Introduction

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

In this OPEG Feeder Report, we assess the physical state of the UK’s seas and so provide a context for the clean, healthy, safe, productive and biologically diverse aspects in the other Feeder Reports.

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

Since *Charting Progress* we have made considerable progress in our ability to assess the state of ocean process variables. This Report builds on the findings of *Charting Progress*. Although the conclusions in this assessment generally reinforce those from 2005, recent awareness of ocean acidification, and concerns about the ability of our seas to continue to take up carbon dioxide (CO_2) from the atmosphere, means we have added this issue as an explicit topic.

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

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

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

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

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

Overall Assessment

We follow the summary table below with an overview of the respective ocean process variables, a summary for each *Charting Progress* region and an outlook for further work to improve assessments.

Summary of state of physical processes, main influencing factors and significance for UK seas. Major changes result mainly from the global consequences of increasing greenhouse gas emissions to the atmosphere.

Variables assessed	**State in UK atmosphere and Seas**	**Main influencing factors and significance for UK Seas**
Air temperature	**Rise in all regions** UK annual mean temperature has risen by approximately 1°C since the beginning of the 20th Century. 2006 was the warmest year in central England since records began in the seventeenth century.	**Influencing factors -** Global climate change resulting from anthropogenic greenhouse gas emissions.
Sea temperature	**Rise in all regions** Sea-surface temperature has risen by between 0.5 and 1 degree C from 1871 to 2000. Warming since the mid 1980s has been more pronounced in regions 2, 5 and 6 (southern North Sea, Irish and Hebridean seas)	**Influencing factors -** Air temperature **Significance** – Reduces the ability of the oceans to soak up carbon dioxide, forces certain species to adapt move or suffer, and contributes to rising sea level. Shifts in plankton populations on which most marine animals feed are associated with temperature rise.
Carbon dioxide and pH trend	**Acidification in all regions** Oceans are acidifying (pH decreasing) as carbon dioxide is absorbed. We have no baseline measurements of pH against which changes in UK waters can be judged, and it will be some time before we can make accurate judgements about the rate of acidification relative to natural annual and inter annual cycles of pH	**Influencing factors –** carbon dioxide which is present naturally and occurs from anthropogenic sources (e.g. combustion of fuel). Various climatic factors influence its concentration in the sea. **Significance** – There are potential threats to marine species and ecosystems if acidification continues.
Sea level	**Rise in all regions** Mean sea level around the UK coast rose by about 1.4mm per year during the 20th century	**Influencing factors -** Temperature (the larger effect hitherto) and melting ice (potentially more in future). **Significance** – Intertidal habitats and ground water regimes are affected, and the flooding risk for vulnerable coastal populations will increase, notably in region 2 (southern North Sea), if upward trends continue
Circulation, suspended particulate matter, turbidity, salinity and waves	**Variable** These processes vary on daily to inter-annual timescales but show no significant trend over the last decade, except for a slight salinity decrease in region 2 (southern North Sea) and a slight increase in salinity in the (northern) regions 1, 7 and 8.	**Influencing factors –** *Circulation* - tides and weather, especially winds. *Salinity* - rainfall near the surface and near river outflows; adjacent Atlantic salinity **Significance –** *Suspended particles* - can reduce light availability and inhibit plankton growth. *Waves* - the main cause of damage to offshore and coastal structures

1. Weather and climate

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

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

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

2. Marine temperature, salinity and circulation

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

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

Ferrybox system for continuous measurements as installed on the RV *Cefas Endeavour*

2.1. Temperature

Globally, sea surface temperatures rose by about 0.3 °C from around 1910 to 1940, remained steady until the 1970s and have risen since by about another 0.4 °C. Since the mid-1980s, Atlantic surface waters adjacent to the UK have warmed by between 0.5 and 1 °C, with a spatial and interannual-to-decadal variability of between 0.5 and 2 °C superimposed on this background trend.

In shallower UK shelf seas, mixing of water masses and especially local weather largely control the temperature, on timescales of a day (for 1 m water depth) to a few months (for 100 m water depth). There is also some influence from adjacent Atlantic water where it moves onto the shelf. The annual sea surface temperature, averaged around the UK coastline, has increased by about 0.5 to 1 °C for the period 1871 to 2007 (Figure 2.1). Much of the warming took place in the 1920s and 1930s and again since the mid-1980s; this later warming was especially pronounced in the Southern North Sea, Irish Sea and the Minches and western Scotland. Spatial and interannual temperature variability in UK waters is of the order of 0.5 °C; but can be up to 2 to 3 °C in shallow areas for an extreme month.

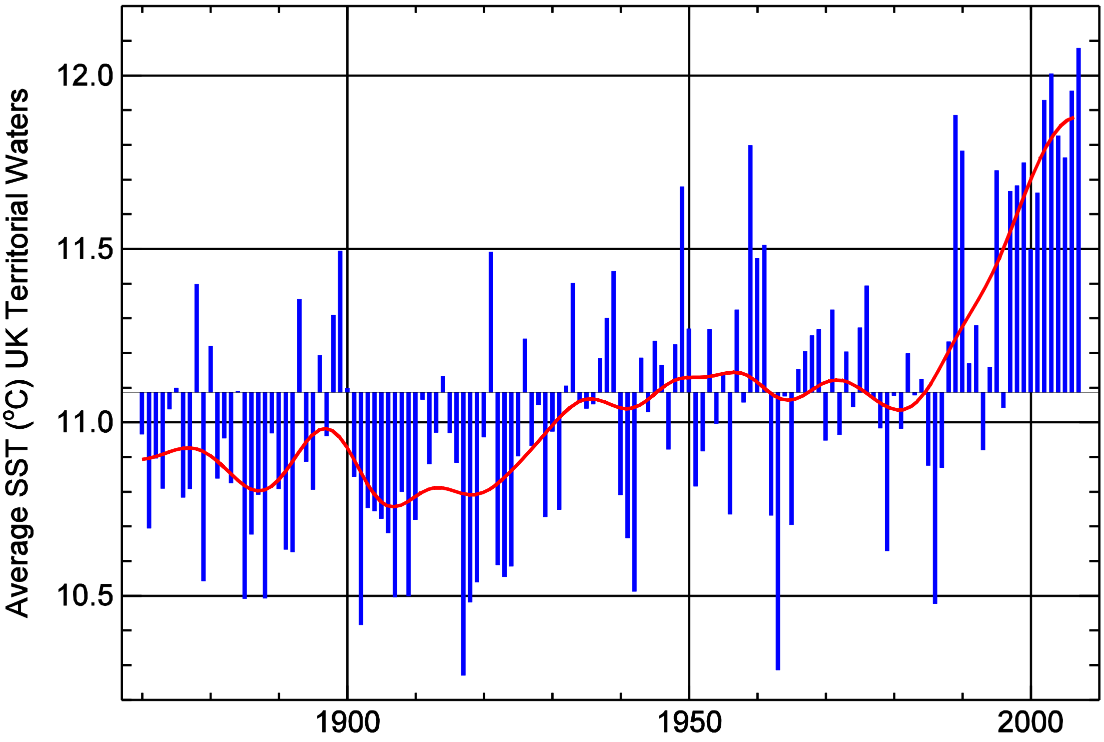


Figure 2.1. Annual average sea-surface temperature for UK Seas, 1870-2007, shown by tips of blue bars. The 1961-1990 average was about 11.09 degrees. The red line smoothes out fluctuations shorter than 5-10 years to clarify the longer-term trend. Courtesy of Met Office.

2.2. Salinity

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

2.3. Circulation

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

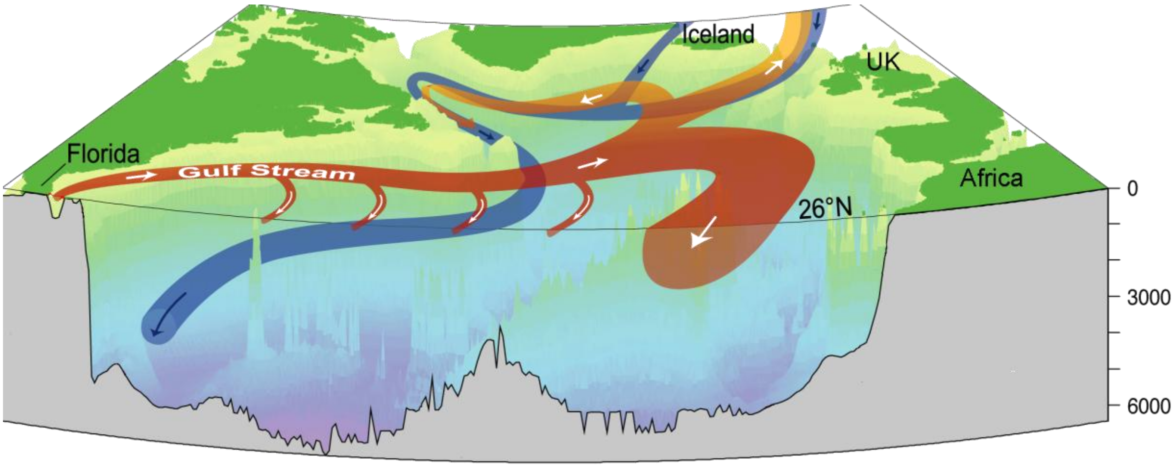


Figure 2.2. Schematic of the North Atlantic ocean circulation showing the northwards transport of relatively warm surface water (red) and the southwards return of cooler, subsurface water (blue). The Gulf Stream is a component to the overall circulation. Note the partial recirculation of northward-flowing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

We have assessed the long-term circulation in the adjacent North Atlantic using tracks of drifters and Argo floats, and in shallower UK waters using distributions of tracers, drifter tracks or numerical hydrodynamic models. We have also used data from current-meter measurements in a few long-term mooring arrays and from submarine cables. For components with timescales longer than a day, we inferred circulation from ship-based temperature and salinity measurements. High Frequency radar gives spatial coverage for surface currents, although the range is limited to the order of 50 to 100 km. A recent development is the NERC-funded RAPID programme which maintains an array of moored sensors to study the sub-surface temperature and salinity distribution, and hence monitor transport of the AMOC, across a section of the Atlantic Ocean at 26° N where the AMOC is strongest.

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

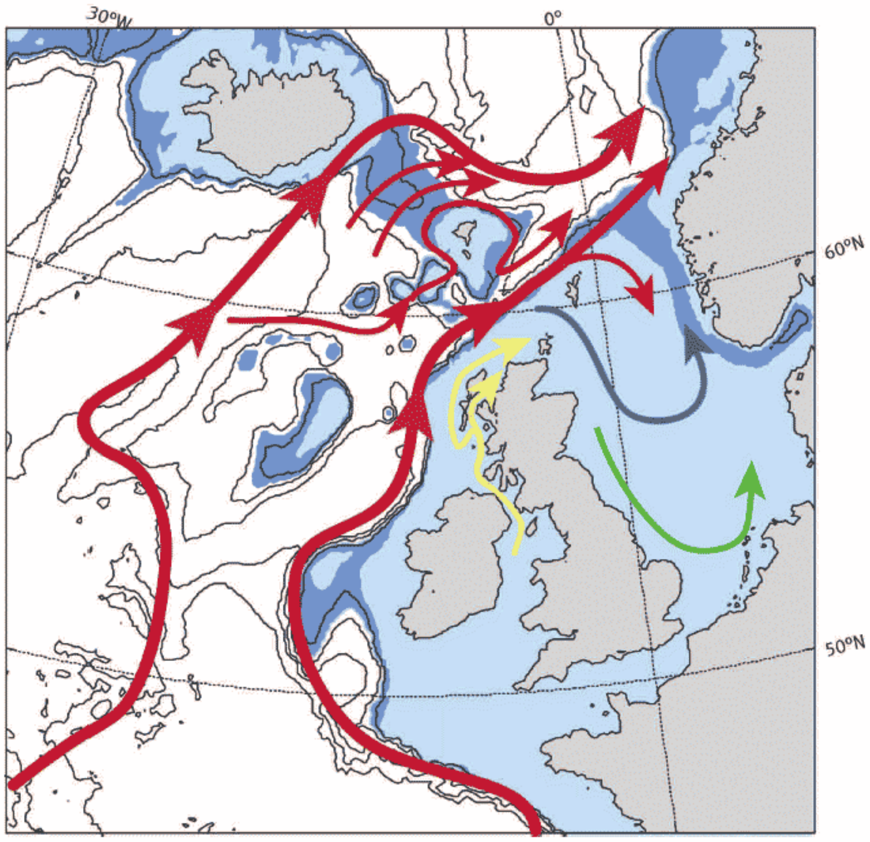


Figure 2.3. Map shows the circulation of surface waters. Red arrows are the flow of warm, salty Atlantic waters along the continental slope and further west. Yellow, blue and green arrows show the flow of coastal waters. Yellow arrow shows the path of the Scottish Coastal Current. Blue arrow shows the inflow of mixed coastal/oceanic water past Fair Isle (the Fair Isle Current). Courtesy of S. Hughes, Marine Scotland.

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

3. Carbon dioxide and acidification

The oceans play an important role in reducing the contribution of CO_2 to climate change, by soaking up more CO_2 than they release, which substantially reduces the rate of increase in the atmosphere. However it also makes the oceans more acidic and potentially reduces their capacity to take up CO_2 in the future. Continental shelf seas play a key role in this global CO_2 uptake. Changing the pH of seawater alters the balance of and rate of conversion between different nitrogen compounds, changing their availability to support the growth of phytoplankton and hence eutrophication. Biogeochemical and ecosystem processes affected include planktonic calcification, carbon and nutrient assimilation, primary production and physiology; many marine animals have planktonic larval stages that are likewise vulnerable. Organisms such as bivalves and tube worms may have difficulty forming shells in lower-pH waters. Changes in pH also affect the availability of trace metals, which may be necessary for plankton growth, or may in some cases be toxic. We assessed the state of CO_2 uptake and acidification in UK waters using models of the sea, inverse modelling of atmospheric concentrations and validation with evidence from direct measurements.

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

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

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

4. Sea level

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

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

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

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

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

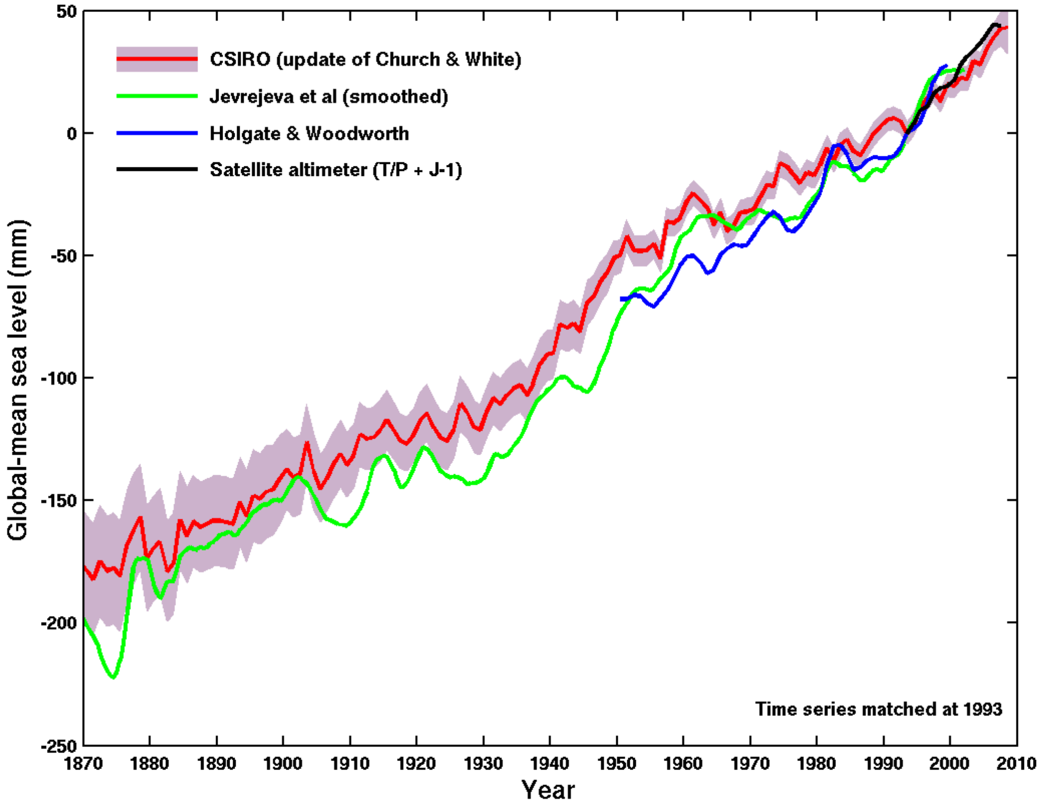


Figure 4. The red, green and blue curves show global sea level estimated by different ways of averaging coastal tide gauge data (all held by the PSMSL). The grey envelope shows the estimated uncertainties (of the red curve). The black line shows quasi-global sea level measurements from the TOPEX/Poseidon and Jason-1 altimeters which are independent of the tide gauge data.

5. Waves, suspended particles and turbidity

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

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

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

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

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

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

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

6. Sedimentary processes and morphology

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

In areas of relatively rapid coastal erosion, rates of change are being monitored. Offshore, there are several means of mapping the seabed. Multibeam Echosounder Systems (MBES; Figure 6) provide a new approach, and MBES data collection programmes have expanded dramatically since Charting

Progress (ref). We now have new measurements from all CP2 Regions using MBES, although as of 2008 MBES data cover only about 15% of the UK seabed.

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

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

To underpin future marine spatial planning and to support commercial exploitation and legislative drivers such as environmental monitoring and conservation, we now need more high-quality bathymetric data and to match this with analysis of the geology and habitats, so forming coherent maps and models. We should optimise use of the several existing UK programmes that collect MBES data for a wide range of different uses (unlike Ireland, for example, which has a single integrated marine mapping programme). Better integration of Government-funded surveys is being achieved through (1) the Civil Hydrography Annual Seminar (CHAS) meetings organised by the Maritime and Coastguard Agency (MCA), (2) a Memorandum of Understanding between several public sector organisations to share data, (3) several initiatives to collaborate in the collection and interpretation of data (e.g. Channel Coastal Observatory and MCA; NERC research centres and others). Adding in commercial data, and further collaboration between programmes building on the Civil Hydrography Programme, would help in developing marine renewable energy and meeting the challenges of the EU Marine Strategy Framework Directive (2008/56/EC).

Erosion at Hunstanton Cliffs (left) and erosion defences at Brancaster (right). Both photos supplied by Environment Agency

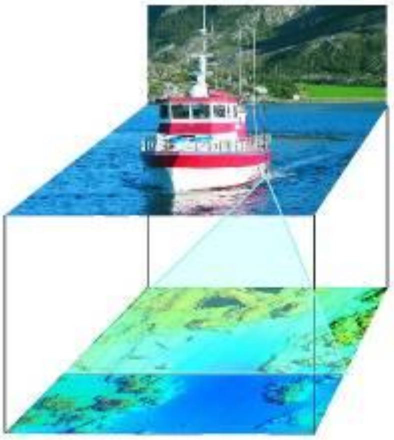
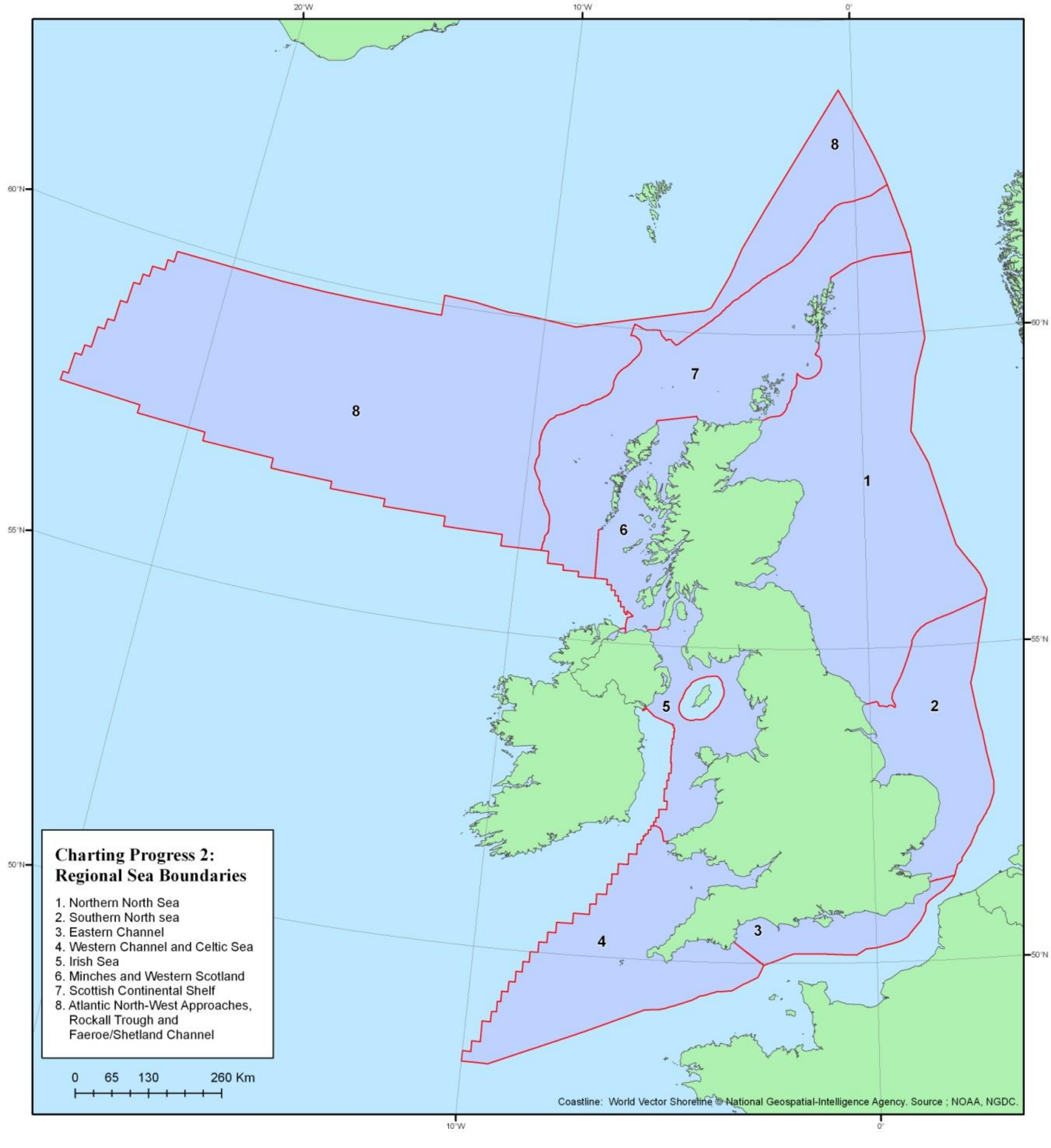


Figure 6. Schematic demonstrating the principles of MBES collection. Figure provided by the Geological Survey of Norway (NGU)



Coastline: World Vector Shoreline © National Geospatial-Intelligence Agency. Source ; NOAA, NGDC.

7. Regional seas statements

7.1 Northern North Sea (Region 1)

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

7.2 Southern North Sea (Region 2)

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

7.3 Eastern Channel (Region 3)

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

7.4 Western Channel and Celtic Sea (Region 4)

Depths here are mostly between 50 and 150 m (shallower near coasts); they increase rapidly at the edge of the continental shelf to more than 4000 m (just beyond the edge of the region). The shelf is very wide, with very high tides and hence strong tidal currents. [The Avonmouth mean spring tidal range 12.3 m is only exceeded globally in the Bay of Fundy (eastern Canada) and Umgava Bay (north Labrador, Canada)]. However, the net inflow of Atlantic water is weak relative to the large area of the Celtic Sea. There are sharp boundaries ("fronts") between summer-stratified waters (in the outer Celtic Sea) and mixed waters: the fronts are across the western Channel (Brittany to south Devon), Bristol Channel (north Cornwall to Pembrokeshire) and St George's Channel into the Irish Sea. Sea temperatures are strongly related to the weather in any one year and to water depth (shallow waters have a wider range because heat is lost or gained by less water). The climate being strongly maritime, typical winter minima are 8°-11°C and summer maxima 14°-18°C (but 11°-16°C below summer stratification; the maximum here is reached typically in October when the heat of surface waters is fully mixed down). Temperatures are rising. Salinities are typically greater than 34.5 (the adjacent Atlantic value is about 35.5) except in the Bristol Channel and where river outflows reduce salinity locally. There is a tendency for eastward flow through the English Channel (tending to be nearer the south side) and for weak anti-clockwise circulation around the eastern and northern Celtic Sea from off Brittany to south of Ireland. Sea level is rising at rates typical or faster than for the UK as a whole. The near-resonance that gives high tides in the Bristol Channel also makes this area susceptible to wind-forced surges and occasional flooding of low-lying areas (e.g. north Somerset). The region is very exposed to the Atlantic in the west, resulting in large average wave heights. Turbidity is high in the Bristol Channel (helped by tidal currents up to 2 m/s) but moderate in deeper waters.

7.5 Irish Sea (Region 5)

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

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

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

7.8 Atlantic North-West Approaches, Rockall Bank and Trough, Faroe-Shetland Channel (Region 8)
This region differs from Regions 1-7 in having no coastline (except Rockall). Depths range from 200 m at the edge of the continental shelf (less over Rockall Bank) to about 3000 m in the Iceland Basin west of Rockall. Region 8 is fully exposed to Atlantic influence: weather (strong westerly winds prevail), waves (the highest around the UK) and water. There is overall passage of Atlantic water northwards through Rockall Trough, with much variability; eddies have been found over seamounts and there can be clockwise circulation over Rockall Bank. A poleward current along the upper continental slope in eastern Rockall Trough is augmented along the west Shetland slope (Faroe-Shetland Channel) by some re-directed water from Rockall Trough and by recirculating Atlantic water that circuited the Faroes clockwise. There is summer stratification except locally over the shallowest part of Rockall Bank. Surface (0-50 m) temperatures in Region 8 typically have a winter minimum

9°-10°C (but as low as 6°C on Rockall Bank) and summer maximum 12°-14°C; at depths 200-500 m temperatures 9°-10°C prevail for most of the year. Typical temperatures at 2000 m are 3°-4°C; however, Norwegian Sea and Faroe-Shetland Channel bottom waters are below 0°C, even at 1000 m. Temperatures are rising but also vary with the origin of waters arriving in the region, as does salinity. Upper-level salinity is 35.3-35.4 in Rockall Trough and decreases slowly to the north-east (still exceeding 35.3 on the West Shetland slope); salinity decreases downwards to about 34.9 at 1000 m in the Faroe-Shetland Channel (in Rockall Trough, minimum salinity is deeper). Sea-level rise is not relevant in the absence of any significant coastline. Waves have impact primarily at the surface and not on the sea bed (only a relatively small area is less than 100 m deep); turbidity is low.

8. Further work

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

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

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

Abbreviations

ADCP	Acoustic Doppler Current Profiler
AFBINI	Agri-Food and Biosciences Institute, Northern Ireland
ALSF	Aggregate Levy Sustainability Fund
AMOC	Atlantic Meridional Overturning Circulation
AR4	IPCC Fourth Assessment Report (2007)
AUV	Autonomous underwater vehicle
BCP	Biological carbon pump
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
CANOBA	Carbon and Nutrient Cycling in the North Sea and the Baltic Sea
CASIX	Centre for observation of Air-Sea Interactions and fluxes
CAVASSOO	Carbon Variability Studies by Ships of Opportunity
CCO	Channel Coastal Observatory
CCW	Countryside Council for Wales
CDOM	Coloured dissolved organic matter
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CET	Central England Temperature
CHAS	Civil Hydrography Annual Seminar
CO_2	Carbon dioxide
COSH	Committee on Shipping Hydrography
CP2	Charting Progress 2 (2010)
DAC	Data Archive Centre
DECC	Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DIC	Dissolved inorganic carbon
DJFM	December to March
EA	*Environment Agency*
EEZ	Exclusive economic zone
ENSO	El Niño – Southern Oscillation
EPOCA	European Project on Ocean Acidification
ERSEM	European Regional Seas Ecosystem Model
EU	European Union
FLY	Free-falling Light Yo-yo (profiler for microstructure)
FOAM	Forecasting Ocean Atmosphere Model (Met Office)
GCOS	Global Climate Observing System
GHG	Greenhouse gas
GLOSS	Global Sea Level Observing System
GOOS	Global Ocean Observing System
GPS	Global Positioning System
HERMES	Hotspot Ecosystem Research on the Margins of European Seas
HF	High Frequency (radar)
H_S	Significant wave height ~ average peak-trough height of highest third of waves
ICES	International Council for the Exploration of the Sea
ICOS	Integrated Carbon Observation System
ICZM	Integrated coastal zone management
IOCCP	International Ocean Carbon Coordination Project
IoMGL	Isle of Man Government Laboratory
IOPs	Inherent optical properties

IPCC	Intergovernmental Panel on Climate Change
JIBS	Joint Irish Bathymetric Survey
JNCC	Joint Nature Conservation Committee
LIDAR	LIght Detection And Ranging
LISST	Laser In-Situ Scattering and Transmissometery
LOIS	NERC Land-Ocean Interaction Study
LSSW	Low-salinity surface waters
LV	Light Vessel
M_2	Tidal constituent, two tides per lunar day
MAREMAP	Marine Environmental Mapping Programme
MAWS	Marine Automatic Weather Stations
MBA	Marine Biological Association
MBES	Multibeam echosounder system
MCA	Maritime and Coastguard Agency
MEDIN	Marine Environmental Data and Information Network
MESH	Mapping European Seabed Habitats
MLWS	Mean Low Water Springs
MSL	Mean sea level
MSS	Mineral suspended matter
NAO	North Atlantic Oscillation
NCC	Norwegian Coastal Current
NCOF	National Centre for Ocean Forecasting
NE	Natural England
NEODAAS	NERC Earth Observation Data Acquisition and Analysis Service
NERC	Natural Environment Research Council
NGU	Geological Survey of Norway
NIEA	Northern Ireland Environment Agency
NIOZ	Netherlands Institute for study of the Sea
NMW	National Museum of Wales
NOC	National Oceanography Centre
OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis
OWS	Ocean Weather Ship
pCO_2	Partial pressure (in sea) of CO_2
PFT	Plankton functional type
PML	Plymouth Marine Laboratory
POLCOMS	POL (now NOC, q.v.) Coastal Ocean Modelling System
PSMSL	Permanent Service for Mean Sea Level
RACE	Risk Analysis of Coastal Erosion
RAPID	NERC Rapid Climate Change programme name
RIKZ	Dutch National Institute for Coastal and Marine Management
RIZA	Dutch Institute for Inland Water Management and Waste Water treatment
RLR	Revised Local Reference
RMS	Root mean square
ROV	Remotely operated vehicles
S_2	Tidal constituent, two tides per solar day
SAC	Special Area of Conservation
SAMS	Scottish Association for Marine Science
SCC	Scottish Coastal Current
SEA	Strategic Environmental Assessment
SEPA	Scottish Environment Protection Agency

SLP	Sea-level pressure
SMP	Shoreline Management Plan
SNH	Scottish Natural Heritage
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
SNS2	Southern North Sea Sediment Transport Study Phase 2
SOLAS	Safety of life at sea
SOO	Ship of opportunity
SPA	Special Protection Area
SPM	Suspended Particulate Matter
SSC	Suspended sediment concentration
SSSI	Site of Special Scientific Interest
SST	Sea surface temperature
TA	Total Alkalinity
TAR	IPCC Third Assessment Report (2001)
TOBI	Towed Ocean Bottom Instrument
Tp, Tz	Wave periods: peak of spectrum, average of zero-upcross interval respectively
UEA	University of East Anglia
UHI	University of the Highlands and Islands
UKCIP	UK Climate Impacts Programme
UKCP09	UK Climate Projections 2009
UKDMOS	United Kingdom Directory of the Marine-observing Systems
UKHO	United Kingdom Hydrographic Office
UKMMAS	UK Marine Monitoring and Assessment Strategy
UNCLOS	UN Convention on the Law of the Sea
VOS	Voluntary Observing Ships
WMO	World Meteorological Organisation

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