Scanning the Horizon:

The Future Role of Research Ships and Autonomous Measurement Systems in Marine and Earth Sciences

Foreword

The Challenger Society for Marine Science and the National Oceanography Centre (NOC) Association have for some time felt that the rapid advances in marine science, the recent large capital investments in the UK research vessel fleet as well as advances in technology mean that it is timely to give serious thought to the ways in which marine and allied earth sciences in the UK will sustain their current excellence into the future. For these reasons we convened a one-day workshop, the aim of which was to review achievements and look to the future of Marine and Earth Science. We invited a number of prominent researchers who make measurements at sea and to ensure a strong future-focus we included a good number of early- and mid-career scientists. We believe that the results of this exercise, described in this report, show conclusively that new technologies do indeed provide some important opportunities to access and measure the ocean in new ways over the next 10-years and we expect uptake of this technology to accelerate rapidly in some fields. This exciting prospect is, however, tempered by the realism that these systems cannot do everything and their use should be viewed as part of a wider suite of measurement systems. Research ships will remain critical to key areas of Marine and Earth science for the foreseeable future and are fundamental assets enabling the UK to sustain its international scientific competitiveness and to tackle scientific challenges important to the future wellbeing and prosperity of society.

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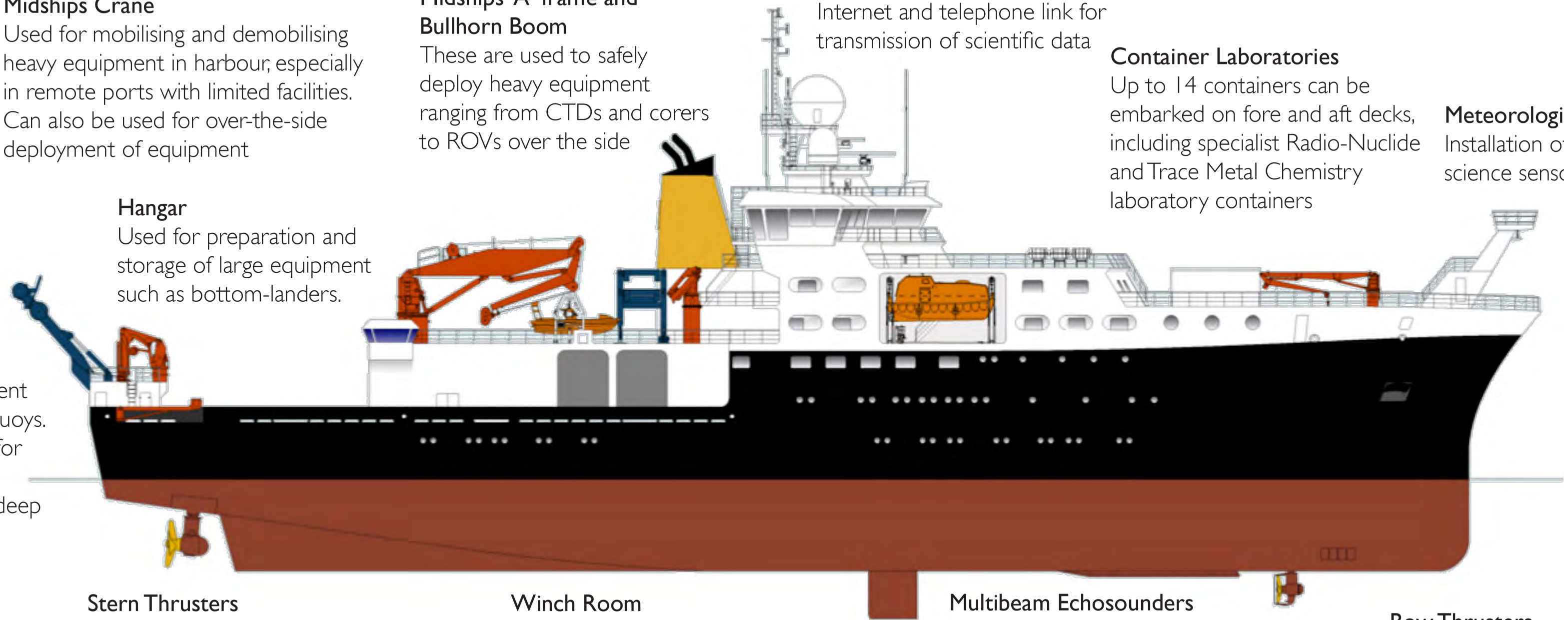
Headline Messages

The United Kingdom

1. **is a world leader in ocean affairs**
   - has vital economic, business and policy interests in the ocean
   - these interests will grow as the importance and value of the ocean becomes ever-more clear
   - our marine industries compete strongly in global markets
   - is home to world-class ocean scientists and engineers
   - our industry is supplied with skills, expertise and knowledge from the research base
2. **has invested heavily in world-class ocean science infrastructure**
   - £120m in two new global-class research ships – both delivered on time and to budget
   - tonne for tonne now has the most advanced research ship fleet in the world
   - has made a recent investment of almost £15m in autonomous marine measurement technologies – one of "eight great technologies" where the UK leads and which has growth potential
3. **should now fully harness its superb assets to secure long-term scientific return on investment**
   - autonomous and robotics technologies can transform specific types of critical marine measurements
   - sustained funding for development and use of these technologies is needed to secure this transformation in the long-term with the UK in a leading position
   - further new advanced ocean-sensing infrastructures are poised for new investment which will support excellent science and deliver beneficial wider impact
   - research ships will remain integral to delivering strategically important science that cannot be done in other ways
   - our world-class research ships should be fully exploited to drive home the UK's scientific competitive advantage, train skilled people, attract the best scientists to come here, and enable us to heavily lever our investments internationally through collaborative partnerships and to secure access to other facilities we do not have
   - UK scientists stand ready to fully exploit our world-class research infrastructures in search of new discoveries and to undertake strategically important science in the national interest.

Science Capabilities of a Multipurpose Research Ship



Working Decks
Extensive open and reconfigurable decks, enabling installation of a wide variety of portable and containerised systems, as well as seismic survey systems

Midships Crane
Used for mobilising and demobilising heavy equipment in harbour, especially in remote ports with limited facilities. Can also be used for over-the-side deployment of equipment

Midships 'A' frame and Bullhorn Boom
These are used to safely deploy heavy equipment ranging from CTDs and corers to ROVs over the side

VSat Communications Dome
Internet and telephone link for transmission of scientific data

Container Laboratories
Up to 14 containers can be embarked on fore and aft decks, including specialist Radio-Nuclide and Trace Metal Chemistry laboratory containers

Meteorological Mast
Installation of atmospheric science sensors

Hangar
Used for preparation and storage of large equipment such as bottom-landers.

Stern Frame
Used for deployment of moorings and buoys. Can also be used for towing equipment such as TOBI and deep trawling

Stern Thrusters
The ship's main propulsion; these are designed for good manoeuvrability and efficient operation, especially while maintaining station in Dynamic Position mode for ROV operations.

Winch Room
Comprises a suite of 6 deep-sea winch systems for deployment of heavy overboard equipment using a range of specialist cables including synthetic, conducting and fibre-optic systems

Multibeam Echosounders
Seabed mapping down to full ocean depth integrated with a sub-bottom profiler to map geological structures. Acoustic Doppler Current Profilers are also fitted to measure currents

Bow Thrusters
Used for accurate positioning of ship for precision sampling.

Laboratories
Ten laboratories with a range of specialist facilities including fume hoods, clean seawater and gas supplies. Laboratories uses include wet and dry sampling areas, as well as constant temperature and trace-metal facilities. The control room also houses instrumentation for acoustic sensors

Drop Keels
Deploys acoustic sensors more effectively below hull interaction effects like bubble sweep-down. A wide range of acoustic sensors can be deployed, including systems used for marine biomass estimation

The Earth System

1. The ocean, its life and the earth interior it covers are integral components of the Earth system and thus of our lives. The components of the Earth system that we need to access the ocean to sample range from the Earth's core and crust through the seafloor and its sediments, the dark bottom waters to the upper sunlit ocean, the continental slopes, shelves and coastal seas, to the air-sea boundary. The influence of the ocean is pervasive but largely hidden. It affects seasonal weather and climate, even in regions far inland, and provides many of the day to day resources we take for granted.

40% of the world's population lives within 100 km of the sea where population is growing fastest

2. Understanding in detail how the components of the Earth-system work individually and collectively and their interactions with people is crucial for tackling some of the greatest human-focussed challenges of our age:
   - benefiting from natural resources
   - increasing resilience of people, infrastructure and economic wellbeing to environmental hazards
   - managing environmental change and variability affecting the growing human population – which is growing fastest in urbanised, low-lying coastal regions
   - responsible stewardship of the ocean for the benefit of ourselves and future generations

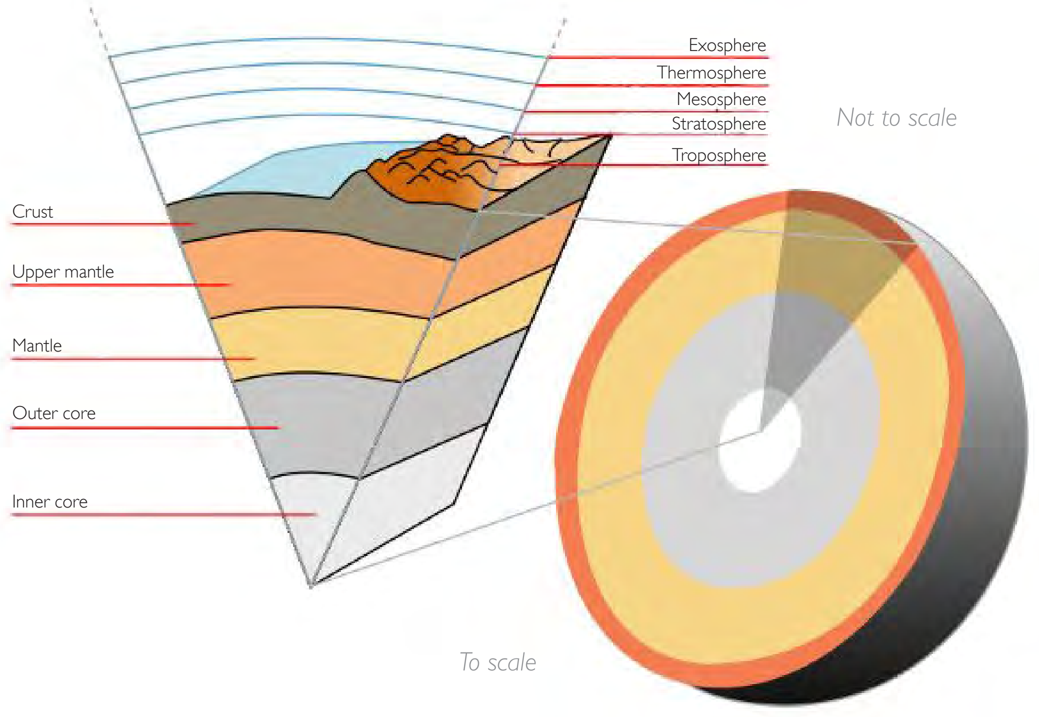
Over one billion people in the world rely on the ocean for their primary source of animal protein

The ocean

- 71% of the planet and its interior is covered by the ocean;
- 50% of oxygen we breath is produced by ocean plankton;
- 80% of the Earth's living organisms are in the sea;
- 93% of the Earth's CO_2 is stored and re-cycled by the ocean which absorbs 30% of CO_2 emissions caused by humans;
- the upper 3m of the ocean contains as much heat as the overlying atmosphere meaning the ocean is critical in regulating seasonal weather and climate;

3. This understanding is used to develop and test the models of the Earth system which we rely on to make predictions and test future scenarios (the basis of many practical applications such as seasonal weather forecasts) and to inform future measurement strategies. This knowledge is derived from observations of, and experimentation within, the ocean, atmosphere, seafloor and earth interior. It is fundamental to informing the evidence base required for the responsible management of our planet. It provides the information, technology, expertise and know-how that underpin decisions made by businesses, governments and individual citizens which have fundamental impacts on our lives.

Natural disasters – most of marine origin – have cost the world economy $2.5 trillion since 2000



Slice of Earth core to atmosphere

The Ocean and the United Kingdom

4. As an island trading nation the UK is strongly affected by the ocean which exerts substantial influences over our climate and weather, harbours natural hazards, supports significant levels of economic activity, and offers future opportunities for economic growth and jobs.

5. The varied maritime climate of the UK is much warmer (about 5°C on average) than that of countries at similar latitudes, due in part to the release of heat within the North Atlantic west of the UK. Moreover, the ocean has stored 93% of the Earth's excess heat energy over the last 50 years and acts to slow the rate of climate change by absorbing one quarter of anthropogenic CO_2 emissions.

6. Natural disasters (most of marine origin) have cost the world economy $2.5 trillion since 2000. The UK is particularly vulnerable to storm surges with £3bn of assets directly at risk and £30bn of wider economic activity in jeopardy in the event of serious flooding from the sea in London alone. The UK operates within the globalised economy and even hazards on the other side of the world such as submarine earthquakes, submarine landslides and their resulting tsunami or extreme weather such as hurricanes or typhoons affect us indirectly (such as through insurance losses, commodity and fuel prices, or disruption of transport and supply chains). Effective response to natural hazards requires a comprehensive assessment of hazard potential, vulnerability and risk in the context of future environmental change.

7. The UK benefits from ocean resources which include hydrocarbons (the largest contributor to the UK Gross Value Added of all industrial sectors); building materials (12% of aggregates used in construction come from the sea), renewable energy (the UK has the largest installed offshore wind power in the world and the largest tidal energy potential). The ocean also offers potential for more novel resources (natural products and pharmaceuticals such as cancer drugs that come from marine organisms). Due to increased pressure on global land-based resources and growing fears over their security of supply, resource exploration and exploitation is moving into progressively deeper waters as reserves in shallower near shore environments become depleted (in 2000, world-wide there were 44 oil and gas fields in water deeper than 500m – in 2007 there were 157).

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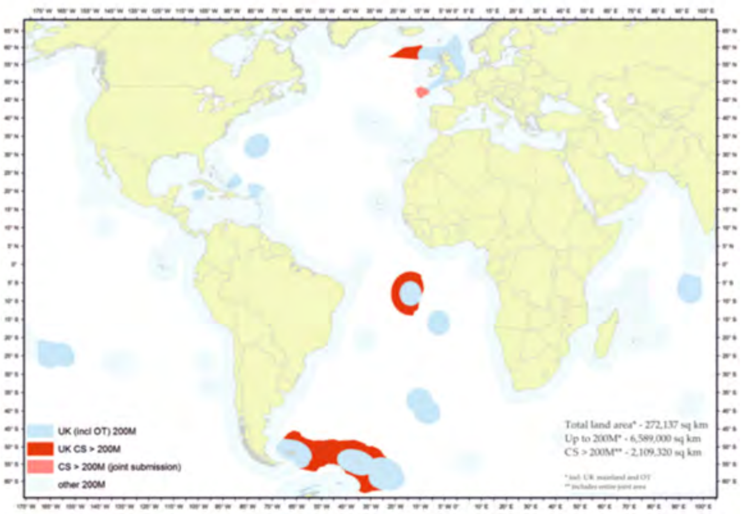
8. The UK Exclusive Economic Zone is 781,800 km^2 in size, about three times its land area. Jurisdiction gives us rights of exploitation but also carries responsibilities for stewardship based on a sound evidence base. The shared vision of the UK Government and Devolved Administrations is for clean, healthy, safe, productive and biologically diverse oceans and seas. The European Marine Strategy Framework Directive (MSFD) requires EU Member States including the UK to achieve Good Environmental Status in their waters by 2020.

9. Combined, the UK and its Overseas Territories have one of the top-5 largest EEZs in the world with an undersea area of nearly 9 million km^2 comprising extensive continental shelf, continental margin and deep sea provinces - over 30 times their combined land area. Beyond the waters claimed or under the jurisdiction of the countries of the world, an area of the ocean equivalent to the entire land-surface of the Earth is under no national jurisdiction and is governed by international agreements - including the United Nations Convention on the Law of the Sea, the London Convention, the Convention on Biological Diversity and various Regional Seas Conventions such as the Oslo and Paris Convention covering the North Atlantic. The UK has a vital and growing national interest in maintaining its presence in the open ocean and in playing a continuing leadership role in international ocean affairs, informed by sound science.



UK's Exclusive Economic Zone including overseas territories

10. The marine sector (industries and their supply chains that rely directly on the sea) makes an important contribution to the UK economy (over £49bn Gross Added Value per year, 900,000 jobs, 4.2% GDP) and this will continue to grow as economic activity shifts into the ocean and major world-wide opportunities increase. The UK marine sector has extensive experience and global reach underpinned by a strong marine science and technology base which contributes to its competitive edge (eg, the output of graduates and PhD level skills grounded in marine geophysics research supplies the UK oil & gas sector). Beyond the marine sector, many other areas of the UK economy are affected indirectly, often in hidden and surprising ways by the ocean (eg, sectors sensitive to seasonal weather such as water utilities, energy supply and distribution, agriculture, retail, transport and healthcare). Over 95% of the internet traffic we take for granted and communications for financial markets is carried by sub-sea fibre optic cables – with some important hubs potentially vulnerable to disruption by submarine landslides.

> Marine industries contribute 4.2% to UK GDP and many other business sectors are impacted indirectly by the ocean

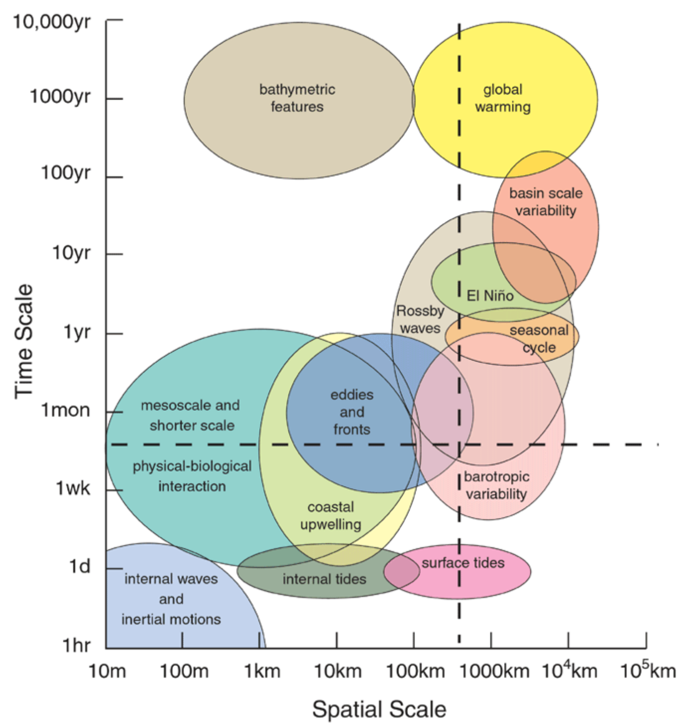
UK Marine Science

11. The United Kingdom has world-class marine and earth science expertise based on seagoing measurement as measured by the scientific impact of its research. At least 53 scientific papers published in Nature and Science journals since 2002 (with at total of 5,000 citations and an overall h-index of 31) resulted directly from the UK multi-purpose ships and ships bartered with them (**Appendix 1**).

Over the last decade the research ships have supported a number of NERC-and European funded large strategic research programmes and other consortia and smaller projects (**Appendix 2**). The large strategic programmes include: Rapid Climate Change (RAPID, RAPID-WAVE); Surface Ocean Lower Atmosphere Studies (SOLAS); Marine Productivity (the UK contribution to GLOBEC); Ocean Surface Boundary Layer (OSMOSIS); Integrated Ocean Drilling Programme site surveys (IODP); Shelf Edge Exchange (FASTNEt); ECOMAR; GEOTRACES; Ocean Acidification; Hotspot Ecosystem Research and Man's Impact On European Seas (HERMES). The ships have also been central to delivering sustained ocean observation programmes including the Extended Ellet Line (Repeat Hydrographic Section from Scotland to Iceland); the Antarctic Circumpolar Current Repeat Hydrographic Sections (Drake Passage); the Porcupine Abyssal Plain Deep Sea Observatory (PAP) and the Atlantic Meridional Transect (repeat Biogeochemical Section and AMT).

The ships will be supporting major future funded programmes including RAPID continuation (joint with USA); Overturning in the Sub-polar North Atlantic Program (OSNAP, joint with USA); Greenhouse Gases; Shelf Seas Biogeochemistry.

13. In recent years, UK-based scientists have achieved a series of outstanding breakthroughs based on new measurements from the ocean. These include:



Time and space scales of physical and biological processes in the ocean

- discovery of the first hydrothermal vent systems in the Southern Ocean and discovery of the world's deepest, hottest hydrothermal vents in the Cayman Trough,
- discovery of the largest submarine landslide in the world off Northwest Africa
- quantifying the role of desert dust is biogeochemical cycling and primary production in the upper ocean;
- the first ever extensive measurements under a rapidly melting Antarctic ice shelf using an autonomous submersible

14. These insights have been supported by world class research infrastructure in which the UK has been investing strongly, and which is vitally important for the vibrancy of the UK marine and earth science base. The primary platforms for making marine measurements fall into three broad classes:

- Ships
- Satellites
- Autonomous and robotic systems and observatories

15. Different types of platform are better suited to making measurements of (a) different parts of the broad spectrum of space- and time-variability, and (b) different parameters and processes (**Appendix 3**). For example, satellites give global coverage but at low time resolution, see only the thin surface skin of the ocean and give only indirect measurements of biological processes (eg,. via sea-colour) that ultimately must be measured directly within the sea. Consequently the different platforms need to be used in a complementary way because each has their own strengths and weaknesses and hence each has a distinctive role to play in the ocean observing system.

1-50 million undiscovered life forms are thought to live in the sea

16. Research ships play a distinctive and versatile role within the range of available ocean observing platforms. Indeed, everything we know about the ocean below 2km depth and the Earth interior below has depended on ships. They are indispensable for key areas of marine and Earth science including:

- Deep sea and open ocean biology – needing *in situ* cameras, specimen sampling, large volume water sampling, in situ experimentation, incubations (enabling marine resources and discovery science)
- Biogeochemistry – needing laboratory based analytical facilities at sea and where there is limited availability of sensors sufficiently reliable or miniaturised for deployment on autonomous platforms (enabling environmental change, climate change and discovery science)
- Deep and shallow Geophysics – needing high energy seismic streamers, deployment of bottom instrumentation, rock drilling (enabling geo-hazards, past environmental change and discovery science)

- Seafloor Geology, Geophysics, Geochemistry – needing Remotely Operated Vehicle (ROV)-based sampling; sediment sampling by grabs and coring, large area swath-mapping (enabling marine resources, seafloor hazards, environmental change and discovery science)
- Air–Sea Interactions – needing process and experimentation studies to understand energy and chemical fluxing between the ocean and atmosphere, especially at high latitude and high sea-state (enabling environmental and climate change, weather hazards and discovery science).

> 42,000 scientist days at sea delivered from 2008-2013 by UK multi-purpose research ships

17. The main features of large research ships that make them indispensible are:
    - multi-purpose – supporting science from multiple disciplines – ocean physics, biogeochemistry, biology, geology, geophysics, geochemistry, meteorology, engineering and technology innovation.
    - highly flexible platforms capable of being rapidly re-configured for different science – often with containerised laboratories and instrument control systems;
    - equipped with sophisticated winch suites for over-side handling and towing of large, high power-demand instrument packages (Remotely operated vehicles, towed seismic arrays, water samplers) and long cables and tethers (typically up to 10 km length);
    - *in situ* laboratories for both wet and dry processing of samples and large analytical facilities where immediate analysis at sea is essential (sample integrity, adaptive sampling strategies);
    - ship mounted instrument packages for underway and other sampling (multi-beam echo-sounders, Acoustic Doppler Current Profilers);
    - large deck spaces for safe, efficient over-side handling, deployment and recovery of instruments, sea-floor landers, moorings;
    - highly manoeuvrable (dynamic positioning) with high precision (metres) surface and sub-surface positioning over-the-ground (for handling of deep diving remotely operated vehicles, precision repeat sampling and sampling of metre-scale sea-floor features such as hydrothermal vents).
    - accommodation spaces for up to 30 scientists and technicians essential for multi-disciplinary sciences and able to operate a 24/7 work-pattern over extended durations (50 days) unsupported in the remote parts of the ocean and able to endure high sea states without recourse to refuge in port.
18. In contrast, autonomous vehicles such as profiling floats, sea-gliders, unmanned surface vehicles (USVs) and autonomous underwater vehicles (AUVs) are designed around low power requirements and make their own distinctive contributions to ocean measurement. As the next generation of miniaturised low-power sensors become truly operational, autonomous systems offer the prospect of transforming particular areas of marine science by allowing increasingly cost-effective measurements in places and in ways that would never be possible with ships (eg under Antarctic ice shelves) and to tackle the gross under-sampling of the ocean in space and time by having continuous mobile sampling in place all day every day. Their promise is continuous, unmanned missions to Planet Ocean.

    However it is also important to be realistic about the time-scale and degree to which these systems can or will replace ships. They will not replace the measurements where high-power, high volume sampling methods are needed. Where autonomous systems can replace ship-based measurement an overlap period with ships will be needed as will continuous investment in the long-term (it took 10 years for the Argo profiling float array to reach its target sampling regime for upper ocean temperature and salinity). It is clear that many of the most exciting applications involve ships and autonomous vehicles working very closely together – such as broad-scale mapping by a ship to target detailed sampling by an AUV.

> The UK has the most advanced research ships in the world

    The distinctive strengths of autonomous systems are
    - increasing the spatial coverage of small numbers of parameters by using large numbers of lower cost units – the Argo profiling float programme, which has seeded the ocean with over 3,000 floats, has transformed the global coverage of upper ocean (2 km) temperature and salinity;
    - potential continuous measurement for extended periods for routine measurements (when ships need to return to port);
    - their capability to make measurements in regions inaccessible by ships (eg under ice shelves)

Autonomous Underwater Vehicle (AUV)

19. In recent years, the UK Government with the Natural Environment Research Council (NERC) has made £120M of capital investments in two advanced, global-class, multi-purpose research vessels, the RRS *James Cook* and RRS *Discovery*. Moreover, nearly £15M additional investment is being made in marine autonomous and robotics systems, one of "eight great technologies" identified as where the UK has distinctive expertise and growth potential.

> Over 50 *Nature* and *Science* papers published sinces 2002, 5,000 citations

20. These investments, coupled with (a) the rapid evolution in marine science; (b) the cost of shipboard measurement programmes and (c) the opportunities presented by autonomous technologies, mean that it is timely to consider the future likely role research vessels will play in maintaining the UK position as a leader in ocean and earth sciences.

21 To this end the Challenger Society for Marine Science and the NOC Association convened a horizon-scanning workshop focussed on the likely future demand for, and usage of, large scale oceanographic research vessels. The meeting was held at the Institute of Marine Engineering Science and Technology in London on 3 October 2013. Invitees and participants included a range of active sea-going oceanographers, atmospheric scientists and geoscientists from a variety of UK Universities and Research Centres.

22 The workshop focussed on identifying the key Earth system science questions to which understanding the marine environment contributes, determining the extent to which ship-based measurements are key to addressing them and the likely future prospects for some component of this work migrating to autonomous systems.

23. The following sections review, from the perspective of the science community, the key areas of Marine and Earth science that are likely to remain critically dependent on research ships for at least the next decade, whilst identifying areas where autonomous measurements offer increasing prospects over the next 1-10 years. The review is organised to look upward from the Earth's interior, through the ocean and its continental shelves to the interface between the sea and the lower atmosphere

> Autonomous systems offer the prospect of umanned missions to Planet Ocean

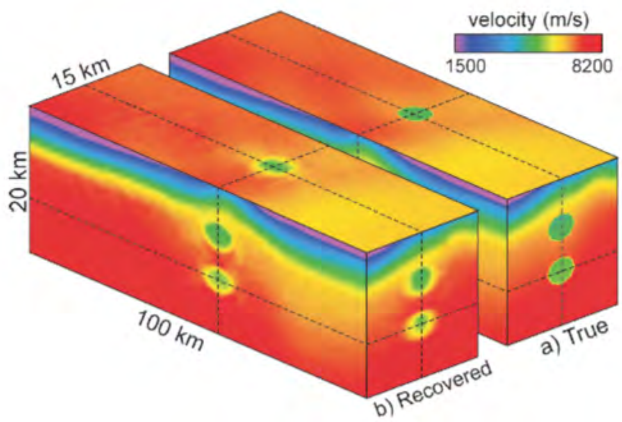
Recovering the Isis *deep water Remotely Operated Vehicle (ROV)*

The Earth Interior

21. Processes operating within the Earth from core to surface
    - control the heating and cooling of the planet;
    - control the motion of plates;
    - drive the climate and the hydrodynamics of the oceans;
    - generate the protective magnetic field;
    - result in most of the world's exploitable resources.
22. Our understanding of these processes is built on observational data, and much of this observational data has been acquired from ships. Through measurements from ships we know that tectonic plates have moved across the Earth's surface, that regions of continental extension provide good prospects for hydrocarbon exploration, and that the largest recorded earthquakes are associated with gently dipping plate boundaries beneath subduction zones.
23. Continuing ship-based geophysical programs, combined with appropriate sampling from research vessels or via the International Ocean Drilling Program, allow us to develop further this understanding. For example, processes of plate formation, destruction and recycling control the location of critical metal deposits. The recycling of plates creates the continents and can result in the release of volatiles to the atmosphere, volcanic eruptions, large magnitude earthquakes and associated tsunami. As continental plates rift, margins are formed that accumulate significant amounts of sediment, within which oil and gas reserves evolve from organic matter. The nature and volume of these reserves depend critically on the rate of plate margin subsidence and cooling after rifting. Understanding this thermal window of opportunity is critical to oil and gas exploration and the economic viability of identified reservoirs.

The role of ships in future science

24. Modern satellite technology has provided impressive insights into the interior structure of the Earth and other planets, on a global scale. However, satellite imaging of the Earth's solid surface is limited by the fact that electromagnetic waves are strongly attenuated by seawater. Satellites can make highly sensitive measurements of magnetic and gravity fields, but ultimately their resolution is limited to 10s to 100s of kilometres, and they cannot resolve structures at the scales of interest for many Earth processes. Therefore most of our insights come from acoustic or elastic waves, which are attenuated little by seawater but require sources and receivers immersed in the ocean, by measurements of potential fields at or beneath the ocean surface, and by autonomous instruments placed on the ocean floor.
25. All of these technologies require the use of ships. Acoustic and elastic imaging of the Earth's interior beyond depths of a few hundred metres typically requires seismic sources involving large volumes of air, delivered rapidly and at high pressure from onboard compressors, and the towing of long sensor cables. Autonomous systems cannot deliver sufficient power over long enough periods to run sensors that measure the static magnetic field, nor provide the stable platform required for gravity measurements. Autonomous seabed instruments require ships to deploy and recover them. These techniques are all dependent on equipment of significant size that consumes significant power; in the foreseeable future the power requirements will not be deliverable by battery technology alone and the equipment sizes will continue to exceed the available payload of autonomous vehicles, so large surface vessels will still be required.



Simulation of seismic imaging of the magma storage system beneath the active Soufriere Hills Volcano by full waveform inversion using offshore shots and seabed receivers

26. ***Case Study: Characterising the Earth's Core***

    The Earth's core generates the magnetic field which protects the atmosphere and the solid Earth and its inhabitants from harmful incoming solar radiation. Recently the outer core has been found to be inhomogeneous on a hemispherical basis. This has implications for the uniformity of magnetic field coverage and the nature of field reversals. These findings are based on earthquake data from stations installed on land, which means most of the planet's surface is currently un-instrumented.

    To fully characterise the core's heterogeneity requires statically instrumenting the oceans. This has become technologically feasible, even in the deepest of waters; it just requires the equipment and a vessel to install it from, and to recover it for subsequent maintenance and reinstallation. The NERC's newly funded UKARRAY will require an offshore component spanning its entire territorial waters to deploy such instrumentation.

27. ***Case Study: Monitoring Gas Hydrates***

    Methane hydrate deposits accumulate within the sediment column on the margins of continents. These deposits represent both an energy resource and an environmental threat, because of the potential for release of methane, a powerful greenhouse gas, to the atmosphere. The processes that facilitate hydrate storage also have potential to underpin carbon sequestration. To understand hydrate accumulation requires the capability to image at high resolution well below the seabed. This is achieved using seismic and electromagnetic approaches from both ship towed and ship deployed seabed instruments.

The role of autonomous and robotic systems

28. Autonomous and robotic systems present exciting new opportunities to explore beneath the seabed, for example through direct sampling and acoustic sub-bottom profiling. Typically they are used for detailed sampling and imaging of structures that have been identified previously using more power-hungry geophysical tools mounted on surface vessels, and subsurface imaging is limited to the top few tens to perhaps hundreds of metres.

29. A key strategic danger of focusing all efforts on delivering sub-sea surface exploration solely by autonomous vehicles would be the loss of the ability to find targets of interest, to deploy and recover instrumented observatory arrays from the seabed, and undertake any research that has a sub-seabed focus beyond a few hundred metres depth.

Delivering Benefit

30. Many of the natural hazards humanity faces are driven by processes happening at sub-surface depths too great for AUVs to sample. For example, deep-seated plumbing systems feed magma to the near surface and thereby control volcanic eruptions, while plate boundary locking and slipping generates devastating earthquakes and tsunami.

31. The geophysical techniques used by the offshore hydrocarbon and minerals industries to locate and define critical resources were developed primarily in academic institutions. The selection of suitable targets for exploration is underpinned by an understanding of Earth interior processes that is built on marine geophysical datasets. Much of the specialised workforce leading this exploration effort has been trained through participating in ship-based geophysical research in academic institutions.

Mapping the seabed off Monserrat

Ocean Sediments

32. Ocean sediments provide a record of past climate, carbon cycling, and ecosystem change. Modern instrumental climate records do not capture a wide range of climate states, and are not long enough to assess the response to today's greenhouse forcing, or to fully understand the climate system. Ocean sediments indicate the range of possible climate behaviour, the processes that drive change, and the response of ecosystems to change. Important examples include assessment of the rates and magnitude of sea-level change; the discovery and characterisation of abrupt climate change; and ecosystem responses to ocean acidification.

33. The vast majority of material entering the ocean is removed to ocean sediments. Sediments close mass budgets for ocean particulate input, and chemical budgets for major elements and for key chemical species including nutrients and pollutants. The sea-floor alteration of sediments also controls the return flux to the deep-ocean of important chemical species.

34. Chemical and physical processes in ocean sediments control the burial of organic carbon, removing carbon from the ocean-atmosphere system, and creating the majority of exploitable hydrocarbons. Periods of earth history during which sediments were devoid of oxygen produced particularly important source rocks. Understanding sedimentary processes in the past and present is critical to assess the workings of the carbon cycle – fundamental to climate change and to hydrocarbon formation.

The role of ships

35. Sediment cores critical for assessment of past climate, and for understanding of global chemical cycles, cannot be collected without ships. Ships are fundamental for the present and future research on ocean sediments.

36. Long sediment records require ocean drilling, for which NERC ships are not equipped, but for which NERC buys into the IODP programme. NERC ships provide critical site survey data for IODP missions, including sediment cores and multi-channel seismic lines. This survey data gives UK scientists significant leverage in the international IODP programme.

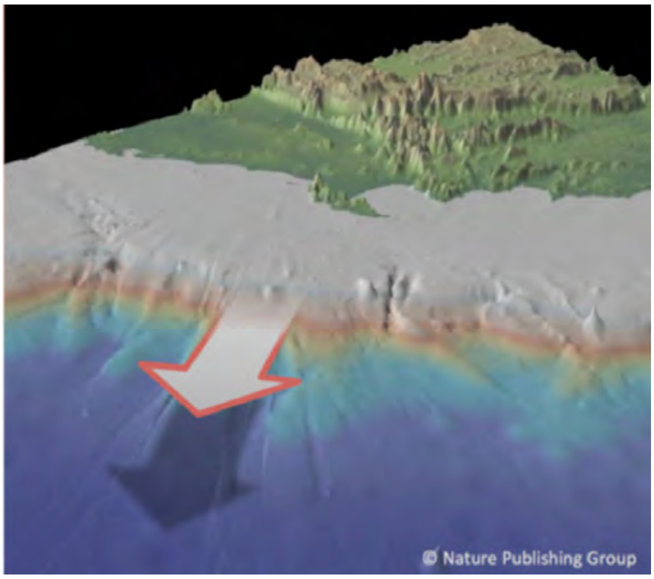
37. Powerful information about sedimentary process can be collected using sediment landers and flux chambers. Such sea-floor equipment relies on ships for deployment and recovery.

38. *Case study: Abrupt climate change*

Observations of past climate suggest that large and rapid (as fast as 10-20 years) changes occur and that changes in the Atlantic Meridional Overturning Circulation (AMOC) are a major factor in these changes. Recent work by UK scientists (eg, within the NERC Rapid Programme) have employed a novel combination of present day observations, sediment-based palaeo-reconstructions and a hierarchy of models (from local process models to global general circulation models) to improve our understanding of the role of the AMOC and other processes in abrupt climate change, and of the global and regional impacts of such change. As a result, our ability to monitor and predict potential future rapid climate change, particularly in the North Atlantic region, has been enhanced.

39. *Case study: Nutrient fluxes*

We sample the deep sea sediment-seawater interface to understand the rates and mechanisms of biogeochemical processes that control the composition of the oceans, and preserve records of past and present climate and planetary processes. Specific sampling locations are informed by real-time information gathered at sea. Samples are processed immediately on board ship in specialized lab environments so that natural systems are preserved. A recent study assessed the sediment supply to the South Atlantic margin of the limiting nutrient – iron. This work, part of the UK-GEOTRACES programme, set sediment fluxes of nutrients in the context of other fluxes to assess how ocean nutrient chemistry responds to changing conditions.



Distinct iron isotopic signatures and supply from marine sediment dissolution. *Nature Communications*, **4**, 2143.

The role of autonomous and robotic systems

40. Sediment traps constrain fluxes to sediments, and instrumented seafloor observatories provide useful future information about chemical and physical processes. Such systems require ships for deployment and recovery.

Delivery benefit

41. Predicting the response of the climate system and its constituent components to increasing levels of greenhouse gases is of major societal importance. Study of the past environment captured in ocean sediments continues to be a powerful approach for assessing climate processes and improving prediction. Areas of particular societal relevance include assessment of climate variability during warm periods, and the ice-sheet/sea-level response to forcing similar to that expected for the future.

42. Improved knowledge of the formation and distribution of hydrocarbons, including unconventionals, will be derived from study of modern and past ocean sediments. Ocean sediments are also a significant location for the sequestration of CO_2, requiring better knowledge of fluid movement and chemical reactions occurring in marine sediments.

43. Sediments are the ultimate sink for pollutants entering the ocean, including radionuclides (eg, from reprocessing), antifoulants (eg, tributyl tin), and those transported through the atmosphere (eg, lead, mercury). Sediment processes set the concentration and distribution of such pollutants in seawater, and for ecosystems on and in ocean sediments.

44. Deep-sea mining is increasingly considered as a viable resource for economically important metals. Knowledge of the distribution and formation of such deposits, and the likely environmental damage imposed by their possible exploitation, requires research on marine sediments.

The Seafloor

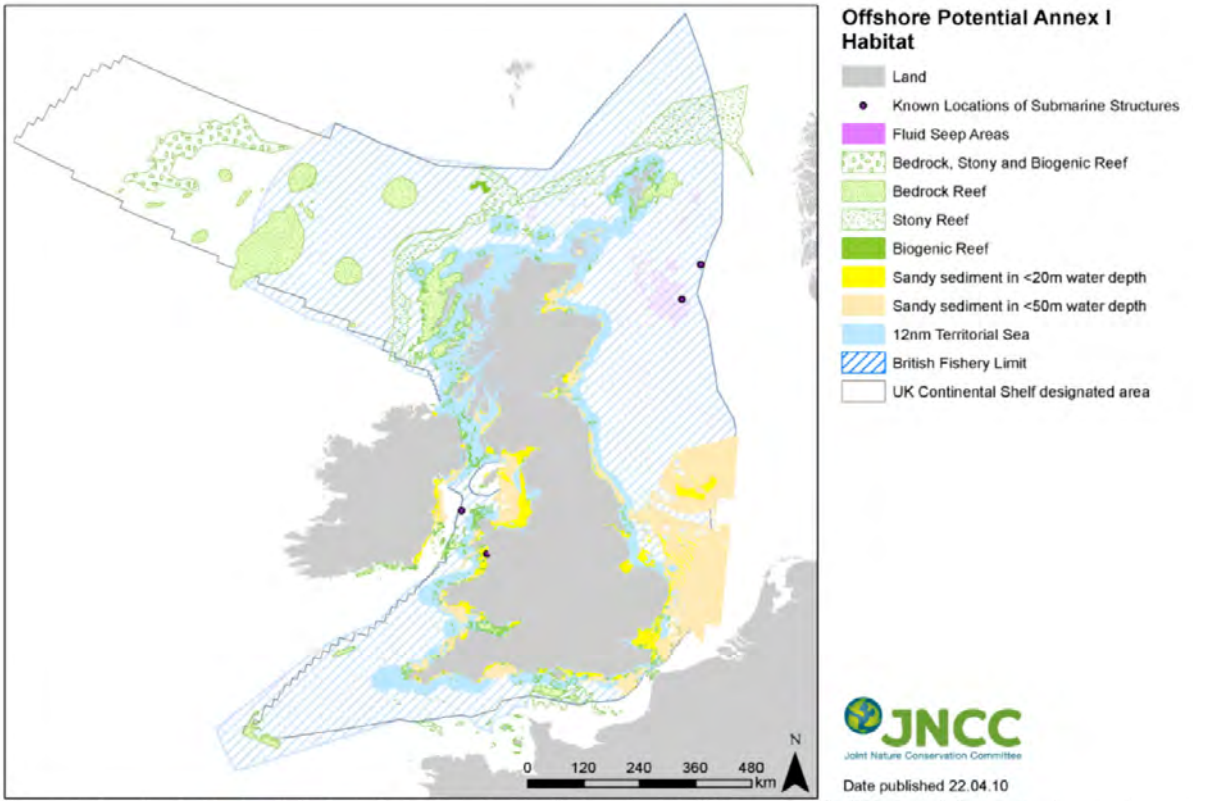
45. The UK is responsible for a large share of Europe's deep-seabed territory in the northeast Atlantic Ocean as well as broader areas associated with overseas territories globally. These areas support a range of poorly understood deep-water habitats from biodiverse abyssal plains through to rocky seamounts, sponge grounds and areas where cold-water corals have grown for thousands of years.

46. Many seafloor habitats qualify as Vulnerable Marine Ecosystems (VMEs; United Nations General Assembly Resolution 61/105) and as Ecologically and Biologically Significant Areas (Convention on Biological Diversity), yet we have only the most basic understanding of their biodiversity, functional ecology and resilience to change.

47. The UK plays a frontline role in the exploration of these ecosystems, the documenting of anthropogenic damage in the deep ocean and in the development of international policy and regulation of fisheries in the deep sea. The data collected as part of this research is actively used in marine management and by marine industries to enable efficient, environmentally responsible, cost-effective exploitation of organic (fisheries) and inorganic (offshore oil and gas) marine resources. The continued importance of this research, and its potential to add value for the UK, as well as international partners in the sustainable exploitation of deep-sea resources, is widely accepted.

The role of ships in future science

48. Understanding deep-sea and seafloor ecosystems requires fully interdisciplinary marine research fusing physical, geological, biogeochemical and ecological approaches. The UK is uniquely placed to address the challenges of deep-sea ecosystem science. Building upon the long history of deep-sea biology, the UK science community has embraced interdisciplinary research using NERC research vessels and innovative sampling and survey technologies.



The extent of UK seabed territory extending into the Atlantic Ocean (http://jncc.defra.gov.uk/page-4543)

49. Research vessels give the UK marine science community the ability to deploy amongst the most sophisticated deep-sea technology available. From the 6500 m remotely operated vehicle *Isis* through to autonomous underwater vehicles and seabed drills, these approaches are vital to sample and study seafloor ecosystems. Alongside this technology it is also critical that experienced and specialized technicians are available to work with scientists, often representing a seagoing element of science projects that maximize data collection and utilization of expensive facilities.

50. Surface vessels allow researchers to work within what are frequently structurally complex, long-lived habitats. Sampling remains a mainstay of deep-sea marine science, vital to underpin species identifications, genetic analysis, biogeochemical flux measurement and geological process studies among others. Autonomous systems and robotics have a vital role to play in this work, but they cannot replace the multipurpose roles performed by research vessels.

51. In general, the geographical location and size of both mineral and biological resources is poorly understood. Many are remote and qualifying and quantifying them requires global reach for data collection. Currently, and in the near to mid-term that capacity is provided predominantly by the use of ships. A combination of ship and AUV technology can be very effective at specific locations, such as locating the vent sites in the Caribbean, however, ships are still required to get to those locations as demonstrated in the following case study.

52. *Case Study: Hydrothermal exploration*

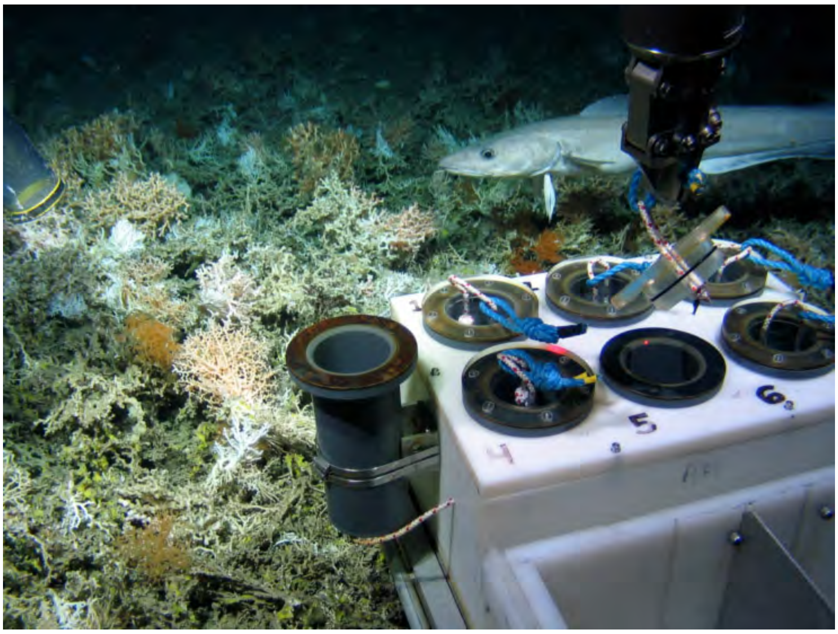
In recent years the UK research community has led the world in the location and study of hydrothermal vent fields. These have ranged from discoveries in the Antarctic, Caribbean and Atlantic. Three of these discovered sites are in UK territorial waters: Cayman Islands, Ascension Islands and the South Sandwich Islands. Whilst two of the vent fields are very remote, they all offer opportunities as mineral and biological resources. Around these active sites are many relict sites enriched in polymetallic sulphides, which are increasingly being viewed as exploitable resources; especially appealing as they could be exploited without the destruction of the associated unique biological communities.

These discoveries were, and will continue to be, enabled by use of our world class research vessels and associated AUV and ROV technologies. The multidisciplinary nature of cruises undertaken has led to significant new discoveries on the biogeography, evolution and ecology of the vent biota and the chemistry and geology associated with vents.

Delivering benefit

53. Pressures on marine ecosystems in the UK and around the world are increasing. The physical impact of fishing extends into the deep-waters west of the UK where both fish populations and seabed habitats have already been substantially modified in areas with little or no baseline data. Alongside global warming, the release of carbon dioxide from the burning of fossil fuels is causing global acidification of the oceans. This change in ocean chemistry threatens marine organisms that rely on calcium carbonate shells and skeletons including corals that structure habitats for many other species.

54. Research ships are central to the UK's ability to understand ecologically and economically important seafloor and deep-sea ecosystems and the consequences of over-harvesting and future physical and chemical changes. This knowledge directly affects the UK's capacity to inform national and international policy and ensure the future sustainable exploitation of organic and inorganic marine resources.



Remotely Operated vehicles (ROVs) allow for precisely controlled sampling within delicate deep-sea habitats. Image shows the dense coral framework on the Logachev coral carbonate mound province (Rockall Bank) courtesy Heriot-Watt University Changing Oceans Expedition 2012 (RRS James Cook *073)*

The Deep Ocean

55. The ocean is responsible for absorbing 30% of anthropogenic carbon released into the atmosphere. Carbon is transferred from the surface ocean to intermediate depths and to the deep ocean via processes of vertical mixing and the sinking of organic primary production (the biological carbon pump) where it is stored on climatically significant time scales. Similarly, the deep ocean, between 700 – 2000 m, has a significant role in storing heat that has resulted from anthropogenic CO_2 emissions.

56. Future effects of climate change, including ocean acidification, have the potential to significantly disrupt the biological carbon pump and directly impact the oceans ability to uptake anthropogenic CO_2. However, our current knowledge regarding potential disruptions is impaired due to a relatively poor understanding of processes acting below the epipelagic zone (upper 200m of the water column). A key research priority for the future is to quantify the component of active carbon transport in to the deep ocean resulting from the diurnal migration of mesopelagic fauna and the death and sinking of marine organisms.

57. How ocean currents interact with topography to influence pelagic and benthic ecosystems and the role of these systems in bentho-pelagic coupling are also important areas of future research, which have both regional and global relevance and implications for resource management and conservation. The UK has already established a lead in some areas of this research using multidisciplinary approaches. For example, in Drake Passage through studies of diapycnal mixing and in the Indian Ocean through investigations into the effects of water masses on pelagic ecosystems, seamount biota and human impacts on seamounts/ridges and associated ecosystems.

The role of ships in future science

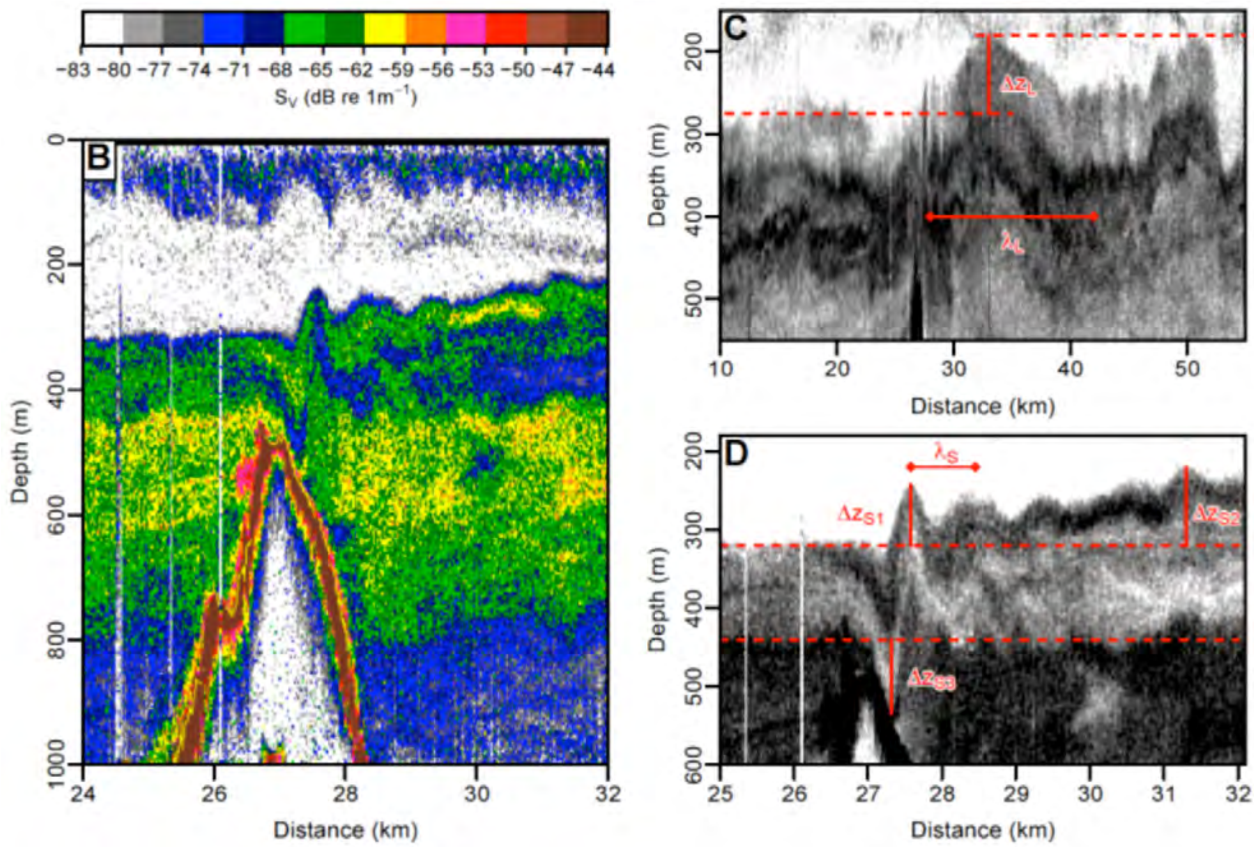
58. Biological studies to assess deep pelagic and benthic ecosystems typically require vast amounts of coincident measurements including

- Sea bed mapping using SWATH bathymetry;
- Physical oceanographic data using CTDs, ADCPs and microturbulence probes and;
- Biological data using multi-frequency biological acoustics, remotely operated vehicles (ROVs) and automated underwater vehicles (AUVs).

58. To fill the significant gaps in our understanding of deep ocean biology and oceanography a multidisciplinary approach to studying the deep pelagic biosphere is essential. This requires the continued deployment of ocean-going research vessels capable of undertaking oceanographic studies, acoustic survey and deploying AUVs, ROVs and other forms of sampling gear within a single cruise.

59. *Case Study: Seamounts*

Seamounts, often over 1000 m in height, cover large areas of the deep seabed and are known to be hotspots of biodiversity. The flanks and summits of such elevated topography can be associated with significant increases in



Multifrequency acoustics showing hydraulic jump entraining the deep-scattering layer on unnamed seamount on the SW Indian Ridge. Displacement is about 250m in the vertical and internal waves are detected to ~100km from the seamount summit abundance and biomass of pelagic communities. Seamounts also exert a profound influence on hydrography, redirecting ocean currents and inducing ocean mixing through effects such as hydraulic jumps, internal waves and wakes. Recent work as part of the NERC-NSF funded DIMES programme (Diapycnal and Isopycnal mixing Experiment in the Southern Ocean) has demonstrated the importance of the interaction between deep currents and rough seabed topography in generating turbulence and upwelling, important for the global overturning circulation.

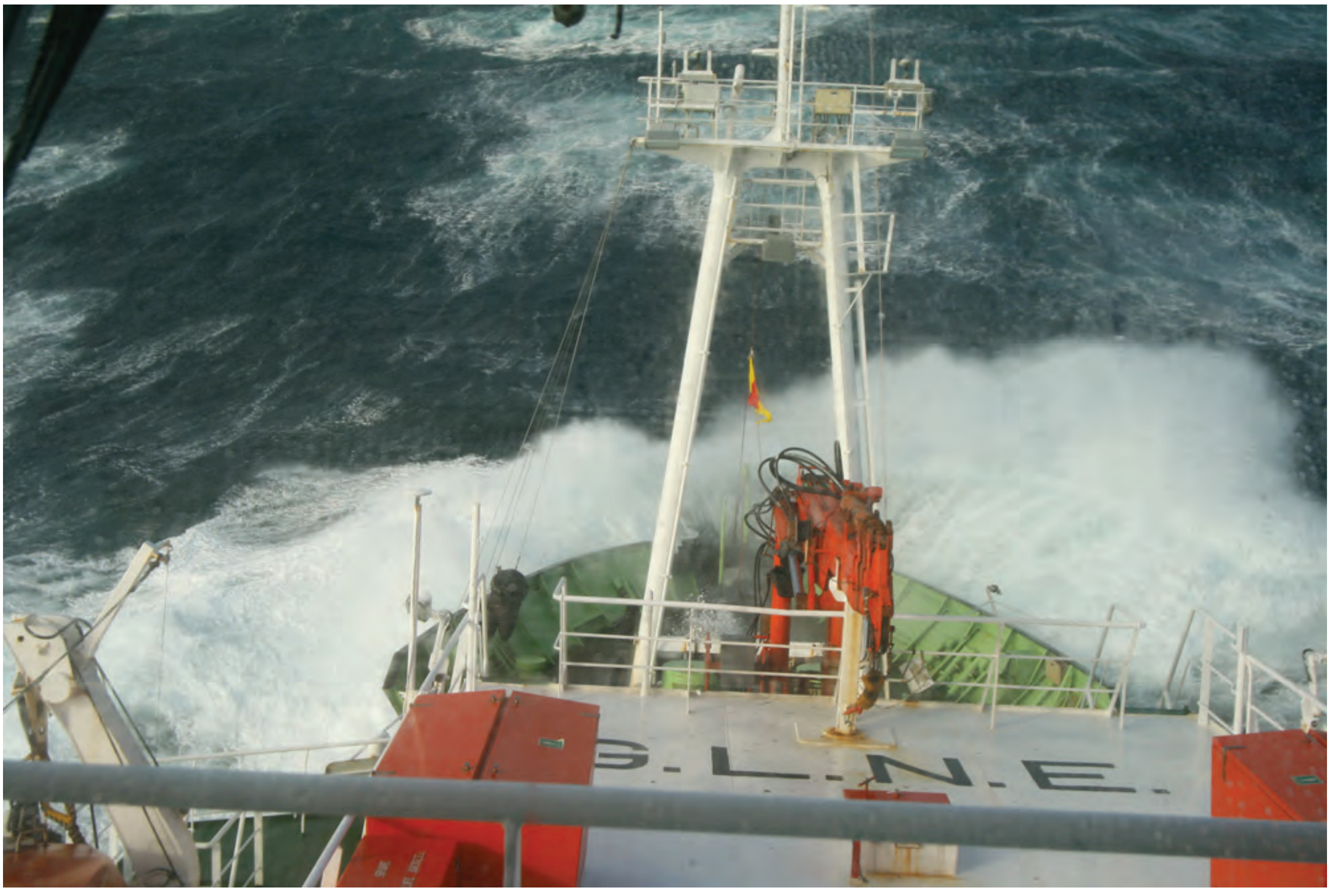
DIMES required an extensive field campaign that combined moored and ship-borne measurements to study horizontal and vertical mixing in the Southern Ocean. Five UK cruises (combined with five US cruises) in successive years provided unprecedented insight into Southern Ocean processes, especially through measurements of a seawater tracer that can only be analysed from water samples collected by a ship.

The role of autonomous and robotic systems

60. The deep water column may comprise the largest reservoir of marine animal biomass, however many animals such as gelatinous zooplankton and fast-moving cephalopods have defied detailed study because surface deployed sampling gear is unsuitable for quantitative studies. Development of new technologies including remotely operated and autonomous platforms may in future revolutionise our ability to undertake quantitative studies of the biology of these ecosystems.

Delivering Benefit

61. The study of the deep ocean will form key inputs into national and international policy including management of marine ecosystems in the light of activities such as fishing and deep-sea mining and in the understanding of global biogeochemical cycles with direct relevance to predicting the effects of climate change on the Earth System. These studies will inevitably rely on a multidisciplinary scientific approach that is supported by research ships. Without this ability, many of the processes occurring in the deep seas will remain poorly understood.



Atmospheric sampling

The Upper Ocean

62. Understanding and predicting global climate change is one of the most profound challenges facing mankind today. Although we experience climate change through the atmosphere, the oceans dominate global climate change signals.

63. The ocean contains 90% of the excess heat from global warming and plays a vital role in absorbing CO_2 from the atmosphere. It is therefore critical to understand the processes by which the ocean absorbs, redistributes, and on occasion returns to the atmosphere those elements of the climate system. While ocean heat is the most obvious physical parameter, experienced by human populations through air temperature, the oceanic freshwater balance is also critical for the hydrological cycle, determining access to rainfall for agriculture and human health.

64. Key scientific research over the coming decades will focus on three themes:
    - quantifying the role of the ocean in the coupled climate system;
    - small-scale processes in the ocean that determine the way the ocean responds to perturbations in climatic forcing and;
    - quantifying changes in ocean heat, carbon and freshwater storage;

65. The UK science community has identified two high-level research questions that it aims to address in the coming years; one is global and fundamental the other is specific to the needs of the UK. These are
    - How much heat and carbon does the ocean absorb?
    - How does ocean circulation affect global and European climate? How will that change in the future?

The role of ships in future science

66. Future research into basin-scale physics and biogeochemistry will continue to require access to global class research ships for the foreseeable future. Understanding and predicting the oceans' impact on climate requires basin-wide data from full ocean depth. Research cruises will range from basin-scale inventories, to small-scale process studies that quantify the processes that control ocean circulation. Such cruises provide information to explain and predict the redistribution of heat and carbon within the Earth system. Programmes including the Atlantic Meridional Transect are invaluable platforms for addressing such questions at very broad scales on a repeated basis.

Preparing a mooring for deployment

67. Future research cruises will continue to contribute to the international GO-SHIP program of sustained observing to which the UK aspires to supply two to three major cruises in each 5-year planning cycle.

68. The requirement for ship time will not be significantly reduced by the growth in capability of unmanned platforms. Rather, such capability enables new science and understanding, interpolating between ship-borne measurements in space and time. Some parameters can only be measured on ships. Others require ship-borne analysis for calibration to detect small climate-change signals. This multiplatform approach is demonstrated in the OSMOSIS case study.

69. ***Case Study: OSMOSIS (2011-2015)***

    The multi-disciplinary OSMOSIS consortium project addresses the question: What processes determine the evolution of the ocean surface boundary layer over an annual cycle? Climate-scale ocean models need to represent upper ocean physics and the rate at which the atmosphere can exchange properties with the ocean interior. Models don't include sub-mesoscale (ie, processes that occupy a few km horizontally). These need to be quantified so their effect can be represented in models and to overcome systematic model biases.

    OSMOSIS has an array of 9 moorings around the Porcupine Abyssal Plain site in the northeast Atlantic. These are spaced 3 to 30 km apart, and measure physical properties (temperature, salinity, velocity) every 15 minutes, as well as mixing determined from very fine-scale (cm) measurements. The 30 km area is patrolled by two gliders, with physical parameters supplemented by fluorescence and photosynthetically-available light. Sixty days of ship time were required to deploy and maintain the moorings and gliders, and provide calibration data for the unattended sensors, especially the non-physical parameters.

The role of autonomous and robotic systems

70. Unmanned platforms have become a major source of ocean observations. Platforms include ocean gliders, Autosub, surface drifters, neutrally buoyant and profiling floats and fixed moorings. Each technique is capable of underpinning important science that addresses the critical questions.

71. The RAPID array of moorings at 26°N has revealed unprecedented detail about the variability of the Atlantic Meridional Overturning Circulation (AMOC) and has provided critical data for the evaluation of numerical models. However, ships are required to deploy and recover such moorings and ship borne data is often needed to support research questions and to calibrate sensors.

72. Unmanned platforms, such as Argo, are limited in both depth capability and the limited number of parameters that they can measure. For example, present engineering limitations confine Argo floats to the upper 2000m, leaving more than half the ocean that can only be observed using conventional ship-board techniques. Future developments in sensor technology are likely to address this issue however these are some way from full maturity.

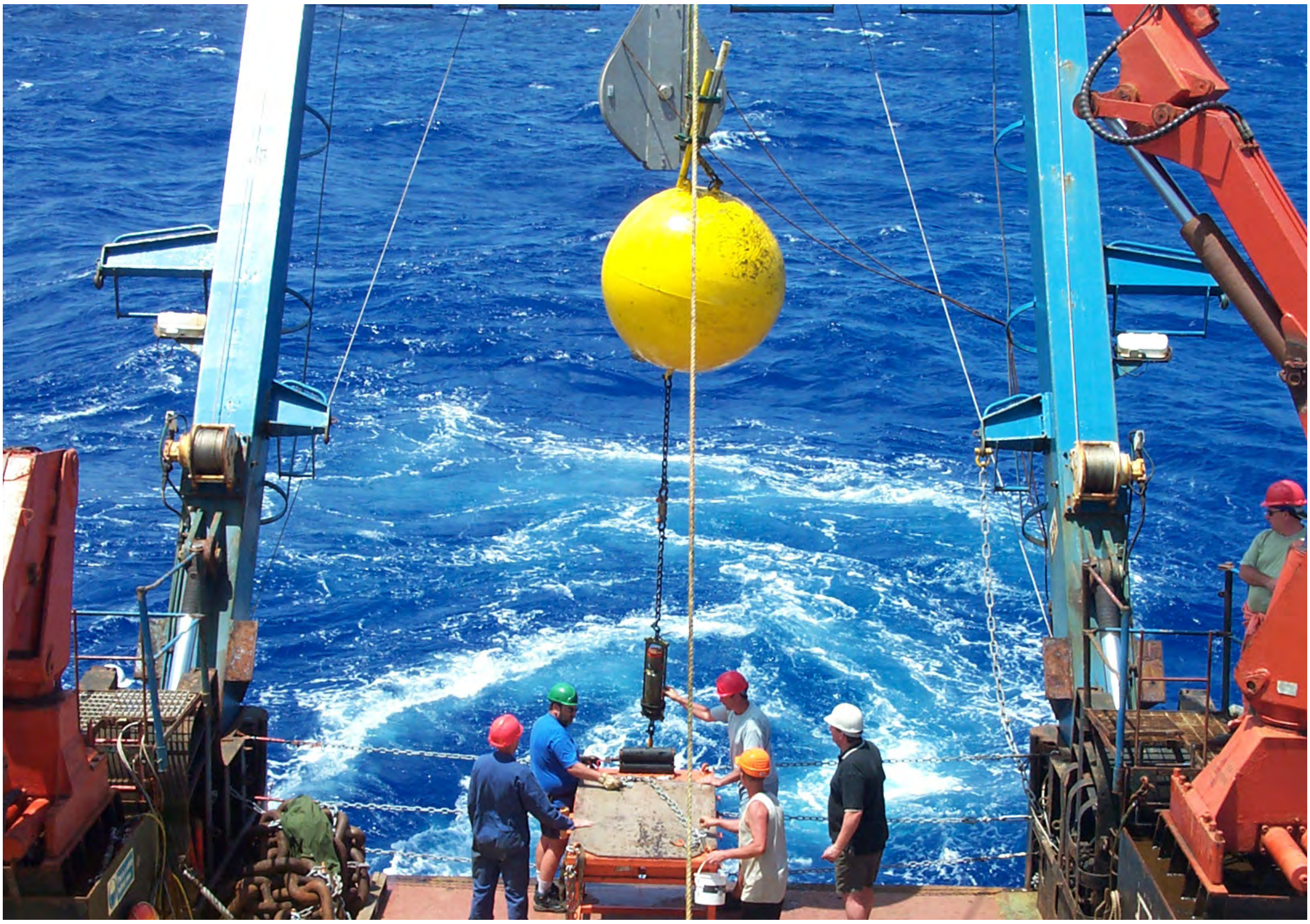
73. Prototype deep floats are being prepared for an international trial in 2014. If deep floats are able to survive for hundreds of profiles, funding could be sought by the international community for a Deep Argo array. However, recalling that it took 7 years to complete the Argo array, we anticipate a minimum of 10 years before Deep Argo could be making sufficient full-depth global measurements to describe global warming of the deep ocean.

74. Unattended sensors need to survive with low power consumption, and sensor drift smaller than the signals being measured, for periods of years. The only water property that is accepted from unattended sensors without further calibration is temperature. Salinity data from platforms are carefully compared with ship-borne conventional measurements and ultimately calibrated by analysis of samples in ships' laboratories. At present, sensors to measure fundamental parameters that described the oceans' role in the climate system, such as Dissolved Inorganic Carbon (DIC) do not exist.

75. In almost all cases the value of unmanned platforms is in enabling new science that uses measurements that could not previously be made using ships, rather than replacing or replicating ship-based campaigns. They provide complementary not alternative approaches to understanding the ocean and its response to, and impact on, climate change

Delivering Benefit

76. Projected impacts of future climate change, including changes in precipitation, temperature and sea level, have the potential to seriously affect our society. It is imperative for climate research that the international community continues to observe and study the oceans, and that the UK maintains its role in that community. A fuller understanding of the mixing of physical properties (heat, kinetic energy and momentum) controlling circulation and the drawdown of CO_2 through the carbon cycle is required for these processes to be correctly represented within the models used to predict future changes in global and European climate. These predictions are necessary to identify future risks to health, resources and infrastructure and to ensure the development and implementation of adaption procedures and risk management practices.



Laying moorings across the Atlantic Ocean – RAPID Programme

The Continental Shelves

77. Continental shelf seas account for around 15% of primary production in the ocean due to their high nutrient concentrations and are the regions where humanity predominantly interacts with the sea. They have significant economic and social importance because of their wide range of uses including fisheries, oil and gas exploration, telecom and power cables, defence, leisure and recreation, renewable energy and raw materials.

78. The importance of understanding continental shelf sea processes has been recently recognised through the NERC funded FASTNEt consortium. FASTNEt focuses on understanding exchange processes across the shelf break between the sub-polar north Atlantic and UK shelf seas and how these vary both with region and seasonally. However, FASTNEt is primarily a physical programme and, looking forward, a subsequent study of biogeochemical exchange is needed. Key discovery areas for the future include examination of the specific role of canyons in carbon export from, and nutrient supply to, the shelves and the quantification of eddy and gradient pelagic biogeochemical exchange fluxes (in particular their seasonality).

79. Another major area of future research in the shelf seas lies in land/coastal interactions. Strong latitudinal gradients exist in the source strength, physical behaviour and effective residence time of coastal discharges into the shelf seas. This is a true discovery area, ripe for concerted international action, given the potential impact of coastal waters on human health (nutrient status and harmful phytoplankton) and food security (aquaculture and fisheries), and the raft of associated legislation (eg, OSPAR and MSFD).

The role of ships in future science

80. Modern discovery science in shelf seas is increasingly multi-disciplinary and focussed on understanding processes, rather than monitoring parameter status.

81. Process studies are inherently heavily interdisciplinary and demand large ships with up to 30 science berths. The key science areas outlined above look to place multi-disciplinary (and multi-national) teams on UK research vessels through into 2019/20, optimally fully occupying one vessel through 18 months of seasonal process research. These comprehensive studies require a range of large platforms, many of which rely on ship deployment, and laboratories for shipboard analyses and experimentation.

82. The increasing technical complexity of scientific systems will require dedicated expert technical support for ocean-going research, otherwise novel instruments cannot be used, and ships risk being used sub-optimally.

83. *Case Study: Shelf Seas Biogeochemistry*

    The NERC-funded Shelf Seas Biogeochemistry programme (SSB) and shelf seas ecosystem programmes will be heavy users of large research vessels for their multi-disciplinary teams for the next two years. Both of these programmes aim to address regional-scale processes from the physics through biogeochemistry to ecosystem structure, focusing on timescales ranging from tidal through to seasonal. These heavily interdisciplinary programmes are at the forefront of international efforts aimed at understanding how shelf seas function in both local and global contexts, and both include partners from within the EU and further afield. The fieldwork for these programmes requires extensive ship time and is being designed alongside the modelling community, with a high-level aim of providing more robust model driving parameters and new descriptions of processes known to be poorly represented in the models.

The role of autonomous and robotic systems

84. Numerical models and autonomous instrument platforms have an important and increasing role to play in physical process studies, underlined by their extensive use in the FASTNEt programme. However, models use the process understanding already extant, and autonomous systems are presently capable of measuring frighteningly few pelagic parameters.

85. It is perhaps in the routine monitoring of the shelf seas that autonomous systems may have their biggest impact, but only once reliable water biology and chemistry sensors have reached technology readiness level 5 (TRL); the ability to measure a handful of biogeochemical parameters is currently at TRL 2, with a series of major technical hurdles associated with data precision, calibration and sensor drift yet to be overcome.

Delivering Benefit

86. Shelf seas impact the UK economy predominantly through human health and food security. Access to research vessels is essential for studying these environments and defining the complex processes occurring within them. Globally, aquaculture is a vital source of human food protein, and this will increase as population rises. Highly productive shelf seas form 90% of fisheries, but global catch is under threat of decline through poor management. A greater understanding of shelf sea systems will allow better management and growth of provision of food and services to island nations such as the UK.

CTD and water sampler

The Ocean – Atmosphere Boundary

86. The transfer of energy, gases and particles across the air-sea interface represents a critical pathway for the coupled ocean-atmosphere climate system, atmospheric chemistry, biogeochemical cycles and marine productivity, and thus exerts a controlling influence on ecosystems and ecosystem services. Understanding the fluxes of these materials across the air-sea interface, and the feedbacks that connect the two fluids, is vital to predict how the system will respond to a changing climate and to anthropogenic perturbations.

87. Key future research areas for understanding ocean - atmosphere interactions include:

- **Air-sea transfer: Heat and momentum** – Heat transfer plays a fundamental role in the global energy budget and the development of tropical storms and cyclones. However, significant uncertainty still remains regarding air-sea exchange rates of momentum, sensible heat and latent heat (moisture), particularly at high wind speeds.
- **Aerosols, nuclei and clouds** – Sea spray aerosols act as effective cloud condensation nuclei (CCN), control drop size distributions and hence the albedo of marine clouds. Aerosol production needs to be further constrained by taking account of factors other than wind speed and determining chemically resolved source fluxes.
- **Greenhouse gases** – Coastal upwellings are well known as significant local sources of CO_2, N_2O and CH4. The exchange rate of these gases is however poorly known, leading to uncertainty when quantifying global or regional budgets.
- **Atmospheric oxidation chemistry** – The oceans represent a significant source of halogen radicals, oxygenated volatile organic compounds and DMS and act as sinks for ozone and other anthropogenically affected species. However, other than for DMS, little is known about how concentrations of climate-active gases in the oceans will respond to ocean acidification and/or climate change.
- **Role of atmosphere as a source of nutrients** – The supply of iron not only controls marine productivity and hence carbon cycling in much of Equatorial Pacific and Southern Oceans, but also nitrogen fixation in large parts of the Atlantic Ocean. Questions remain over how the supply of iron from the atmosphere to the world's oceans might alter in response to changes in climate and land use and how iron is processed and cycled within the atmosphere and surface ocean.

The role of ships in future science

88. Research ships are absolutely vital for UK research into atmosphere-ocean connections. These large platforms allow us to take complex research instrumentation into the field, to sample both within the air and water and to conduct experiments in the field.

89. In order for us to test hypotheses and develop predictive mathematical models, we need to be able to measure process rates and concentrations of species in the field. Experimentation usually requires large teams of multidisciplinary scientists (chemists, physicists, biologists), working in both air and water; thus a wide range of systems and sensors need to be deployed together. These sensors and systems tend to be delicate and power hungry and are often rather large and heavy: they cannot be deployed on UAVs or buoys.

90. Further, research ships are able to work anywhere in the world's oceans, often in areas where ships of opportunity do not transit through. Although ships of opportunity can be exploited to obtain large quantities of data (eg, for CO_2), this is limited to systems that are capable of running autonomously.

91. Research ships are also an important platform for atmospheric research and complementary to aircraft and land-based observatories. For example, aerosol/cloud interactions remain one of the least well understood aspects of the planet's climate, especially over the oceans where very few aerosol measurements have been made. Ship-based measurements offer a number of important advantages over aircraft-based studies in that measurements can be made very close to the sea surface, over longer periods of time and in remote locations.

92. *Case study: Air-sea gas and particle transfer*

The air-sea interface is particularly challenging to study but the UK has long been a world leader in this area. In particular, UK scientists have excelled in making field measurements of transfer rates using the NERC research ships and parameterised field data. More recently, we have used micro-meteorological techniques to make in-situ measurements of CO_2 fluxes over short timescales and at high winds in order to test model predictions. Further, these measurements have been extended to DMS and methanol which will allow us to better understand the role of bubbles and breaking waves in air-sea transfer.

Significant progress is being made by UK scientists in using Earth observation techniques to obtain fluxes of CO_2 over wide temporal and spatial scales and these are being further developed via the NERC Shelf Seas Biogeochemistry and Greenhouse Gas programs. Other work is using satellite retrievals of whitecap fraction to assess second order controlling factors on gas and aerosol fluxes. Future research will aim to better parameterise air-sea gas and aerosol transfer with variables determined directly by satellites. Such studies require in situ measurements with which to develop and validate retrievals and parameterisations; these can only be undertaken by research ships.

The role of autonomous and robotic systems

93. Earth observation technologies (principally satellites but also aircraft) have a considerable utility for air sea transfer studies due to their wide geographical and long temporal

coverage. Parameters such as surface roughness, ice cover and draught and surface temperature and biological activity levels can be diagnosed,. When these are coupled to shipboard observations or data from ARGO floats considerable insights can be obtained. Buoy systems have a particular role to play in addressing surface flux issues. They are able to sample for long periods of time remote from research vessels in relatively non-intrusive ways.

Delivering Benefit

94. Knowledge of coupled ocean-atmospheric dynamics is central to understanding climate variability across different time scales ranging from short term seasonal cycles to decadal variability. Improving our understanding of ocean-atmospheric boundary processes and quantifying the rates at which gases, heat and momentum are exchanged is of ever-increasing importance for the accurate parameterisation of coupled ocean-atmosphere models, such as those being developed by the UK Met Office. Coupled models are essential for predicating future changes in the global climate, which guides national and international policies and international agreements aimed at mitigating long-term climate change.

Airgun deployment – UK / Spanish / German barter

Conclusions

The ocean plays a vital but largely hidden role in our lives – it regulates our climate and weather, provides valuable resources that fuel our economy and improve our lives, and generates some dangerous hazards, putting lives and economic assets at risk. However, the ocean is also under pressure from human activities, risking the opportunities for future generations to benefit from it as we do.

The UK is home to world-leading scientists who are investigating the ocean, seafloor and the solid earth interior beneath it. Marine and Earth science is difficult and expensive, not least because to undertake the necessary measurements requires access to large research infrastructure. In this way, scientists can get into the harsh marine environment and measure processes that take place in the ocean and the Earth's interior across ranges of different magnitudes in space- and time.

The various platforms from which the ocean and solid-earth beneath are measured include satellites, dedicated research vessels, opportunistic use of commercial ships, observatories fixed to the sea-floor, floating buoys, shore-based instruments and autonomous vehicles such as small robot submarines and under-sea gliders. These are complementary to one another, each suited in their own ways to measuring different parts of the space-time spectrum of variability, and for measuring different physical, chemical and biological properties.

The development and increasing use of autonomous measurement platforms and miniaturised sensors to equip them is important and the UK is investing strongly in this field. They offer the promise to transform some particular fields of marine science – in areas inaccessible by ships such as under ice and where broad scale continuous measurement and monitoring is needed – providing the promise of "unmanned missions to Planet Ocean"

However, dedicated research ships will continue to have a prominent and distinctive role within the suite of ocean and earth science platforms. They are highly versatile, support a wide range of scientific disciplines and are critical for enabling measurements of places and processes that cannot, for the foreseeable future, be realistically measured in any other ways. Research ships are also used to deploy and supply energy to many of the other fixed and mobile measurement platforms.

The UK Government with the Natural Environment Research Council (NERC) has invested £120m in two new Royal Research Ships, RRS *Discovery* and RRS *James Cook*. Although relatively small in number, tonne for tonne, the UK now has the most advanced multi-purpose research vessel fleet in the world.

This investment could not have been completed at a better time. It is precisely the research infrastructure needed to enable the UK to maintain its international scientific competitiveness and to scientifically lever these investments through strong international collaborations and partnerships. The science community now stands ready to fully harness this advanced capability in search of new discoveries and in tackling what are probably the most important human-focussed challenges of our age – managing environmental change, benefiting from natural resources, increasing resilience to natural hazards and responsible stewardship of the ocean for future generations,

These challenges are central to the UK's national interest – especially in securing our future well-being, growth, jobs and prosperity – in underpinning UK business and enabling the UK to continue to exercise leadership in international ocean affairs, grounded in sound scientific evidence.

Since 2006 NERC multi-purpose research ships have carried scientists from 34 UK universities,
10 other UK organisations, 51 European institutions,
24 United States institutions,
16 other institutions worldwide

Appendix 1

Publications in *Nature* and *Science* journals since 2002 resulting from multi-purpose research ships and associated barter ships

1. Allen, JT, Brown, L, Sanders, R, Moore, CM, Mustard, A, Fielding, S, Lucas, M, Rixen, M, Savidge, G, Henson, S, Mayor, D (2005) Diatom carbon export enhanced by silicate upwelling in the northeast Atlantic. *Nature*, **437**, 728-732, doi:10.1038/nature03948
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5. Boyd, PW, Jickells, T, Law, CS, Blain, S, Boyle, EA, Buesseler, KO, Coale, KH, Cullen, JJ, de Baar, HJW, Follows, M, Harvey, M, Lancelot, C, Levasseur, M, Owens, NPJ, Pollard, R, Rivkin, RB, Sarmiento, J, Schoemann, V, Smetacek, V, Takeda, S, Tsuda, A, Tu (2007). Mesoscale iron enrichment experiments 1993-2005: Synthesis and future directions. *Science*, **315** (5812), 612-617, doi:10.1126/science.1131669
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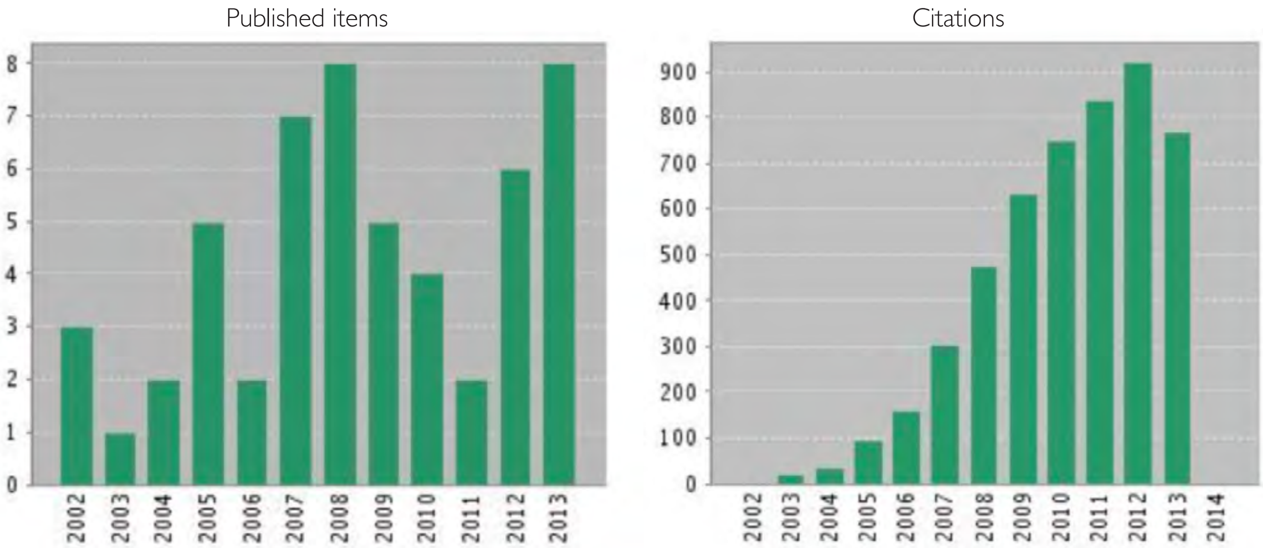

53 papers; 5,003 citations; average citation 94.40; h factor 31

Appendix 2

Principal NERC funded programmes and projects supported by the research ships since 2002

	Programme	Title
1	SOLAS	DOGEE-SOLAS: The UKSOLAS Deep Ocean Gas Exchange Experiment
2	SOLAS	Reactive Halogens in the Marine Boundary Layer
3	SOLAS	Investigation of Near-Surface Production of Iodocarbons - Rates and Exchange (INSPIRE)
4	SOLAS	The impact of atmospheric dust derived metal and nutrient inputs on tropical North Atlantic near surface plankton microbiota
5	SOLAS	The impact of coastal upwellings on air-sea exchange of climatically important gases
6	RM – Standard	Iron Biogeochemistry in the High Latitude North Atlantic
7	RM – Standard	A thermocline nutrient pump
8	RM – Standard	Comprehensive calibration of critical paleoceanographic proxies
9	RM – Standard	Physical and chemical forcing of diazotrophy in the (sub)-tropical Atlantic Ocean
10	OA	Ocean Acidification Impacts on Sea-Surface Biology, Biogeochemistry and Climate
11	OA	Impacts of ocean acidification on key benthic ecosystems, communities, habitats, species and life cycles
12	RM – Standard	Nitrous oxide and nitrogen gas production in the Arabian Sea - a process and community based study
13	OSEE	FASTNEt - Fluxes Across the Sloping Topography of the North East Atlantic
14	RM – Standard	Autonomous Ecological Surveying of the Abyss (AESA): Understanding Mesoscale Spatial Heterogeneity in the Deep Sea
15	OSBL	OSMOSIS: Ocean Surface Mixing, Ocean Sub-mesoscale Interaction Study
16	IODP	Origin, structure and deformation of low-magmatic oceanic lithosphere in the vicinity of ODP Leg 209, Mid-Atlantic Ridge 14°N - 16°N
17	RM – Consortium	ECOMAR; Ecosystem of the Mid-Atlantic Ridge at the Sub-Polar Front and Charlie Gibbs Fracture Zone
18	RM – Standard	The impact of submarine diagenesis of tephra on seawater chemistry
19	IODP	Accretion of the lower oceanic crust at fast-spreading ridges: a rock drill and near-bottom seafloor survey in support of IODP drilling in Hess Deep
20	RM – Standard	Structure and evolution of Axial Volcanic Ridges: Constraining the architecture, chronology and evolution of ocean ridge magmatism
21	RM – Standard	Turbulence in Antarctic Circumpolar Current standing meanders
22	AFI	Antarctic Deep Water Rates of Export (ANDREX)
23	RM – Consortium	DIMES: Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean
24	RM – Consortium	Chemosynthetically-driven ecosystems south of the Polar Front: biogeography and ecology
25	RM – Standard	Hydrothermal activity and deep-ocean biology of the Mid-Cayman Rise
26	IODP	Emplacement process and timing of large volcanic debris avalanches, Montserrat, Lesser Antilles: implications for volcanic and tsunami hazards

Appendix 2 – *continued*

	Programme	Title
27	IODP	IODP Site Survey of V-Shaped Ridge Features, North Atlantic Ocean
28	RM – Standard	Benthic biodiversity of seamounts in the southwest Indian Ocean
29	RM – Small	Biogeography and ecology of the first known deep-sea hydrothermal vent site on the ultraslow-spreading Southwest Indian Ridge
30	RM – Consortium	Ocean micronutrient cycles: UK GEOTRACES
31	RM – Small	How is ash dispersed in the ocean around volcanoes?
32	RM – Standard	Building and testing a new ROV-based vibrocorer for precisely located coring and coring of sandy substrate in water depths of up to 6000 metres
33	IODP	IODP Survey of the "Shackleton sites" on the Southwest Iberian Margin
34	RAPID	Monitoring the Atlantic meridional overturning circulation at 26.5 degrees N
35	RAPID	A monitoring array along the western margin of the Atlantic
36	RM – Standard	Oceancirculation and ice shelf melting on the Amundsen Sea continental shelf
37	RM – Standard	Marine geophysical and geological investigations of past flow and stability of a major Greenland ice stream in the Late Quaternary
38	RM – Consortium	Subduction zone segmentation and controls on earthquake rupture: The 2004 and 2005 Sumatra earthquakes
39	RM – Standard	Continental extension leading to breakup: determining the 3D structure of the west Galicia rifted margin
40	RM – Standard	The Louisville Ridge-Tonga Trench collision: Implications for subduction zone dynamics
41	RM – Standard	Flow dynamics and sedimentation in an active submarine channel: a process-product approach
42	RM – Standard	Ocean Circulation and Ice Shelf Melting on the Amundsen Sea Continental Shelf
43	RM – Standard	Investigating Sediment Transport Processes During Climate and Sea-Level Change in the Pleistocene-Holocene Indus System
44	RM – Standard	Waves, Aerosol and Gas Exchange Study (WAGES)
45	RM – Standard	Great Race Eddies and Turbulence
46	RM – Standard	Sea ice Processes and Mass Balance in the Bellingshausen Sea
47	RM – Standard	Arctic hydrate dissociation as a consequence of climate change: determining the vulnerable methane reservoir and gas escape mechanisms

Appendix 3

Strengths and weaknesses of observing platforms

Ocean Observing Platform Category	Advantages/Preferred Applications	Disadvantages
Research ship	1. Multi-purpose capability 2. Large scientific teams 3. Full control of location 4. Large high-power instrument deployments 5. Ideal for targeted experiments 6. Essential for biology, chemistry geology/geophysics	1. High cost, people intensive 2. Complex logistics 3. Limited duration experiments 4. Not suited to continuous measurement
Ships of Opportunity (ferries, merchant ships, naval vessels)	1. Low cost 2. Greater spatial coverage if many ships participating 3. Repeat routes	1. A few targeted measurements
Satellites	1. Large spatial coverage (global) possible 2. Long time series acquisition possible 3. Low cost from a user perspective	1. Surface ocean only 2. Limited number of mostly physical parameters 3. *In situ* calibration needed 4. Low temporal resolution
Moored Systems (Observatories, Arrays)	1. Continuous measurement – long periods	1. Few fixed points in space 2. Limited number of mostly physical chemical parameters 3. Vulnerable to loss 4. Cabled observatory systems very expensive 5. Ships needed to service
Drifters, Argo floats	1. Extensive spatial coverage possible if many used 2. Low unit cost	1. Limited number of mostly physical parameters 2. Low power instrumentation 3. Upper ocean only (Argo floats max 2km)
Autonomous vehicles (AUV, USV gliders)	1. Extended spatial coverage possible – especially if many used 2. Extended mission durations (months-year possible) 3. (relatively) low cost	1. Mostly limited to upper ocean – though small number of deep sea AUVs exist 2. High risk of loss 3. Limited number of mostly physical and chemical sensors 4. Smalll low-power payloads only
Airborne measurements	1. Good spatial and rapid synoptic coverage possible	1. Usually one-off measurements 2. Limited number of mostly physical and chemical sensors

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The Challenger Society for Marine Science aims:

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- to disseminate knowledge of marine science to the public with a view to encouraging a wider interest in the study of the seas and an awareness of the need for their proper management
- to publish, among other things, news of the activities of the Society and of the world of marine science; material intended to present new activities and developments in a way to bring them to public attention; such other papers as may from time to time be deemed appropriate
- to provide or arrange, in suitable cases, financial assistance to students in marine science

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The National Oceanography Centre Association (NOC Association)

The creation of the National Oceanography Centre (NOC) envisaged the development of an association of Universities and research institutions to support wider engagement with the marine science community in an open and impartial way. The Association acts as a strong voice to the Natural Environment Research Council (NERC), to Government directly and through the Government's Marine Science Co-ordination Committee (MSCC) and internationally on issues affecting marine science and its delivery in a UK context.

The Association has developed a community vision "Setting Course" which takes a broad view of the priorities for science and national capability, within the context of the NERC and UK Marine Science Strategies. The Steering Board Membership:

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DISCOVERY
JAMES COOK

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