount, HTS = Hebrides Terrace Seamount, WTOW = Wyville Thomson Overflow Water, NAW = North Atlantic Water, ENAW = East North Atlantic Water, SAIW = Sub-Arctic Intermediate Mater, MOW = Mediterranean Overflow Water, LSW = Labrador Sea Water.
Source: Sherwin et al. (2015)

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).

Seamounts have been shown to be areas of dynamic hydrography, including internal waves and seamount trapped waves, due to their interaction with ocean currents. 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 0.1-0.2m/s in the upper layers and, about 0.05m/s 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 was 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 0.25m/s.

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 (e.g. New 1988, Small *et al.* 1999). 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 0.5m/s). 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 0.02m/s. 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).

A1d.11 Evolution of the baseline

Climate change is likely to have a pervasive effect on all aspects of the coastal and marine environment including flooding, coastal erosion, water quality and resources. The Defra UK Climate Projections (UKCP09) considered marine and coastal environments in a dedicated report and detailed predictions for impacts of climate change, including some measures of uncertainty (Lowe *et al.* 2009). Subsequently the UK Marine Climate Change Impacts Partnership (MCCIP) was set up to provide a coordinating framework for marine climate change impacts in the UK. 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 & 2013) and supporting scientific evidence below.

A1d.11.1 Sea surface temperature

Charting Progress 2 indicated that sea-surface temperatures (SST) had risen by between 0.5 and 1°C from 1870 to 2007. Much of the warming occurred in the period 1920 to 1940 and again since the mid-1980s; warming since the mid-1980s has been more pronounced in the southern North Sea, Irish Sea and Tiree Passage (Figure A1d.21). However, between the years 2008-2012 the SSTs observed in most areas did not rise or were slightly lower than observed in 2003-2007. MCCIP corroborates these findings suggesting a 0.1-0.5°C temperature rise per decade from 1985-2012, with the greatest temperature rise in the eastern English Channel (Regional Sea 3) and southern North Sea (Regional Sea 2) (Figure A1d.21). It does however also highlight significant internal variability superimposed on the long-term trend in rising temperatures (Jenkins *et al.* 2009, Dye *et al*. 2013).

Temperature changes are recognised as a combination of global climate change and natural variability attributed largely to the Atlantic Multidecadal Oscillation (AMO) and variability in composition of water masses in UK waters; the decadal scale patterns observed in UK waters are similar to that of the AMO. As a result of both of these factors or drivers a significant period of rapid warming occurred from 1985 to 2003.

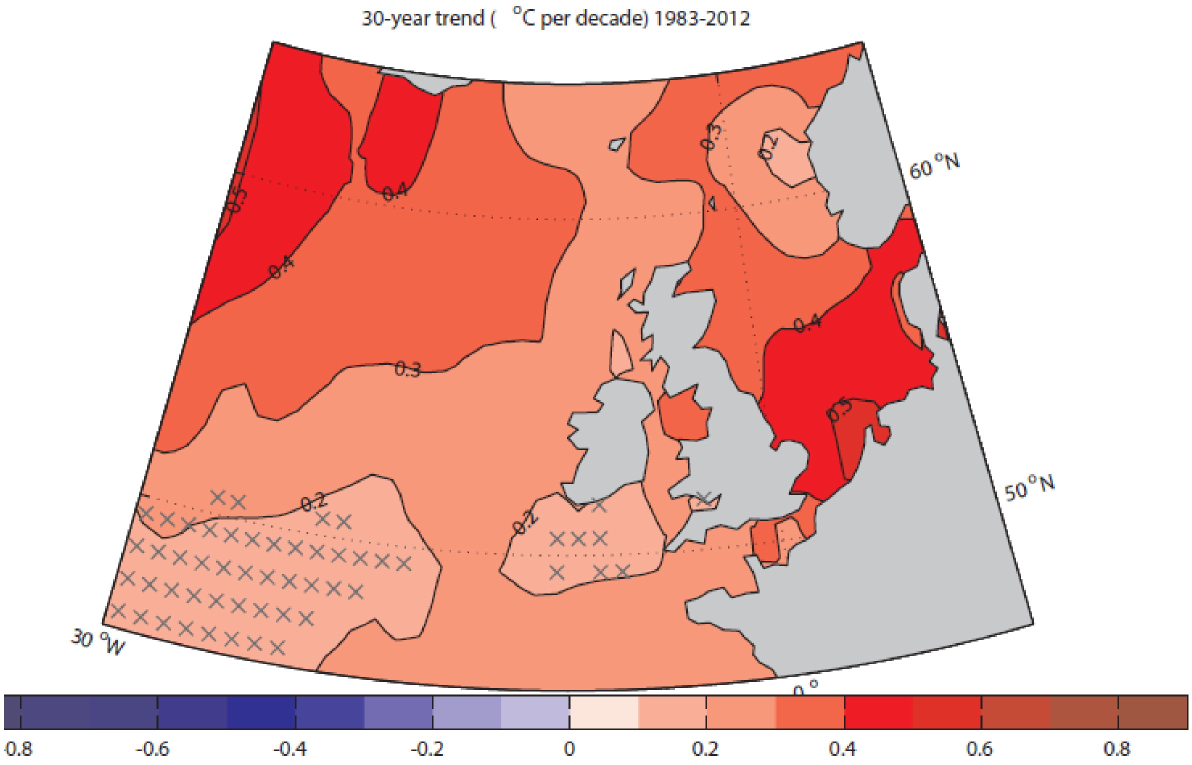
In the Rockall Trough (Regional Sea 10), average near surface sea temperatures (top 800m) have risen since the 1970's to a peak in 2006, with again significant year to year variability. These persistently warm conditions are similar to those found in all regions around the NE Atlantic (Defra 2010a), with the greatest warming in the upper 1,000m between 50-70ºN (Dye *et al.* 2013). Around the north of Scotland a slightly different pattern of progression to warmer temperatures occurred over the same time period, reflective of the changes of inflow and influence of subtropical and subpolar waters in the area.

Interannual variability can generally be attributed to local processes such as, changing position of fronts, passing of eddies, change in freshwater input from rivers, change in influence of different water masses and variations in heat exchange with the atmosphere (Dye *et al.* 2013).

In the most northern part of the North Sea the temperature is influenced by inflowing North Atlantic water and has seen a general warming since the mid-1980s. The influence of ocean currents on temperature is decreasingly evident in the shallower areas of the North Sea where most of the interannual variability in winter temperature can be explained by interaction between and with the local atmospheric conditions (Dye *et al.* 2013). Colder conditions in the last few years have brought lower SSTs than at their peak in around 2003 but remain above the long-term average.

In the southern North Sea, atmospheric forcing is the dominant influence and inter-annual variability can be large relative to multi-decadal trends. Observations of annual sea surface temperature anomalies at Southwold coastal station in Suffolk show a 1.5ºC rise from 1966-2006, with regular inter-annual changes of 0.5-1.5ºC (Cefas 2006). Overall temperatures were lower from 1970 to 1987 followed by a change to warmer conditions, generally higher than the 1981-2010 average. However, since 2009 conditions have been cooler and nearer to the long term average. North Sea winter bottom temperatures have also shown an overall rise since 1971 although temperatures in 2009, 2010 and 2011 were low as a result of the very cold conditions that occurred during these winters. Winter temperatures rose again in 2012 (Dye *et al.* 2013).In the eastern English Channel annual mean surface temperature measurements taken at Eastbourne have generally risen since the early 1980s. The years 2008-09 and 2011-12 were amongst the warmest in the record while cooler conditions in 2010 made this year close to the 1971-2000 average temperature. The western English Channel experienced average or below average temperatures in the early 1980s. This was replaced by warmer than average waters on resumption of sampling, with particularly warm conditions around 2007, more recent years have been close to but slightly higher than average.

Figure A1d.21: Trend in annual sea surface temperature from 1983-2012



Notes: Data are from HadISST1.1 data set. Hatched areas have a slope which is not significant at 95% confidence level.
Source: Dye et al (2013)

Sea temperatures in the Irish Sea are influenced by waters from the North Atlantic, but in this shallow coastal zone atmospheric processes are also important. Data from a sample station at Port Erin on the Isle of Man have displayed a rising trend in temperature, with warming at a rate of 0.08°C per decade over the whole time-series (1904 to present) and at a rate of 0.4°C per decade over the last 3 decades (Dye *et al.* 2013). Modelling and measured temperatures at the Cypris Station (south-west of Isle of Man) show summer sea surface temperatures in the Irish Sea to be warming at a rate of 0.01^{0}C per year (Young & Holt 2007).

Temperature readings from the west coast of Scotland show a cooling from 1981 to the mid-1980s followed by strong warming between 1986 and 1990, a minimum in the early 1990s and then generally warm conditions apparent between 2002 and 2008 (Inall *et al.* 2009).

Depending on the scenario global climate models predict an increase in SST of 0.6-2^{0}C by 2100 (IPCC 2013), with UKCP09 predicting 1.5-2.5^{o}C this century for UK waters (Lowe *et al*. 2009).

A1d.11.2 Stratification

In areas where stratification is controlled thermally, modelling work has suggested that the timing of peak stratification was delayed over the period of 1960-2000 (Young & Holt 2007). There have been no discernible trends identified in either the timing or distribution of stratification in areas influenced by freshwater inputs, as these are dominated by a combination of tidal mixing and cycles of freshwater input. Similarly there is no current evidence for any long-term trends in stratification strength in the north-western North Sea, despite significant short-term variability with a periodicity of 7-8 years (Sharples *et al.* 2013). However recent ICES data has shown that sea surface temperatures trends are increasing at a significantly greater rate than bottom water temperatures in the North Sea, so a corresponding increase in stratification can be expected, although not yet recorded.

Generally strong tidal forcing produces a well mixed water column in estuaries, although in some areas weak vertical stratification occurs (e.g. approaching slack water in the Conwy, North Wales – Howlett *et al.* 2015). Modelling of sea level rise and projected changes in riverine flow in the Conwy over the 21st Century showed a potential increase in the saline intrusion length, although the opposite was seen in other estuaries with increased river flows (Robins *et al.* 2016). A 1m sea level rise is modelled to increase the saline intrustion length by >7% in deep estuaries and >25% in estuaries shallower than 10m, with a change in river flow of 25% expected to have a significant effect on both the vertical mixing and salinity intrusion of estuaries (Prandle & Lane 2015).

A1d.11.3 North Atlantic circulation patterns

Variability in the Atlantic Meridional Ocean Circulation (MOC) was recorded at the RAPID/MOCHA mooring array at 26.5ºN (Florida to Morocco) between 2004 and 2014. The data shows a mean magnitude of 18±1.0 Sv (for 2004-2009), with large variability (4-35 Sv) in the first year of operation and a seasonal cycle of ~6.7 SV between a minimum in spring and a maximum in autumn partially driven by wind stress (McCarthy *et al*. 2012, Srokosz & Bryden 2015). Whilst the record shows a large 30% decrease in MOC strength over the period April 2009 to March 2010, it subsequently rebounded and because of this significant variability year to year, no long-term trend is detectable. Additional records from the North Atlantic over varying timescales indicate that the interannual variability in the MOC is ~5Sv, with no longer-term trends discernible, although the observational records are short (Rhein & Rintoul 2013). Despite substantial progress over recent years in understanding and modelling the AMOC, projections of its future fate are still subject to significant uncertainty (Smeed *et al.* 2013).

The inflow of Atlantic waters to the Nordic Seas through the Faroe-Shetland Channel over a 20 year time period (1992-2012) show no statistically significant long-term variability, suggesting stability of the inflow (Berx *et al.* 2013). This stability is also mirrored in the inflow to the Nordic Seas through the other two Atlantic regions (Denmark Strait and Iceland-Faroe Ridge: Hansen *et al.* 2010, Jónsson & Valdimarsson 2012), as well as the Faroe Bank Channel (Hansen & Østerhus 2007) and the Denmark Strait overflow (Jochumsen *et al*. 2012).

A1d.11.4 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. The link between the hydrography of the North Sea and the North Atlantic Oscillation (NAO) index has been well documented. Studies have shown an enhanced water mass exchange between the North Atlantic and the North Sea during periods of positive NAO (e.g. Reid *et al.* 1998, Winther & Johannessen 2006, Kühn *et al.* 2010). Positive NAO is also associated with higher precipitation across Scandinavia which increases run off from the Baltic Sea into the North Sea and is in addition to increased westerly winds which push North Sea water into the Baltic Sea (Salt *et al.* 2013). These patterns are generally reversed for periods of negative NAO.

Modelling work by van Leeuwen *et al.* (2015) for the period 1958-2008 suggests that 71% of the wider North Sea region can be classified into temporally and spatially stable hydrodynamic regimes, with 29% showing large interannual variability that cannot be classified into one regime over the time period. As with the North Atlantic this suggests a degree of stability within the longer-term patterns of hydrography, overlaying significant interannual variability.

A1d.11.5 Wave climate

Inter-annual variability in the modern wave climate in the UK is strongest in the winter and can be related to atmospheric modes of variability, most notably the North Atlantic Oscillation. Winter wave heights significantly correlate with the NAO index and other measures of the strength of the westerly winds in the west and Irish Sea (Regional Seas 4-6). This correlation is particularly strong in the north-west (Regional Seas 7-11). The characteristics of fluctuations in the westerly winds in the temperate northern hemisphere may also be described as an 'annular mode'[1], 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). 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.

There have 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. The offshore oil and gas industry has collected data on wave heights over the last 40 years. The data for the northern North Sea indicate that mean significant wave heights during the period January–March have risen between 1973-1995 by about 5-10% (0.2-0.3m), with a decrease thereafter. This general increase in wave height was also observed between 1960 and 1990 in the north east Atlantic and between 1966-1982 (0.02m/yr increase) at the Seven Stone Light Buoy off Lands End (Bacon & Carter 1991). However, there is no clear pattern in results since 1990 suggesting no significant long-term trend superimposed on significant interannual variability. New re-analysis of longer data sets have however suggested a general increase over the whole 20th Century, with the strongest increase between 1958-2001 (Woolf & Wolf 2013).

There is as yet no consensus on the future storm and wave climate, stemming from diverse projections of future storm track behaviour, but 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.

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[1] Annular modes are hemispheric scale patterns of climate variability caused by internal atmospheric dynamics in the middle latitudes. They are the most important patterns of climate variability in mid to high latitudes.

A1d.11.6 pH

Ocean acidification is closely linked with climate change, with increasing atmospheric CO_2 being a driving factor in both cases. The uptake of CO_2 by the global oceans is estimated to total ~25% of all anthropogenic CO_2 emissions (Le Quéré *et al.* 2009), with a corresponding reduction of surface pH by ~0.1 units from the pre-industrial values (Royal Society 2005). Ocean time series station and transects corroborate these changes, with an anthropogenically induced surface pH decrease of ~0.002 units per year since 1990 (Williamson *et al*. 2013). However, within the North Atlantic, this decrease has not been uniform, with ocean acidification occurring more rapidly in the European Region (both on-shelf and in deeper waters), than the central Atlantic or Caribbean (Schuster *et al.* 2009).

Although high resolution, decadal scale records of pH are not available for UK waters, Cefas, Marine Scotland and other partners have implemented a spatially comprehensive observation programme of pH related parameters. Recent surveys have added to that data and initial results suggest there is marked vertical and horizontal variability within UK waters, with significant seasonal and interannual variability superimposed on the longer term trends. Observations and modelling of near surface waters in UK/European shelf seas have suggested that CO_2 can vary by as much as 200-450ppm, a corresponding pH change of up to 1.0 units (typically 0.3-0.4 units) over an annual cycle (Blackford & Gilbert 2007, Artioli *et al*. 2012).

Ocean acidification is a global scale threat but impacts will be felt at the local and regional level. It is highly likely that UK coastal waters, ecosystems and habitats will be significantly impacted this century if global CO_2 emissions continue to rise.

A1d.11.7 Sea level

The 5th IPCC assessment report indicates a global sea level rise of 1.7 ±0.2mm yr^{-1} between 1901 and 2010 (Rhein *et al*. 2013), equating to a total rise of 0.19 ±0.2m. Tidal gauge records from around the UK show a rise of 1.4 ±0.5mm yr^{-1} (Horsburgh & Lowe 2013), broadly consistent with the global value. However, significant multi-decadal variability is seen in numerous long term tidal gauge records, with accelerations in global mean sea level rise seen in 1920-1950 and 1990-present and decelerations in 1910-1920 and 1955-1980 (Rhein *et al.* 2013). Despite this cyclic variation there is evidence for an increase in sea level rise from the 19th to 20th Century (Horsburgh & Lowe 2013).

Church *et al.* (2011) show that from 1972-2008 45% of the sea level rise measured by tidal gauges can be attributed to thermal expansion of the oceans, whilst 40% is due to the melting of ice caps and glaciers and the remainder from ice sheet and terrestrial water storage. Studies have also suggested that the melting of ice masses on Greenland and Antarctica is accelerating, contributing to increased global sea level rise (Rignot *et al*. 2011, Shepherd *et al*. 2012).

Extreme coastal water levels (e.g. storm surges) around the UK are caused by a combination of exceptionally high tides and severe weather events due to meteorological effects such as winds and changes in atmospheric pressure, alongside mean sea level increases. They can last from a couple of hours to multiple days and are very hard to predict. There is some evidence of an increase in extreme water levels around the UK (Menendez & Woodworth 2010, Haigh *et al.* 2010, Haigh *et al.* 2011), with a pronounced increase since 1970 coinciding with the acceleration in global mean sea level rise. A study at 16 sites around the English Channel suggests that the increase in extreme sea levels seen since 1900 is not statistically different from the observed mean sea level rise (Haigh *et al.* 2011). Whilst it is still unclear whether increased storminess or mean sea level increases is the primary driver behind an increase in extreme water levels, observational evidence suggests mean sea level (Menendez & Woodworth 2010, Horsburgh & Lowe 2013).

Global sea level projections of an up to 1.9m increase by 2100 have been published, although these are generally of low confidence (Robins *et al.* 2016). Projections for sea level rise for London over the interval 1990-2095 are in the range of 0.21-0.68m (Horsburgh & Lowe 2013), with suggestions that any future changes in extreme seal level will be primarily driven by mean sea level rise. Sea level rise is not expected to spatially consistent around the UK, due to the effect of isostatic adjustment which is expected to add 1.2mm/yr to sea level in SW England and reduce sea level by 2mm/yr in parts of Scotland (Robins *et al.* 2016). As a result coastal areas and estuaries in SE England are most at risk of a combination of land sinking and seas rising. Based on low, medium and high sea level rise projections (12, 40 and 81cm increase) Haigh *et al.* (2011) suggest an increase in 1 in 100 year extreme sea level frequency in the English Channel by a factor of 10, 100 and 1800 respectively. It has also been suggested that there is an increase in flood risk to UK estuaries through a change in sea level and riverine flow due to climate change, with a positive relationship between storm surge and peak river flows seen in some UK estuaries (Robins *et al.* 2016).

A significant portion of the UK coastline is susceptible to coastal flooding, both from high tides, storm surges, extreme waves, and in estuaries the interaction of tides with high river flows. The UK Coastal Monitoring and Forecasting (UKCMF) is a collaboration of public bodies including the Environment Agency (EA), Met Office, Cefas, British Oceanographic Centre and Flood Forecasting Centre providing coastal flood forecasts for England and Wales. SEPA provides the same service for the Scottish coastline. Joint Defra/EA work suggests that in the future river flows are likely to increase, causing additional flooding issues in estuaries where tidal / fluvial interaction is important (Donovan *et al.* 2013).

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