National Oceanography Centre

Coastal and Shelf Sea Research Strategy

Global challenges in coastal and shelf sea science

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with contributions from multiple co-authors across DST

The NOC endeavours to undertake internationally excellent research and technology development to advance the frontiers of knowledge about the ocean. In this document we identify research challenges and priorities within global coastal and shelf seas. These are the challenges that the NOC is motivated and well placed to tackle, in collaboration with our national and international partners.

This is intended as a living document, to be periodically reviewed and updated in order that it always reflects the most timely and important coastal and shelf sea research questions. It aims to guide where expertise across the science and technology research groups at the NOC can most effectively collaborate, and to stimulate new working relationships, both internal and external.

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Summary

Knowledge gaps in our understanding of the present-day status and functioning of the coastal zone and shelf seas need to be closed

There are significant uncertainties and gaps in our understanding of the physical, chemical and biological processes, their complex interactions, exchanges and time scales of variability in coastal and shelf seas. These gaps must be closed in order to fully understand and quantify the global climate and ecosystem services that the coastal zone and continental shelf provide, to make more reliable predictions of both natural and anthropogenically forced change and to assess the impacts of direct human activity and natural hazards.

The pathways, transformations and storage of freshwater, organic matter, nutrients and sediments within the land-ocean transition zone are poorly understood, yet are fundamental to the functioning of the whole Earth system

Coastal zones and ecosystems are of significant climatic, economic and societal value. The fate and processing of freshwater and its dissolved, particulate and pollutant loads - both natural and anthropogenic - entering the coastal zone and the two-way processes that buffer interaction between the land, estuaries and coastal waters are inadequately understood.

The direct impact of human activity is felt acutely within the coastal zone, yet the scale, longevity and knock-on consequences of these impacts is typically unknown

Human activity directly modifies the natural coastal ocean environment through resource extraction (energy, food, materials), transport, coastal management and climate mitigation schemes, land-use change or the introduction and dispersal of pollutants. The rapid expansion of human populations is accelerating these pressures. Understanding the scale, longevity and remote knock-on consequences of the impacts, whether positive or negative, is of first order importance.

The response of shelf seas and the coastal zone to a changing climate must be elucidated at local, regional and global scales and natural internal variability disentangled from direct human driven change

The present-day balance of physical and biogeochemical processes that determine the status and functioning of the global coastal ocean is being modified by climate change. An understanding of how, where and the speeds at which trends and modified patterns of variability will manifest themselves and how life and biogeochemical cycles will respond and adapt is critical. The consequences of change must be understood at local, regional and global scales and the natural, climatic drivers disentangled from those resulting from direct human activity.

The increasingly frequent risks posed by multiple coastal hazards and extreme events need to be more accurately predicted and the natural resilience and adaptability of the coastal zone better understood

Sea level rise, flooding, wave over-topping, storm surges and tsunamis, turbidity currents, harmful algal blooms and saline intrusion all pose significant and increasingly frequent risks to human life, natural resources, infrastructure and the economy. Conversely, coastal habitats provide natural defences against extreme events. Improving predictions, quantifying uncertainty and understanding coastal and habitat responses to multiple hazards and joint extreme events is therefore essential.

Advances in understanding of the coastal ocean must be coupled with solution focused research in a way that benefits all facets of society and marine policy

Marine assessment, policy and governance in coastal and shelf waters is disjointed across local to international scales, which does not reflect the global scale and interconnecting role that the coastal ocean plays in the whole Earth system. Solution focused research that creates public benefit at both

local and international scales and supports unified approaches to coastal ocean science and management is needed.

Advances in process understanding and realisation of solution focused science is dependent upon the development of next generation technology for the global coastal ocean and the re-purposing of existing technologies from other sectors

The development of next generation technology, including remote sensing, autonomous vehicles, acoustic and optical sensors, integrated sensor networks, data assimilation approaches, new analysis techniques and modelling tools will provide the information needed to explain the historical and present-day balance of processes controlling coastal and shelf sea behaviour, enable understanding of their natural variability and their future response to both natural and human driven changes.

The importance of the coastal zone and shelf seas

Coastal and shelf seas are the shallow water transition zone from terrestrial to deep ocean environments, and vice versa. Their behaviour is governed by a large range of hydrodynamic, sedimentary and biogeochemical processes that have global-scale ocean and climate importance. Shelf seas make a substantial contribution to global marine productivity, they are hotspots for biodiversity, burial grounds for large quantities of carbon, dissipate a disproportionate percentage of global tidal energy and at their boundaries transport climatically significant quantities of heat, freshwater, carbon and nutrients. The ocean, atmosphere, seabed and land (also ice in high latitudes) are all interconnected in shelf seas, creating a dynamically complex environment where the relative importance, interplay and balance of processes and the transformation of properties within and between them, changes on a wide range of spatial (mm's –100's km) and temporal (seconds- centuries) scales.

Shelf seas make a ~20% contribution to total marine biological productivity and account for 20-50% of total oceanic CO_2 storage. They are areas of sequestration for high percentages of particulate inorganic (30-50%) and organic (80%) carbon and are responsible for more than 40% of the global annual export of particulate organic carbon to the deep ocean. The physical and biogeochemical processes in coastal and shelf seas and the interfaces within them play an important role in mediating the transport, storage and modification of carbon and other major bio-essential elements (e.g. nitrogen and iron) that help set the baseline of the global ocean ecosystem.

The health, prosperity, security and sustainability of rapidly expanding human populations, both now and in the future, are intimately reliant upon the functioning and sensitivities of coastal and shelf seas. It is projected that by 2030 the global marine and maritime economy will be worth $3 trillion, with many areas of economic growth centred on coastal and shelf seas. Around 90% of global trade passes through coastal waters and half of all international tourists travel to the coast. More than 99% of all digital data traffic is transmitted by a global network of subsea cables that pass through the coastal zone. Over 90% of the fish we catch come from continental margins and by 2030 near-coastal aquaculture is projected to provide over 60% of fish destined for human consumption. Many millions of people therefore rely on fisheries and mariculture for their main source of animal protein, particularly so in developing countries and island states, and also on energy extraction for power. With the human population predicted to rise to over 10 billion by 2100 the pressure on marine and coastal resources is increasing, both through resource extraction and pollution. For example, 50% of human food production requires nitrogen-based fertilizer and ~50% of this ends up in the marine environment, leading to coastal eutrophication and hypoxia.

More than 600 million people live in areas that are less than 10 m above sea level. Between 1901 and 2010 the global average sea level increased by 19 cm. By 2100 it is likely that there will be a further 20-80 cm rise. Sea level rise and more extreme weather patterns associated with climate change place these populations at increased risk from hazards such as flooding, coastal erosion and saltwater contamination. For example, in the next 30 years 150 million people globally are expected to be affected by coastal flooding. This will cause billions of pounds of damage, disruption, displacement, stress and anxiety.

In comparison to the deep ocean, shelf sea science has a greater potential for rapid uptake and impact of policy advice to help protect marine ecosystems and to increase human and economic resilience to both climatic and human driven changes. The immediate impact of human activity on the ocean is concentrated near the coast, where anthropogenic activities and transboundary fluxes of material accentuate the need for agreements, policies and directives to ensure the health, cleanliness, biodiversity and productivity of coastal oceans. In some regions, marine governance frameworks acting at local to international scales are well established, but in others more work is required, particularly where political sensitivities must be negotiated. It is also at the coast where marine hazards impinge directly on lives, infrastructure and livelihoods and where science can aid multiple stakeholders in mitigation measures.

The overarching challenge

The scientific and technological challenges that we face are associated with processes, interactions and exchanges that take place within shelf seas and at their dynamic ocean-atmosphere-seabed-land boundaries and transition zones.

The overarching scientific challenge is to explain the historical and present-day balance of operative processes controlling coastal and shelf sea behaviour around the world and from pole to pole, to enable understanding of their natural variability and their future response to the changing climate and other direct human impacts.

In tackling this challenge, we will help protect lives, industry, infrastructure, economies, ecosystems and resources from extreme events, anthropogenic and climate changes, and provide societally relevant information, advice and evidence that will support sustainable usage, development and stewardship of the coastal ocean.

Research Challenges

1. System status and functioning

New knowledge and understanding of the complex and intricately linked physical, biogeochemical, sedimentological and geochemical processes together with their temporal (episodic, seasonal-centennial) and spatial (mm's to 100's km) variability within shelf seas and at their land-ocean, air-sea, shelf-basin and benthic-pelagic boundaries is essential to maintaining the status and function of shelf ecosystems and in elucidating the role of shelf seas and coastal zones in global Earth and human systems.

Shelf-basin connectivity and communication with the global ocean

The two-way exchange and transport of heat, salt (freshwater), energy, inorganic and organic particulate matter, nutrients, trace metals, pollutants, carbon and biota between shelf seas and the deep ocean is essential to large scale circulation, shelf system dynamics, productivity, the global carbon and other element cycles. Elucidating when, where and how shallow shelves and the deep, open ocean 'communicate' therefore has both regional and global scale importance.

Boundary currents and shelf-basin exchange

Narrow boundary currents that follow the steep bathymetry of both eastern and western ocean basin margins transport climatically important quantities of fresh water and heat around the global ocean, from equator to poles and shelf-to-shelf. They are also pathways for spawning stocks of commercially important fish species and conveyors of nutrients and carbon. The strength, position and stability of shelf-edge boundary currents plays a key role in setting the strength and direction of shelf-basin exchange and in linking coastal and open-ocean sea level variability. Understanding how contemporary and future slope current behaviours set the direction and magnitude of transport, exchange, coastal sea-level and the associated uncertainties is therefore important.

The maintenance of productive shelf sea ecosystems relies upon processes that control the flux of nutrients from the open ocean across the shelf edge and those that export carbon off-shelf. It has not yet been possible to reconcile the macro-nutrient (N, P, Si), micro-nutrient (Fe, Mn) and carbon budgets, particularly across wide shelves, with our current understanding of the strength and seasonality of shelf-edge exchange mechanisms. There is a need therefore to better understand seasonal to interannual variability in exchange processes and to identify 'extreme' events capable of 'flushing' entire shelves within a growing season.

Rivers, estuaries, glaciers and sea ice melt deliver huge volumes of freshwater to the coast every year. At mid- to high-latitudes, this freshwater typically forms a narrow coastal current but, must eventually escape the continental margin and enter the open ocean where it plays a role in driving the global thermohaline circulation. Further, in setting basin-scale air-sea fluxes and influencing near surface stratification, fresh water may also modify weather patterns and trigger phytoplankton blooms. Our understanding and quantification of where, when and how fresh water crosses the shelf break and enters the open ocean is incomplete. These fresh water sources carry globally relevant quantities of organic matter and inorganic nutrients: the pathways and fate of these are largely unknown.

The intermediate and deep layers of the ocean are a huge reservoir of heat. This heat can be released to the atmosphere and/or come into contact with the coast if it is able to cross the continental slope and make its way across the shelf. This is of particular importance in polar regions where a cross-shelf heat flux may accelerate melting of sea-ice and marine terminating glaciers. Heat exchange is also important in maintaining horizontal temperature gradients across shelves during the winter months, impacting pressure gradients and circulation patterns. Improving our understanding of the processes that drive heat fluxes across the shelf-edge and the spatial extent of transport across the shelf will advance our understanding of the coupling between the ocean and cryosphere and improve projections of the responses to global warming.

Dense and sediment-laden flows, known as turbidity currents, provide an important mechanism for the transport of globally important quantities of sediment from the shelf to the deep-sea, via submarine canyons and channels. Often these deep-water conduits connect to river systems onshore – providing effective transfer pathways from land to deep-sea. As well as sediment, turbidity currents also transport significant quantities of organic carbon, nutrients, oxygenated water and pollutants. The frequency, discharge and runout distance of these flows dictates onshore-offshore flux, as well as regulating the efficiency of carbon burial. Despite their importance, we have a limited understanding of the frequency of these flows, their triggers (and how these vary in relation to terrestrial land-use changes, climate change and ocean conditions), down-slope evolution, internal structure and the fundamental physics that control how these flows interact with other ocean processes. Further, an individual turbidity current can transport volumes of sediment that exceed the annual discharge of the world's rivers, and travel at high velocities (up to 20 m/s), thus threatening seafloor infrastructure such as cables and pipelines. This understanding is therefore also essential to inform future prediction of hazards to seafloor infrastructure.

Remote forcing

The history of water that crosses the shelf break from the open ocean, the pathway that it has taken and the modifications it has undergone along the way, is important to ascertain, as remotely-forced changes in the properties and circulation pathways of oceanic water that floods onto many shelves can lead to both modest variability and dramatic and climatically significant dynamical and biogeochemical regime shifts. We are challenged with understanding how and where shelf seas are affected by remote forcing and conversely identifying more isolated continental margins that do not have open ocean variability and trends imprinted on them. Just as the open ocean impresses variability onto the shelf, intense cooling and densification of water on shallow shelves triggers cascading events that inject variability back out into ocean basins and anomalies that may be carried many hundreds of kilometres within the boundary currents. Dense cascades in the Arctic are particularly important for ventilating the deep ocean. Altogether we require a much more joined up view of the coupled shelf-open-ocean system, at an ocean-basin scale.

Diagnosing shelf exchange processes from observations and pulling them apart in models is non-trivial; many theoretical and practical challenges remain, notably around the small spatial and temporal scales, and the episodic nature of important events. Nonetheless, to determine the present-day balance of shelf-basin exchange mechanisms and property transports and their future equilibrium we must find a way to separate these signals on all spatial and temporal scales.

Improved understanding and quantification of shelf circulation, mixing processes, cross-shelf exchange and basin-scale connectivity will provide advances in our understanding of carbon, nutrient and oxygen uptake, cycling, storage and export, and in assessments of shelf ecosystem status and function that inform sustainable management of ecosystem services. Improved quantification and mechanistic understanding of the freshwater, heat, sedimentary, organic and inorganic elemental pathways across and between shelf seas will enable more accurate seasonal to decadal scale projections of future climate, thereby underpinning mitigation and adaptation strategies.

Turbulent mixing

Shelf seas and coastal zones are regions of strong vertical and horizontal density gradients, most notably at shelf-break and tidal mixing fronts, seasonal pycnoclines and in freshwater plumes. These sharp density interfaces can support internal waves, drive narrow coastal currents or result in jet-like along-front flows. The transfer of elements (carbon, nutrients, oxygen, sediments) and marine life across these dynamic ocean boundaries is intimately related to the turbulence and cascade of energy from large to small scales, within and around them. Turbulent mixing plays a leading role in setting the availability of nutrients and light needed to support phytoplankton growth, in controlling water clarity and in the dispersal of dissolved and particulate loads, pollutants and marine life, both vertically and horizontally.

However, our incomplete understanding of the temporal and spatial variability and interconnections between the drivers of turbulence and thus diapycnal mixing hampers model turbulent mixing schemes and our understanding of how small-scale processes influence large scale properties. Particularly challenging is capturing spatiotemporally intermittent mixing (often associated with internal waves) and the transition between well-mixed and strongly stratified states. For example, mixing models often act as on-off switches, and perform poorly in the weakly stratified state. Errors associated with inaccurately representing micro-scale turbulent processes at sharp density interfaces in shelf-wide ocean models become amplified on larger scales and the consequences cascade throughout all components of the model, notably impacting spring and autumn bloom timing/intensity and summer production driven by diapycnal nutrient fluxes. We are challenged with advancing our understanding of small-scale turbulence at these critical shelf-sea boundaries, improving mixing model schemes and thereby reducing model uncertainty, in both contemporary and future simulations. A central challenge is non-locality of mixing, e.g. horizontally by remotely generated internal waves, or vertically by counter-gradient processes (convection or Langmuir turbulence).

Vertical and horizontal property gradients are in part also set by the magnitude and variability of property sources, for example freshwater input at the coast and the salinity of the adjacent ocean basin. Climatological freshwater discharges that lack interannual variability and episodic extremes combined with imperfect mixing schemes and (potentially) ill constrained shelf-scale circulation, leads to inaccurate horizontal salinity (freshwater) gradients associated with both small and meso-scale frontal features and larger cross-shelf salinity changes. These errors influence the timing and maintenance of stratification and phytoplankton bloom events throughout the year, with the consequences potentially felt further up the food chain, by the benthic communities and in other parts of the Earth system.

Mesoscale eddies, resulting from the inverse energy cascade concentrating energy at the scale of the Rossby radius are a significantly under-studied process in the coastal ocean. These decrease in scale by orders of magnitude in the ocean-shelf transition. How these features respond to strong (surface and seabed) boundary layers is largely unknown and how they can be parameterised in models in a way that is scale aware is a key development requirement of a truly seamless ocean-shelf modelling systems.

Atmosphere-ocean interaction

Shelf seas and the coastal zone are in direct exchange with the atmosphere. Heat and momentum exchange drive seasonality in both vertical (surface to seabed) and horizontal water column structure and stability, which in turn sets the start and longevity of the growing season and the rhythm of higher tropic levels. Wind stress and atmospheric pressure gradients drive surface currents, setup the surface wave field and may lead to coastal flooding, erosion, saline intrusion and storm surges. The interaction between the ocean and atmosphere in the coastal zone, determining for example the sea state, often determines accessibility and usage (shipping and transport, navigation, recreation, energy extraction).

Surface ocean waves are generated locally by surface wind stress, and by remote storms which can propagate long/energetic swells into shelf seas. The characteristics of the wave field are continually modified by changing storm tracks and wind strength, sea-ice cover and waves interacting with bathymetry, local currents and coastal structures, both natural and manmade. Determining the relative importance of the meteorological, oceanographic and geographical conditions, that drive short-lived to seasonal variability in the wave climate, across local to shelf-wide areas, is essential for more accurate predictions of hazardous wave conditions (leading to overtopping, erosion, dangerous navigation), improved sediment transport models and our understanding of air-sea gas exchange (e.g. carbon dioxide, nitrous oxide and other greenhouse gases). Waves also set the lower boundary condition for atmospheric momentum, an important feedback relevant to weather forecasting.

Pelagic-benthic coupling

The interaction between the sediments and bathymetry of the seafloor, and the water column (or even ice) above impacts upon coastal morphology, water quality and optics, benthic and pelagic ecosystems, coastal engineering, mineral extraction, long-term carbon sequestration, nutrient recycling and the stability of material on the continental slope that may pose a risk to seafloor infrastructure.

Our ability to predict fluid flows, sediment transport and sediment-biological interactions, both at the seafloor and in the water column, is held back by our lack of understanding on how both mixed and biologically mediated sediments (sand, fine particles and bio-genic material/binding) affect flocculation, consolidation, bed roughness, erosion and the evolution of wave and current generated bedforms. Equally, incomplete understanding of the range of mixing processes within the bottom boundary layer, notably turbulence associated with small scale bedforms, is hampering our ability to adequately describe sediment processes and benthic-pelagic exchanges of nutrients, carbon, oxygen and pollutants over tidal to seasonal time scales.

There is a need for improved seabed parameterisations of small-scale processes, including flow conditions, exchanges, turbulence, water depths, near-bed sediment loads, cohesive, non-cohesive and biologically mixed-sediment properties and bedforms. In Polar regions the seabed in ocean models is unable to freeze when it should. The challenge is to represent the spectrum of processes in a way that can be confidently up-scaled for use in coastal, regional and whole shelf hydrodynamic and sediment transport models.

The carbon burial efficiency of the seafloor is tightly coupled to when, where and how often the sediments are disturbed, either by episodic and extreme events (e.g. cyclones, storms, surges, turbidity currents, slope failures, floods) or by more regular hydrodynamic stresses and sediment resuspension (e.g. tides). We require a much better understanding of the variable timescales and magnitudes of disturbance events across all coastal, shelf and slope environments (e.g. fjords, deltas, canyons, vegetated habitats).

Biological pathways of energy and organic matter

Accurate quantification of the fluxes of carbon through the Earth System is fundamental to our contemporary understanding of the global carbon cycle and our ability to predict the impacts of climate and human driven change. Understanding the strength, efficiency and spatiotemporal variability of the biological pathways through which energy and organic matter passes is key to determining the capacity of the coastal ocean to absorb atmospheric carbon dioxide, the potential for organic matter to reach the seabed or for long-term carbon sequestration in the deep ocean.

At present, we do not have a robust or balanced handle on the various biological pathways and their interactions, notably where there are strong temporal and spatial gradients in both physical and chemical properties. Particular challenges concern distinguishing between net and gross estimates of primary production, better quantifying the magnitude and variability of bacterial growth efficiency and respiration, constraining alternative metabolic pathways (e.g. mixotrophy, photoheterotrophy) and understanding the sensitivity of microbial degradation rates of organic matter in sediments to environmental change.

The matter and energy contained within phytoplankton becomes available to higher tropic levels when they are grazed by zooplankton. Vertical zooplankton migration, sinking faecal pellets and/or dead carcasses subsequently contribute to the flux of carbon and nutrients to the seabed. We need to more clearly elucidate the controls on diel vertical migration, and the factors that promote the formation and sinking of organic material, and the rates of fragmentation and/or remineralisation as this material leaves surface waters.

Photosynthetic phytoplankton convert inorganic carbon into both dissolved and particulate organic matter. A fraction of dissolved organic matter is resistant to microbial breakdown and may therefore be sequestered for thousands of years. This pool is significant in size and is approximately equal to the atmospheric carbon pool. At present, we do not understand the relative balance of marine and terrestrial dissolved organic matter sources that resist microbial breakdown, a particular challenge in the coastal ocean. Furthermore, there are many unknowns as to how it is created, the properties that make it resistant to breakdown or whether the pool is in a steady state.

The cause and rate of mortality of primary and secondary producers plays an important role in the fate of organic material. This is because the mode of mortality impacts the composition and quantity of matter produced which dictates its bioavailability and likelihood to aggregate. The role of viruses, fungal-like pathogens and pathogenic bacteria in microbial mortality is not yet understood. We must quantify the relative importance of these different modes and how they vary under different environmental stimuli.

The land-ocean interface

Pathways, transformations and coupling

As part of the natural whole Earth System, rivers, estuaries, melting permafrost and glaciers deliver freshwater, carbon, nutrient and sediment loads into the coastal zone. Dissolved and particulate loads also enter coastal waters from beaches, vegetated habitats and ground-water seepage. Estuaries and shelf seas then act as a two-way buffer between the land and the open ocean, processing these inputs, reducing or modifying material and properties that reach the shelf-edge and eventually the open ocean.

Understanding the pathways and transformations of freshwater (both liquid and solid), its dissolved and particulate loads once it has entered the land-ocean interface and marine environment demands that we improve our understanding of how tidal and estuarine flows, strong density gradients, complex estuarine and near-shore bathymetry and sediments on the seabed interact. Furthermore, the fluxes and composition of organic and inorganic loads are intrinsically linked to ecosystem functioning in the brackish and marine waters into which they flow, and to elemental cycling through the coastal zone. Processes which alter these loads can, for example, lead to increased coastal ocean acidification or alter the composition and bio-availability of dissolved organic matter transferred to the deep ocean.

Improving understanding of the link between physical and biogeochemical process at the land-ocean interface will allow the effective coupling of catchment-river and marine models that provide policy and management advice concerning water quality, eutrophication, hypoxia, harmful algal blooms, fisheries and human health. In some parts of the world, we have no handle on the severity or links between these key issues.

Eutrophication and hypoxia

Around half of all human food production requires nitrogen-based fertilizer and approximately 50% of this ends up in the marine environment, leading to coastal eutrophication. Exacerbating the effects of increases in ocean temperature and stratification, these excessive nutrient loads drive much of the observed decline in near coastal oxygen concentrations, leading to oxygen deficiency and hypoxia, which impacts the survival, growth rates, behaviour and extent of viable habitats for marine species, and can have devastating consequences for commercial fisheries.

Understanding the relationship between terrestrial-nutrient driven low-oxygen and low (climatic) open-ocean oxygen conditions, that via shelf-edge exchange processes and circulation can reach the coastal zone, is crucial for explaining, and mitigating against hypoxic effects (e.g. massive fish kills) around the world. The attribution of drivers behind particular eutrophic events is essential, but our understanding is hampered by, for example, uncertainty about the magnitude of the total nutrient and organic matter transport from land to ocean and unknown variably associated with land-type use and change. Even the hydrological cycle (rainfall, river input) differs widely across global atmospheric/land-surface reanalysis products. Atmospheric nutrient sources are also highly uncertain, but in some regions (e.g. East Asia) likely to be highly relevant. Furthermore, the relative roles played by biological oxygen consumption/respiration, and the quantity and composition of organic matter produced during photosynthesis, transported by rivers or released when sediments are resuspended are unresolved. Addressing the challenges associated with eutrophication and oxygen deficiency requires close partnerships with the land-surface, hydrological and biogeochemical observational and modelling communities.

Coastal ecosystems

Mangroves, seagrass beds, coastal wetlands, tidal marshes and coral reefs provide natural coastal defences, nursery grounds for fish and invertebrates, food security, recreation and a tourist industry for many coastal populations, as well as being important habitats for both marine and terrestrial wildlife, and climatically important storage reservoirs of carbon. The real and perceived value of these coastal ecosystems however varies and is often dependent upon regional socio-economic factors.

The majority of carbon fixed by photosynthesis is stored in the biomass of marine plants, sediments and soils (termed blue carbon). Vegetated marine coastal habitats (mangroves, seagrass beds, coastal wetlands, tidal marshes) are the primary blue carbon stores. Unlike terrestrial ecosystems, where carbon is typically sequestrated for centuries, carbon in marine systems, when conditions are favourable and if left undisturbed, may be locked away for millennia. As a consequence of human population growth, coastal reclamation, urbanisation and engineering, vegetated coastal habitats are being destroyed at a rate exceeding the loss of any other ecosystem on the planet. Furthermore, on tropical shelves, rising water temperatures, ocean acidification and oxygen starvation are leading to longer coral bleaching events and killing coral on unprecedented scales.

At present, we do not know enough about the carbon stocks and fluxes in vegetated coastal ecosystems, including how the loss of these habitats exacerbates the accumulation of atmospheric carbon dioxide. It is unclear whether the restoration and conservation of blue carbon ecosystems is a viable climate mitigation strategy. We are challenged with quantifying where and how fast coastal ecosystems are disappearing or transitioning into different habitats. We must understand the impact this has on the ecosystem services they provide, both to Earth system functioning (carbon cycling and storage) and to the sustainability and resilience of local populations. Specifically, protection from storms and sea level rise, regulation of coastal water quality and the provision of nursery grounds vital to fisheries and endangered marine species are ecosystem services that require further research.

Coastal ecosystems are often found in the inter-tidal zone where the shoreline is covered in sea water at high tide and exposed to the air at low tide. They are neither fully-marine nor fully terrestrial and fall into the land-ocean-benthic interface, the complexities of which we have not yet fully grasped, limiting our ability to up-scale single site process studies, quantify their global relevance or predict how they may respond both to natural and direct human driven change.

Bathymetry and habitat mapping

Despite their proximity to land, the majority of the world's shelf seas and coastal waters still have not been mapped and characterised to a level that enables efficient and sustainable management. This has severe implications in terms of safety at sea, but also, given the increasing amount of anthropogenic activities in the marine environment, in terms of marine spatial planning and conservation. Even in UK waters, large extents of the shelf are not yet mapped in detail with regard to bathymetry, and even less so with regard to their seabed habitats and benthic ecosystems. The situation is even less favourable in many other parts of the world, where either rapid developments of extractive, fishing, energy or tourism industries are encroaching on the marine environment, or large Marine Protected Areas are declared without prior knowledge of the habitats present, their spatial distribution, their status, the functions they fulfil or the services they provide. Coordinated research effort is necessary to fill in these gaps, and to gather the knowledge on seafloor morphology and benthic habitats that will underpin sustainable management.

2. The impact of human activity

Human activity directly modifies the natural coastal environment, whether through resource extraction (energy, food, materials), coastal management and climate mitigation schemes, land-use change, installation of seafloor infrastructure, or the introduction of pollutants. The rapid expansion of human populations and the growth of mega-cities is accelerating these pressures. Understanding the scale, longevity and more remote knock-on consequences of the impacts is therefore of first order importance.

Disturbing the natural environment

Resource extraction and climate mitigation schemes

Against a projected 50% increase in global energy demands by 2050 and guided by the urgent need to cut greenhouse gas emissions, identified by the IPCC, many countries around the world are working towards renewable energy production targets. The installation of tidal, wave and wind turbines in the coastal ocean and estuarine zones is therefore increasing. In parallel, oil and gas infrastructure across the shelf is being decommissioned and the viability of climate mitigation strategies such as carbon capture and storage are being explored. The potential impacts and/or benefits of installing renewable energy devices, decommissioning old infrastructure or pursuing new carbon capture and storage solutions is unknown. We require greater understanding of the effects on the hydrodynamics of flow and the mobility of sediments associated with both individual installations and large arrays of devices. We must consider the consequences, both positive and negative, of creating artificial marine habitats and potentially introducing new marine species. Further, the impact that underwater noise or the accidental release of carbon dioxide from storage reservoirs may have on both pelagic and benthic organisms needs to be quantified and understood.

Of the order of one million-km^2 of the global continental shelf is bottom trawled, a destructive activity that damages faunal communities, resuspends sediments into the water column and introduces artificial mixing. We require much better understanding of how trawling alters the relationships between benthic communities and the cycling of carbon and nutrients within and between the water column and sea floor, whether the carbon storage capacity of the benthos changes and how long the seafloor and its faunal community takes to recover.

Coastal and port management

In order to defend the coastline from rising sea levels and extreme events local authorities are increasingly reliant upon both ‘hard’ and ‘soft’ coastal management strategies. Extensive concrete sea walls may be built to project valuable infrastructure. Alternatively, sand and gravel from elsewhere may be used to replenish eroded material. Further, port managers regularly dredge sediments and fluid muds from harbours and estuaries to maintain shipping channels, disturbing the natural environment. Aggregate is also extracted across many shelves for use in the construction industry, or as a source of material used to defend against coastal erosion. We are challenged with understanding the local and far-field hydrodynamic consequences of preventing erosion and artificially removing and/or re-distributing sediment along the coastline. We must understand if, how and where marine habitats are impacted by coastal and port management schemes.

Disentangling the direct impacts of human activity in coastal waters from changes forced more remotely by climate change is essential in addressing these challenges, but first requires understanding of the undisturbed environment.

By understanding the impact of human activity on the marine environment and isolating it from natural variability we will inform environmental impact assessments, support the planning of future installations, coastal management schemes and marine protected areas.

Introduction of pollutants

Rivers and estuaries, shipping activity, power plants and dredging activities all inject potentially dangerous levels of pollutants, including plastics, industrial waste and agricultural run-off directly into the coastal zone. Over 70% of marine litter is plastic which can cause injury or death to marine life, including commercially important fish and shellfish species. A large fraction of plastic pollution ends up on beaches where it is susceptible to degradation, leading to the formation of bioavailable micro and nanoplastics that enter the food chain. Further, plastics can have human health, ecological and economic implications, notably in areas of outstanding natural beauty where the economy relies on tourism.

Pharmaceuticals in sewage, agricultural and mining run-off, radioactive waste, toxins from harmful algal blooms, and metals released when harbours are dredged, all pose risks to human health and marine life, both locally and remotely. Widely used pesticides can have long-lasting effects within the aquatic environment. The increased use of fertilizers resulting in elevated nutrient run-off and eutrophication of coastal waters, increasing algal biomass and rates of hypoxia is a concern for biodiversity and ecosystem function. By 2030 it is estimated that the global nitrogen input into the sea will have increased by 14% from 1995 levels. Atmospheric deposition is an additional source of biologically active nutrients and Persistent Organic Compounds to the coastal ocean that place unnatural stresses on coastal ecosystems. While the effects of persistent contaminants are clear for some legacy pollutants (e.g. DDT) for comparatively new chemicals such as pesticides, flame retardants (e.g. PFCs) and synthetic polymers, the long-term fate and implications are less obvious. Lastly, natural events such as storm surges and waves re-mobilise deposited pollutants that may then re-enter the system and marine food chains. These areas often correspond with regions of high aquaculture activity, thus having implications for incorporation of pollutants into farmed aquatic organisms and subsequent ingestion by humans.

Understanding the sources, degradation processes and products, residence times, pathways and impacts of these pollutants once they have entered the estuarine and marine environment is crucial. Multiple approaches will be required to prevent or reduce the release of contaminants to non-target locations, and to manage and mitigate environmental effects. This relies on advancing our understanding of the physical and biogeochemical processes, interactions and exchanges that take place at the dynamic land-ocean-atmosphere-seabed-land boundaries and transition zones. We must then translate this process understanding into coupled catchment-river and marine models that are reliable across large areas.

In addressing these challenges we will liaise with stakeholders to provide policy and management advice and enable early warning alerts to protect aquaculture and human health, advise on water quality and identify areas where the ecosystem is most at risk from eutrophication, hypoxia and exposure to hazardous contaminants. These actions will enable the identification and preservation of key environments that provide human and ecosystem benefits.

3. Responses to a changing climate

As the ocean warms, stratification strengthens, sea-levels rise, sea-ice retreats and atmospheric pressure systems and the hydrological cycle are modified, the present-day balance of forces that determine the hydrodynamics and connectivity of shelf seas will shift. An understanding of how, where and the speeds at which these trends and modified patterns of variability will manifest themselves and how planktonic and microbial life in the oceans will respond, is critical to our predictions of coastal hazards, future shelf-sea ecosystem structure and functioning, and the role of shelves in global climate. The consequences of change must be understood at both regional and global scales and the natural drivers disentangled from the impact of direct human activities.

Regime-shifts and tipping points

In many cases, especially at regional scales, the sign of potential future environmental change is poorly understood and highly uncertain. This is particularly true of large-scale shifts in oceanic circulation and thermohaline properties which could have a dramatic effect on shelf-seas. We must identify when, where and if 'tipping points' will be reached, beyond which shelf and coastal zones may be characterised by new combinations of physical and biogeochemical processes and different communities of marine organisms (a regime shift). It is important to identify not only the sign of trends (positive or negative), but also the speed at which change is taking place, since this will have implications for whether the ecosystem and human populations can adapt or not.

If we are to understand whether the physical relationships valid in the present day will persist or be modified in future climate states, the multi-faceted, multi-directional and non-linear interactions between rising ocean and atmospheric temperatures; the strength, depth and duration of stratification; the intensity and location of turbulent mixing; rising sea level; shifting weather patterns and storm events; circulation patterns and tidal regimes; and changes in precipitation, river-runoff and ice melt need to be elucidated. The high levels of uncertainty surrounding potential hydrodynamic changes amplifies the challenges associated with understating how coastal ecosystems and habitats and the services they provide will respond to climate change.

Terrestrial fluxes of organic matter and nutrients

As the hydrological cycle is modified, permafrost in Polar regions melts, groundwater seepage alters and land-use across river catchments becomes less natural the source, concentration, composition and fate of organic matter reaching the coastal zone (and via turbidity currents the deep-ocean) is changing. Melting permafrost is also triggering an increase in CO_2 release. We must understand how, why and where changes in terrestrial fluxes will impact the bioavailability of organic matter, the rates of remineralisation and the net transfer of carbon dioxide to the atmosphere. Much of our current understanding is based on studies of rivers and estuaries that have human modified catchment areas and may therefore not apply to undisturbed catchments or those in remote locations.

Driven by excessive concentrations of nutrients in rivers, coastal eutrophication and low oxygen levels are already a cause for concern across many shelves. We are challenged with understanding what future combinations of physical and biogeochemical processes, anthropogenic nutrient loading and open-ocean climatic drivers will ameliorate or exacerbate these problems. With this knowledge we must predict where the most vulnerable areas are and how fast the changes will be, effectively downscaling from global scale assessments to accurate regional and local predictions. This is essential if we are to better inform mitigation and adaptation strategies.

Elemental cycling

The capacity of coastal and shelf seas to absorb atmospheric carbon dioxide and retain biological carbon relies on the balance between primary production and respiration. The impact that increasing temperature has on net metabolic balance (the difference between primary production and respiration) however is uncertain. This obscures our understanding of how the global carbon cycle may be modified. Furthermore, we must get a handle on how the cycling of nutrients and other key trace elements may change. There is limited knowledge on the potential shifts in phytoplankton nutrient preference and stoichiometry, and different sets of balances between new and regenerated production as a result of changes in the quantity, quality and location of nutrient sources to the coastal ocean (e.g. terrestrial, marine, atmospheric, sedimentary, melting permafrost). We are also challenged with elucidating how changes in the strength, depth and longevity of stratification across shelf seas will alter the balance between the vertical (turbulent fluxes) and horizontal (advective) supply of nutrients and removal of carbon.

Productivity and community composition

Worldwide, millions of people rely on fishing and aquaculture for their main source of animal protein, the vast majority of which comes from productive shelf and coastal waters. On both local and global scales, we must understand how changes in temperature, the strength and persistence of stratification and altered sets of atmospheric conditions and variability will affect phytoplankton; both directly through their physiology and indirectly by changing the length, timing and intensity of the growing season and resource (nutrients, light) availability (e.g., through changes to coastal upwelling conditions). We must subsequently ascertain whether these changes are likely to impact on marine food production (wild fish stock and aquaculture). We do not yet know how and where the taxonomic composition of phytoplankton communities may change, whether they will be able to adapt or what the impact of any change may be on the nutrient and carbon cycles.

Coastal hazards and extreme events

By 2030 the world's population is predicted to reach 8.5 billion, with the greatest population growth rates continuing in coastal areas. Furthermore, ports, harbours and shipping are essential to the global economy, international trade and the future economic health of many countries around the world. Coastal communities, industry and infrastructure at the coast are most vulnerable to sea level rise and extreme events such as flooding, wave overtopping and storm surges, particularly those in the low-lying regions of developing nations. Sea level rise and flooding are also driving increases in river and ground water salinity, notably in low-lying heavily populated areas like the Bangladesh delta. Saline intrusion is leading to shortages of water for drinking and crop irrigation, reductions in crop yield and damage to transport links. To protect human life, natural resources and economies we must improve both our short- and long-term predictions of sea level rise, the wave climate, storm surges, flooding, tides and saline intrusion events.

Multi-hazards

As a consequence of sea level rise, coastal flooding and wave overtopping is occurring more frequently. Hazardous events often result from regionally variable, complex, nonlinear interactions of multiple oceanographic, hydrological, geological, and meteorological processes (e.g. tides, sea-level anomalies, storm surges, waves, winds, atmospheric pressure, fluvial discharges, precipitation, ground-water levels, beach loss and land subsidence). In the case of saline intrusion, natural extremes may be exacerbated by freshwater extraction for direct human consumption, use in industry and for crop irrigation. Although the exceptional extreme variation of a single process (e.g. storm surge) can result in flooding, the more normal situation is that a combination of notably high values of more than one process constitute the precursor mechanism, leading to a compound extreme event. It is essential that we develop the capability to forecast the frequency, magnitude and probability of these joint extreme events, at both observed and unobserved locations. At a national scale multiple events occurring simultaneously also need to be more reliably identified.

Quantifying probability and uncertainty

Nuclear power stations for example are required to have defences that protect them from 1:10,000-year flood events and coastal managers plan on 100-year time frames. Quantifying both the probability and uncertainty of hazardous events is therefore critical in assessing and managing the threats posed by defence overtopping, beach erosion, and scour around structures. Quantifying uncertainty will also help maintain and optimise safe operating windows for coastal industry (ports, harbours, energy) and minimise disruption to shipping routes.

Improved, publicly available early warning systems that have wider spatial coverage will mitigate the impact of flooding, surges and hazardous wave conditions, saving lives and protecting businesses. We will inform structural design, both nearshore and at the land-sea interface and improve long-term planning and adaption of coastal management strategies, the defence of power assets, food resources (e.g. aquaculture, fertile land) and essential infrastructure. Reducing uncertainty in predictions will help limit over-designed safety tolerances, resulting in cost- and carbon-savings for new build projects.

Natural vs. human induced variability

The whole Earth system has natural internal, multi-scale variability forced by changes and feedbacks within and between the atmosphere, ocean, cryosphere and land. Human activity (e.g. burning fossil fuels, dredging, fishing, energy extraction, land reclamation) is now introducing additional variability which has a direct impact near the coast and is felt acutely by human populations living there. We are challenged with pulling apart natural versus human driven variability, and also disentangling direct human impacts and those that act via the climate system, as the mitigation approaches are then very different. We must also identify where environmental change and hazards experienced in one area, have been triggered by human activities elsewhere (remotely).

As well as looking forward, we must also invest effort in understanding how humans have been perturbing the whole Earth system over the past centuries. For example, how has human activity perturbed the global marine nitrogen and phosphorous cycles on centennial scales? Does the nitrogen signal in present day upwelling systems reflect last centuries agricultural practices? These questions demand improvements in our understanding of the links between physical and biogeochemical processes at the land-ocean interface and more effective coupling of land-shelf-ocean models. Establishing a baseline is often highly problematic: in many cases human impacts pre-date modern measurement capability, requiring data archology and proxy methods.

4. Science and society

In the global ocean context, there are a small number of unifying frameworks that set the policy agenda around some well-articulated objectives, e.g. IPCC Assessment Reports, UNCLOS, SDG's etc around some well-articulated objectives. In coastal and shelf seas there are diverse marine assessment, policy, and governance approaches acting at international, national, and local scales that must be navigated to put the science challenges above into a societal context. For example, just in Europe, OSPAR, HELCOM, the Barcelona Convention and Black Sea Commission are active alongside European Union (CFP, MSFD, WFD etc) and national legislation. Elsewhere issues of political sensitivity abound, relating to, e.g., disputed territorial and resource claims and issues of transboundary pollution. Unifying approaches to coastal-ocean science exist (e.g. IGBP – LOICZ, Future Earth Coasts), but generally these have had much less international traction than their open ocean counter parts.

A central challenge therefore, that cuts across all the scientific unknowns, is the need to translate our advances in understanding and predictive skill into useful and sustainable outputs for society. Our outputs should drive unified approaches to coastal ocean science and evidence informed policies that transcend territorial boundaries and are reflective of the global scale and interconnecting role that the coastal ocean plays in the whole Earth system. Furthermore, our scientific insights and discoveries should help to instil in society an interest, respect and wonder for the ocean. The vast majority of people will experience the ocean at its coasts, hence communication and outreach initiatives based on coastal and shelf sea scientific research are an optimal way to improve world-wide ocean literacy. The UN Decade of Ocean Science for Sustainable Development provides a substantial opportunity to address these challenges.

In order to make our science more solution focused and to create public benefit that is aligned with the financial and practical limitations of local communities and nations, we must build partnerships with economists and other social scientists, industry experts and local stakeholders. These relationships will support effective translation of our expertise into quantifiable and understandable assessments, predictions and valuations of coastal ocean resources, health and hazards.

5. Next generation observing and technology for coastal and shelf seas

New observations, methods and technologies

Making measurements and running models that will advance our process understanding and provide accurate and timely policy relevant evidence in the coastal ocean demands that we develop and adopt new marine technologies, including: autonomous marine vehicles, acoustic and optical sensors, remote sensing technologies, chemical and genetic methods and the latest modelling capability.

Marine Autonomy

Autonomous marine technology such as ocean gliders, un-manned surface vehicles and autonomous underwater vehicles provide the means to make multi-parameter, surface-to-seabed measurements of Essential Ocean Variables for sustained periods of time without the presence of a research ship. They provide the means to address boundary current, shelf-edge exchange and shelf scale circulation questions and move us towards quantification of climatically significant transports of heat, freshwater, carbon and nutrients and the biological impacts. They will be an essential tool in elucidating the role of turbulent mixing processes and we are challenged with using them to advance our understanding of gas exchange across the air-sea interface. Marine autonomy offers the ability to make measurements at locations and times of the year that are typically under-sampled (e.g. during winter, through storms, under ice-cover) and at a fraction of the cost of traditional oceanographic research platforms. We must use this capability to close gaps in our understanding of physical and biogeochemical seasonality, inter-annual and spatial variability. Marine autonomy is also key to resolving sub-surface property gradients, both physical and chemical, that drive shelf sea dynamics across all scales.

Acoustics and optics

New acoustic and optical sensing techniques must be embraced if we are to make significant step changes in our understanding of benthic boundary layer dynamics, sediment re-suspension and transport processes, the role of mixed-sediments and the evolution of bedforms. A particular challenge here is to make measurements on small temporal and spatial scales, without artificially disturbing the properties and gradients being targeted. Further, fibre optic cabling used for telecommunications has the potential to monitor changes in bottom temperature and current magnitude and to detect instabilities and slope failures along the continental slope.

Remote sensing

Remote sensing technologies, including marine radar, flown onboard satellites and aircraft and installed on ships and along the coastline provide synoptic views of highly dynamic areas and will allow us to address many of the coastal ocean questions that we are faced with. We are challenged with harnessing recent advances in shallow water, intertidal and shoreline mapping capabilities to understand, on locally relevant scales, the changing hydro- and sediment dynamics of the coastline, both natural and forced by human activity. Mapping and assessment of the state of vegetated coastal habitats using remote sensing can contribute to blue carbon stock assessments.

Improved coastal altimetry products, salinity derived from satellite sensors and high-resolution, remotely sensed information about coastal currents, sea-level, wind and wave characteristics must be used to improve understanding of the pathways of freshwater and its material loads as it enters and leaves the coastal ocean zone and to study storm surge and flooding events along the coast. Further, ocean colour products from space provide information on suspended sediment loads and water quality and the composition of phytoplankton communities.

Chemical and genetic methods

(Include bio-sensing and human health hazards…..)

The next generation of sensors for macro- and micro-nutrients, trace metals, carbonate chemistry, oxygen and micro-plastics (others…) will drive forward step changes in our understanding of carbon and nutrient cycling in the coastal ocean, eutrophication and hypoxic events, harmful algal blooms and the introduction and dispersal of pollutants.

Next generation modelling for coastal and shelf sea science

The development of comprehensive land-ocean-atmosphere modelling capability at resolutions appropriate for the coastal ocean demands that we find the optimal balance between scale, process complexity, simulation length and uncertainty analysis. Coupling between these components remains a perennial technical challenge, and when to couple (and when not) a crucial context dependent question. We must bridge the gap between blue skies processes identification and understanding with process representation in models, and acknowledge that there is often a tension between model accuracy (in an operational sense) and representation of complex processes. Improvements in modelling capability and resolution creates new challenges around the storage and analysis of 'big-data'. Ultimately, optimal modelling capability will require a whole-systems approach.

Integrated sensor networks and adaptive sampling

The coastal ocean and its interactions with the open ocean, atmosphere, land and cryosphere operates on a wide spectrum of temporal and spatial scales. We are challenged with marrying together large-scale synoptic observations of the surface made from space, with the sub-mesoscale to very fine resolution observations of the sub-surface made in-situ from a variety of static and moving platforms.

At a time when we have the technology to rapidly transfer large volumes of data all over the world and to communicate in near-real time with instrumentation deployed at sea or in orbit around Earth, we must develop integrated networks of sensors across shelf seas and the coastal zone, including both new and existing technology, that provide the spatially and temporally resolved suites of measurements we require to improve our process understanding, modelling capabilities and predictive skill.

We are challenged with designing sensor networks that, based on real-time measurements, are able to adapt their sampling strategies thereby delivering highly resolved measurements throughout key (e.g. spring phytoplankton bloom) and episodic, extreme events (e.g. storm surges) as well as seasonal to interannual scale monitoring of essential ocean variables. This may require the use of artificial intelligence algorithms (e.g. machine leaning) and statistical modelling to autonomously make decisions on sampling strategy.

Sensor networks will need to include smart technologies (e.g. the 'internet of things', Sensor Web Enablement, data brokering application programming interfaces) and common metadata standards to support sensor-to-sensor communication and the aggregation of data across sensor networks.

Integrated sensor networks and adaptive sampling approaches that provide quicker access to publicly available data over wider areas will improve early warning systems, protecting people and coastal assets from hazards such as tsunamis, storm surges, wave overtopping, harmful algal blooms and hypoxia.

The development of marine autonomy, new measurement techniques, integrated sensor networks and processing algorithms will enable new areas of research, stimulate new economic growth, support the planning of naval operations, contribute to international seabed mapping efforts, provide early warning hazard alerts and provide baseline data on ecosystem status and function against which change can be assessed.

Integrating observations and forecast modelling

The dynamic nature of shelf seas makes the spatial applicability of an individual observation a highly complex problem. This is vital for data-assimilation techniques, which have been largely developed for the open ocean and not yet adapted for the differing dynamical regime of the coastal ocean. Furthermore, industry standard remote sensing products are typically of limited use in the coastal zone (e.g. AVISO sea surface height) where much higher resolution datasets are required, and more complex processing algorithms are needed. A step-change in shelf sea observing, prediction networks and dynamical understanding can be made by integrating marine autonomy, near-coastal satellite data and coupled physics-ecosystem models.

We must develop our ability to assimilate, in near-real time, data collected from both autonomous vehicles and satellites into operational model forecasting and reanalysis systems, which in turn are used to identify optimal sampling strategies and survey locations. The challenges surrounding this ambition are numerous. Identifying the optimal combinations of both physical and biogeochemical observations, and the regionally variable sets of spatial and temporal scales across which assimilated data can reliably inform is non-trivial. A specific challenge is the impact of physical assimilation on the ecosystem models, e.g. ensuring that it maintains realistic property balances and gradients.

The design of next generation, cost-effective monitoring systems that integrate the latest advances in marine autonomy, in-situ sensors and remote sensing with high-resolution modelling capability will provide more efficient and effective monitoring than existing *ad hoc* and largely static systems. This will drive improved prediction of key events (seasonal phytoplankton blooms, harmful algal blooms, oxygen depletion) and the fate of pollutants, a more extensive evidence base for assessment of ecosystem health and more reliable projections of climate change.

Research priorities

In light of these research challenges, The National Oceanography Centre identifies the following coastal and shelf-sea research priorities:

1. To understand and quantify the balance and interactions of physical, chemical and biological processes in coastal zones and shelf seas around the world, their seasonal to decadal scale variability and their role in the whole Earth system.

2. To determine how the balance of physical, chemical and biological processes will be affected by climate change over the next century, and the consequences of disrupting these balances, for both regional and remote ocean climate, coastal hazards and resilience, and the health, vulnerability and adaptability of coastal ecosystems, habitats and their peoples.

3. To quantify the magnitudes, rates and spatial scales over which direct human activity is disturbing the natural coastal ocean, and to identify the far-field consequences of these changes.

4. To distinguish between the impacts of climate change and those that result from direct human activity

5. To seek long-term, innovative solutions and mitigation strategies to climate and human driven changes that enable a balance between environmental, economic, political, social and cultural pressures and limitations.

6. To engage coastal communities, marine policy and regulatory bodies and coastal stakeholders to improve the articulation and accessibility of new knowledge and evidence available to address societally relevant questions thereby delivering impact beyond scientific excellence.