Oceans – Perspectives from the Royal Society Global Environmental Research Committee

This paper has been produced following a science meeting of the Royal Society Global Environment Research Committee (see 'context' on page 3), and provides an overview of that discussion. It does not seek to represent the views of the Royal Society or to produce a comprehensive overview of the science, but instead to highlight some specific areas of potential interest to researchers, funders and government.

The Oceans: Executive summary

GERC identified six aspects of ocean research where further study is important. A first is to better assess the role the oceans play in controlling climate: through heat uptake and transport, through the carbon cycle, and through modulation of cloud formation. Five other research areas are similar to key questions identified in the *Foresight Future of the Sea* report[1]. These are: sea-level change; ecosystem response to multiple stressors; ecosystem services; tipping points in ocean systems; and emerging marine-based sectors (e.g. deep-sea mining).

We remain data poor for the oceans compared to the atmosphere or land surface, but there is a revolution in our ability to measure and model the ocean due to technological and computational advances. Research to address present and future priority ocean issues will require diverse and flexible approaches to data collection, making use of new and existing technology, and with the data in highly accessible formats and modeled in high-resolution.

Introduction

The oceans play a critical role in the climate system: they have taken up a quarter of the CO_2 released by humans and thirty times more heat than the atmosphere during recent warming. Oceans are home to ecosystems that produce half of the world's oxygen, are important to food security, and whose genetic biodiversity remains poorly known. Human population density is three times higher near the coast and increasing further with coastal urbanization. Humans rely on the oceans for transport, food, recreation, and a wide range of resources.

Science issues

Five areas of science are identified in the *Foresight Future of the Sea* report published by the UK Government Office for Science in 2018. GERC discussion supports these as important knowledge gaps requiring research, and added a sixth important area. Each of these six areas could represent appropriate highlight topics for NERC, and warrant interdisciplinary consideration (e.g. in the context of UKRI or UK Future Earth).

1. Sea level: Future sea level increase remains uncertain at global and local scale and will have profound impacts on growing coastal populations. Research is required including: the physics that controls the pattern of increase (e.g. heat-uptake and ocean circulation); future variability and extremes, natural and societal impacts, and the adaptation required.

2. Multiple stressors*:* Much understanding of species and ecosystem response to change stems from research into single stress factors. It is now recognized that responses to simultaneous and/or sequential multiple stress factors are more complex, and need to consider clustering, seasonality and historical context. Multiple stressor research requires sophisticated experiments, coupling of experiment and models, and use of new data streams. Stressors include warming, acidification, pollution (not just from plastic, though this is important), and changing nutrient supply. Development of typologies that group stressors by their mode of effect or ecosystem response will be beneficial and accelerate understanding.

[1] Government Office for Science, 2018, London

3. Ecosystem services: The ocean ecosystem provides services to society, many relevant to the Sustainable Development Goals (SDGs). Important questions for future research include marine food security (both fisheries and aquaculture), ocean health near growing coastal cities, and the monitoring and management of Marine Protected Areas (MPAs). A comprehensive treatment of ocean ecosystem services is required.

4. Tipping points: How resilient are earth-ocean systems to change and what is the risk to social, economic and ecological systems? Are there thresholds in behavior of ecosystems, ocean carbon uptake, or heat transport, where abrupt change occurs? Are these systems reversible (e.g. would they deal with climate warming overshoot)?

***5. Emerging marine-based sectors*:** The blue economy is expanding and there is significant capacity for further blue growth, particularly with new uses of the oceans such as renewables, deep-sea mining, ocean genetics, and greenhouse gas removal. The potential for these new sectors, and the environmental risks associated with their exploitation, is poorly known. Mapping and measurement of the sea bed and deep ocean are important for consideration of many emerging ocean sectors. Little is known about the assimilative capacity of different habitats, or the capacity for recovery following exploitation.

***6. The oceans' role on climate*:** The oceans explicitly control several critical drivers of future global climate change, including formation of sea ice and clouds, and uptake of CO_2 and heat. Their circulation (e.g. Atlantic Meridional Overturning) also drives regional change via heat transport. These ocean drivers have economic and societal importance. The oceans' role in CO_2 uptake, for instance, directly controls the emissions budget allowable to meet 2^{o}C or 1.5^{o}C climate targets. Predicting the oceans' role in future climate requires further understanding of the physical and chemical system. The ocean models incorporated in global climate models must accurately predict changes in these climate drivers.

The oceans remain under sampled and under measured relative to other components of the earth system such as the atmosphere, limiting our ability to address scientific questions such as the six above. Measurement of the ocean is also critical for monitoring long-term change in global systems and its impact, and for ocean management. Modeling also continues to be a fundamental tool for study of the oceans. Models help to define questions, assess the interaction of multiple processes, and offer predictive power.

A revolution in ocean data

Satellites provide continuous monitoring of key parameters and are of critical importance, but are generally limited to providing information about the surface ocean (the main reason why the ocean is less sampled than the atmosphere). New techniques (e.g. sensors) and new platforms (e.g. ocean gliders, autonomous underwater vehicles) allow new ways to measure the ocean interior, allowing this data gap to be filled. These approaches can increasingly access the poorly-measured deep ocean, where assessment of heat uptake, biogeochemical cycles, and resources are important research needs.

There are further developments to come, including to hardware (e.g. remote charging, remote data transmission, miniaturization, and use of instrument swarms) and from AI (e.g. machine learning). Such approaches enable flexibility in data collection to address changing future scientific and societal needs. They can also be integrated into increased international ocean data collection efforts, particularly through the Global Ocean Observing System (GOOS), to enable closure of the data gap in oceanography.

Despite measurement advances, research ships remain of fundamental importance for oceanography. They are required for collection of many data streams, including physical samples of water, biota, or from the seafloor, and are often required for deployment, retrieval, and operation of other measurement devices.

There remain some limitations to ocean data collection and management. These include:

- Very few biological parameters are yet measured at high temporal or spatial resolution, limiting assessment of species and ecosystem responses.
- Making ocean data available to the user is improving but remains insufficient, of particular importance given development of AI. This requires a cohort of people skilled in quality control and data management.

- Data collection tends to be compartmentalized (e.g. coastal or deep ocean) and ignores system connectivity. This will be important in reconciling conflicts in management and policy philosophy in neighboring locales (e.g. terrestrial versus marine interventions).

Modeling

A range of model types are useful, from simplified systems probing fundamental processes, to computationally demanding ocean GCMs requiring substantial High Performance Computing resource. High resolution models are required to accurately simulate key ocean features such as eddies and the Gulf Stream, and therefore ocean heat and carbon uptake. Energy and mass transfer between the atmosphere and the ocean make this class of model critical for continued improvement in climate models. Ensemble approaches to modeling the ocean will likely become important in future assessment of this interaction. Inverse modeling is less widely used for the ocean than for atmosphere but is also likely to become an increasingly important tool as data streams continue to grow, and modeling capability improves.

The context for Global Environmental Research Committee reports

The Royal Society's Global Environment Research Committee (GERC) is charged with advising the Royal Society, and with interacting with research councils, the environmental science community, and other bodies. To do this, it is undertaking a rolling series of reviews of areas of science within its remit. The areas it has identified are (in alphabetical order): Air quality, Biodiversity, Carbon and other biogeochemical cycles, Climate, Natural resources (including land use) and food, Oceans, Polar science, and Water. In each area, GERC uses its own expertise, and that of a small number of invited experts to consider the questions:

1. What are the hot research topics in this area at present?

2. What is the status of UK science within this area?

3. What are the most pressing research needs in the next 5-10 years?

4. Are there specific areas where UK science should be focused to meet these needs?

5. How should priority topics be incorporated into multidisciplinary issues that Future Earth and its UK committee should consider?

This paper results from a GERC meeting discussing Oceans, held on 9th May 2018. In addition to contributions from its regular and co-opted members, the committee was advised in person by presentations from Angela Hatton (National Oceanography Centre), Ric Williams (University of Liverpool), Henry Ruhl (National Oceanography Centre,) Mike Elliot (Professor Mike Elliott), and David Marshall (University of Oxford). The resulting paper represents only a snapshot of the issues, and is not a comprehensive survey of the science area. It does not represent the view of the Royal Society, but puts a spotlight on some trends that will inform future activity by the Royal Society, UKRI, and UK Future Earth.

Membership of GERC (including co-opted members) at the time this topic was discussed (May 2018) was: Eric Wolff FRS (chair), Kirsti Ashworth, Mike Bentley, Pierre Friedlingstein, Peter Cox, Maria Dornelas, Joanna Haigh FRS, Kate Hamer (NERC), Gideon Henderson FRS, John Ingram, Yadvinder Malhi FRS, Paul Monks, Peter Smith FRS, Martin Solan, Chris Thomas FRS. Holly Winton acted as Secretary.