Chapter 2. Ocean Processes

2.1. 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 [ref: HBDhabitats] and offshore operations [ref: Prod]; acidification affects plankton physiology, especially calcification [ref: HBDplankton]; sedimentary processes affect the distribution of hazardous material [ref: CSSEG]. 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 chapter, based on the OPEG Feeder Report, we assess the physical state of the UK's seas to lay out the framework for the chapters to follow. This chapter bears a strong relationship with Chapter 6 which looks at the impacts of climate change and makes projections about how the ocean process variables might change over time.

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 chapter 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. Note that Chapter 8 will describe our projections of the future state of the physical environment, based on models of likely changes in climate.

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.

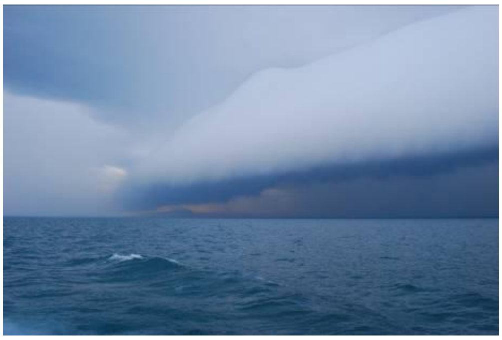
Our confidence in the estimated state and variability or trends is generally high [ref: end-chapter chart]. We found representative data on appropriate scales for all variables except where affected locally by shoals, proximity to land or river outflows. Morphology, rainfall, salinity and circulation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

2.2. 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.



2.3. 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*

2.3.1. 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.

2.3.2. 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.

2.3.3. 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.

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.

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

2.4. 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.

2.5. 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 2.4); the few long European records suggest this rate of rise was slightly faster than in the 19th century. The rate of rise around the UK coast, adjusted for land movements, was slightly less at about 1.4 mm per year during the 20th century. However the rise was not steady. For example, in the 1990s sea level rose by 3 to 4 mm per year.

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

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

2.6. 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.

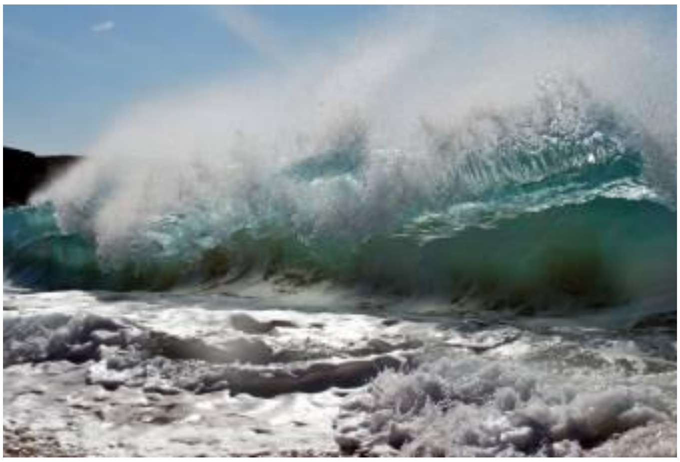
For waves, this assessment uses data from satellite altimetry, wave sensors on moored buoys and lightships, offshore and many nearshore sites. We have also used modelling for wave prediction, forecasts and state estimation, which is well-developed.

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*.



2.7. Sedimentary processes and morphology

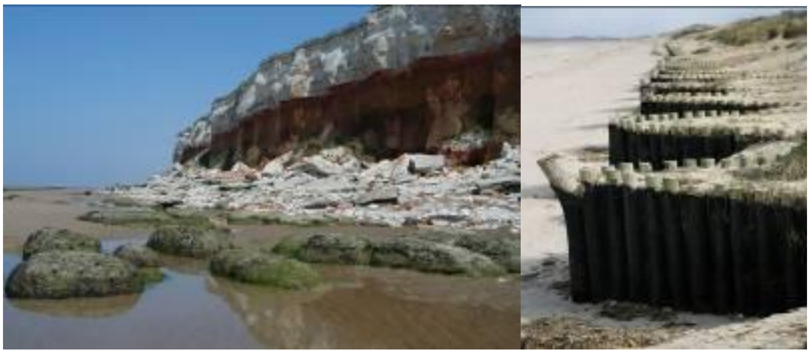
The morphology and sedimentary processes of the seabed play a critical role in the distribution of benthic habitats, which form an integral part of much of ocean life [ref: HBDhabitats]. For this assessment we have brought together data from many sources, including research programmes and commercial 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 2.5) 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

2.8. Further work

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

Better prediction of short-term variability in circulation will require both model validation and the development of new observational networks. For currents, temperature and salinity, model experiments could help design measurement arrays: i.e. the density, frequency and allowable timedelay 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.

Ocean Processes – Assessment summary

Trend in Variable assessed	Status in UK atmosphere and seas	Influencing factors and significance for UK seas
Air temperature Upward trend	**Rising in all CP2 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 17th century	**Influencing factors** Global climate change resulting from anthropogenic greenhouse gas emissions **Significance** Raises sea temperature
Sea temperature Upward trend	**Rising in all CP2 Regions** Sea-surface temperature has risen by between 0.5 and 1 °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 CO_2, 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
Sea level Upward trend	**Rising in all CP2 Regions** Mean sea level around the UK coast rose by about 1.4 mm per year during the 20th century	**Influencing factors** Temperature (the greater effect to date) and melting land-based ice (potentially more important in future) **Significance** Intertidal habitats and groundwater regimes are affected, and the flooding risk for vulnerable coastal populations will increase, notably in Region 2 (southern North Sea), if upward trends continue
Carbon dioxide and ocean acidification Upward trend	**Acidification in all CP2 Regions** Oceans are acidifying (pH decreasing) as CO_2 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 interannual cycles of pH	**Influencing factors** CO_2 which is present naturally and released from anthropogenic sources (e.g. combustion of fossil fuel). Various climatic factors influence its concentration in the sea **Significance** There are potential threats to marine species and ecosystems if acidification continues
Circulation, suspended particulate matter, turbidity salinity and waves No significant trend	**Variable** These processes vary on daily to interannual timescales but show no significant trend over the past decade, except for a slight salinity decrease in Region 2 (southern North Sea) and a slight increase in salinity in the (northern) Regions 1, 7 and 8	**Influencing factors** *Circulation:* tides and weather, especially winds. *Salinity:* rainfall near the surface and near river outflows; adjacent Atlantic salinity **Significance** *Suspended particles:* can reduce light availability and inhibit plant growth *Waves:* the main cause of damage to offshore and coastal structures