10. Integrated Science Themes

Commented [AS1]: Maybe further discussion is needed on whether this is the chapter that's needed or a chapter on critical areas not covered by the Grand Challenges? There's some good content here but I think more thought is needed on the structure/title/content.

Improve Earth science input.

The grand challenge discussions have highlighted key synergies and common issues which are worth exploring further.

10.1 Advancing Understanding of the Broader Earth System

Marine research infrastructure collects atmospheric, lithospheric and cryosphere observations in the marine domain, and plays an important role in connecting up our understanding of the broader earth system.

10.1.1 The Atmosphere: Marine Meteorology, Atmospheric Composition and Air-Sea Fluxes

A significant number of surface ocean-atmosphere variables are measured from marine platforms; Ocean surface stress, ocean surface heat flux and sea state are all essential ocean variables (and also Essential Climate Variables). While Sea Level pressure is an essential climate variable and many other atmospheric essential variables/essential climate variables are measured over the ocean.

Measurements of atmospheric composition are also taken from research vessels, which can take measurements relatively un-impacted by urban pollution.

The development of fully coupled prediction systems right down to weather timescales has strengthened the importance of taking observations above and below the air sea interface to better understand the dynamics of air sea interactions. Such research is technologically challenging due to the microscale turbulent interactions involved – but the real-world benefits are tangible. The move to fully coupled Numerical Weather Prediction has led to significant improvements in predictions of storm track and intensity.

<Met Office Example> Advancing understanding of Atmospheric Boundary Layer

The Global Atmosphere Watch and more recently development of the Global Greenhouse Gas watch has brought new momentum to the need to better understand and predict changes in the global atmosphere and its interactions with the ocean.

The Grand Challenge on Climate noted Sustained observations in air-sea fluxes of heat and carbon and upper ocean dynamics can reduce uncertainties in climate projections. Currently, large uncertainties and the lack of measurements in remote locations prevent us from accurately capturing global and regional changes in air-sea fluxes. Inaccurate data on ocean-atmosphere interactions then lead to biases in global climate models.

Traditionally, atmospheric observations have been taken by research vessels, volunteer observing ships, fluxes moorings, and surface drifters. Increasingly, uncrewed surface vehicles are showing potential to collect comprehensive observations at the air sea interface.

<Cross check BE Grand Challenge>

10.1.2 The Seafloor and the Earth's Crust.

Commented [AS2]: Important to capture here:
1. Natural hazards
2. Chemosynthetic communities and the deep biosphere, these are areas which require particularly close collaboration between biologists, chemists and geologists and are also providing insights into the origins of life on Earth and the potential occurrence of life beyond Earth.
3. Another critical area is palaeosciences which inform us about the impacts of past climate change on the biology and biogeochemistry of the ocean.
4. Finally, there is also the area of abiotic resources in the ocean, including deep-sea minerals and energy, including both energy generation, transmission and CO2 sequestration, for example in old oil well.

Paleoclimate (recognised needs strengthening in Climate GC)

Biodiversity and evolution (needs strengthening in Biodiversity GC)

Geohazards (well represented) ...

10.1.3 The Coastal Interface.

< Synthesise key messages from Grand Challenges>

As outlined in section 6.3, shelf seas connect the open ocean to the coast through cross-shelf exchange processes that are regions of great change and are subjected to a range of environmental and human pressures. They are also often gaps in observational capability – largely because research programmes are mainly focused on the open ocean, and environmental monitoring is focused on the coastal environments. Connecting observation and predictive capabilities across the shelf presents many opportunities for understanding and predicting both open ocean and coastal environments.

The Grand Challenge on the Ocean in a Changing Climate highlighted the importance of better sampling the transition zones between continental shelves and open ocean, which are essential for weather forecasts and for studying the biogeochemistry and productivity of shelf seas. For the Grand Challenge Biodiversity and Ocean Health, the changes and impacts in shelf seas were identified in chapter 6 as key research gap.

10.1.4 Interactions with Ice Shelves and Sea Ice Dynamics

Some of the greatest changes being witnessed are in the polar oceans. The Grand Challenge on Climate (Chapter 5) highlights these changes – including mass loss from ice sheets and glaciers, loss of sea ice and increased permafrost melt - and the resultant change in freshwater discharge is altering ocean circulation and contributing to major changes in sea level. Indeed, uncertainties around the cryosphere changes including the role of the ocean in contributing to ice melt, is a major contributor to uncertainties in sea level projections. The Grand Challenge on Climate highlights understanding the effects of a rapidly changing polar regions on global climate remains a key research priority – and the Grand Challenge on Biodiversity and Ocean Health (Chapter 6) notes that Changes in ice coverage and sea ice dynamics also has major consequences for polar ecosystems. A key gap in observational capability is under the ice, due to the hostility and inaccessibility of the environment, and challenges communicating with deployed equipment under the ice.

10.2 Multiple Stressors and Intersecting Drivers of Change

The synergies between grand challenge issues are discussed in the Grand Challenge Chapters, highlighting in particular that each Grand Challenge can rarely be considered in isolation. For example, understanding changes in a particular coastal ecosystem means unpacking the pressures due to climate change (e.g. heat, acidification), pollution, marine industry as well as natural hazards and extreme events.

Commented [AS3]: The main local human impacts on marine ecosystems include overexploitation of resources and habitat destruction, these should be added to this list.

One intersection in particular stands out: the impact of climate change on all the Grand Challenges. Climate Change provides an additional challenge of a shifting baseline while trying to understand complex ocean processes, feedbacks and how it amplifies other pressures. Climate models will be increasingly needed to determine thresholds and feedbacks, such as the relationship between ocean warming and changes in deep ocean circulation.

For Natural Hazards, climate change will change the frequency, magnitude, nature and location of hazards. Understanding is needed of these intersections and where impacts will be felt into the future to guide efforts in enhancing resilience. Improved predictions of hazards and extreme events will be key, requiring greater understanding of the underlying processes which govern events. Conversely, the feedback of (some) Natural Hazards into climate change (e.g. volcanic eruptions impact on atmospheric conditions, seafloor release of greenhouse gases, carbon transport by turbidity currents) are important factors to consider and will need to be better understood in order to improve our understanding of climate change mechanisms.

With a growing Blue Economy, there is an increased reliance on coastal and offshore industries. Understanding the environmental conditions those structures need to withstand, and where to build, e.g., offshore windfarms with future changes in mind will be critical for future proofing industries. Changing environmental conditions will also impact the planning, location and active management of other Blue Economy areas such as aquaculture, fisheries, coastal infrastructure, and shipping.

For biodiversity and ocean health, climate change is impacting the sensitivities, thresholds, and resilience of ecosystems to changes. Sensitivities to changes are likely to be higher, with resilience likely to lower and thresholds to change likely to be reached more frequently. For instance, a coral reef already under stress due to climate change (i.e. heat and acidification) will have greater sensitivity to, e.g., coastal runoff or impacts due to tourism and fisheries.

Commented [AS4]: May want to rethink order: A coral reef already stressed by local human impacts is more vulnerable and less resilient to the impacts of climate change, such mass coral bleaching.

For the pollution issues, there is strong cross over with the natural hazards and extreme events grand challenge as for instance extreme events can cause pollution (e.g. ships grounding causing spills in storms, pollution caused by Tsunamis) and harmful algal blooms could be considered both a natural hazard and a form of 'pollution' event. Climate Change is likely to input pollutant pathways in the ocean given changes in circulation and stratification, and responses to climate change (e.g. marine carbon dioxide removal), may lead to pollution. Ship pollution around sea-ice (changing the colour and therefore the albedo of ice, fuel slicks) has direct feedback to climate change.

The presence of climate change underlines the importance of not only observing changes, but also deepening our understanding of the underlying processes which govern the manifestation of changes we see (section 6.2). It also presents challenges in the design of multidisciplinary programmes to observe tipping points and non-linear responses at a range of scales and from individual organisms to whole ecosystems.

The intersection of multiple stressors in the ocean will be an important topic of research, challenging our ability to capture key processes by observing and modelling the range of variables and scales, while also challenging our digital infrastructure to bring complex and diverse data together to be able to manipulate and interrogate it (section 8.4).

10.3 Observational Scales and Processes

Commented [KH5]: Consider use cases?

Commented [AS6]: Currently focused on ocean processes but the same issue can be applied to the other parts of the system (earth, atmosphere). Broaden out this section? The fluxes and feedbacks challenge is particularly relevant here, i.e. at and between the different parts of the system and interfaces.

The challenge of measuring processes at the cascade of spatial and temporal scales has been raised throughout grand challenge discussions, highlighting that the issue warrants further consideration; in particular, the implications for capability requirements.

The challenge of capturing the range of scales was highlighted through the NZOC Work Package 1 Report, which noted that *"capturing the range of spatial and temporal scales relevant for understanding oceanic processes is – and will continue to be – a key challenge in marine science".*

Building on section 10.2, there is a consistent theme of the need to capture the underlying processes which govern how changes manifest, and that this is key to unpicking the multiple drivers of changes in the marine system, mechanistic understanding of feedbacks and to improve predictive capability. In chapter 5, it was noted that uncertainties remain in the drivers and future evolution of the mixed layer depth and stratification under a changing climate, which has implications for the sequestration of anthropogenic heat and carbon, and biological productivity. Improved understanding of the underlying processes which govern such large-scale structural changes is essential to improving how we predict future change.

Further afield, the TPOS 2020 project reflected the challenge of trying to understand the ocean variability against the background of a shifting baseline due to climate change, which was increasing the diversity in how the El Niño-Southern Oscillation (ENSO) manifested. There is recognition that rather than measure how we understand ENSO to manifest, we should measure the underlying processes which govern how an El Niño manifests. This shift in emphasis was seen to be key to improving predictions of ENSO and focusing observational strategy where the observations could have most impact on improving predictability.

This is consistent with the findings from the NZOC Work Package 1 report which highlighted: *"there is a need to move from broad correlations to understanding connections, processes, and mechanisms in order to have greater predictive power and confidence"*. Such a paradigm shift throws down the gauntlet to our future capability and potentially a dynamic approach to how observations and models are used in concert to advance understanding – mechanisms, thresholds and feedbacks – and prediction of the changing ocean system.

Key challenges highlighted through Grand Challenge discussions included:

- Shifts in boundaries, ranges and scales presented challenges for observing strategies but also opportunities to consider dynamic/smart/responsive observation and prediction strategies.
- Fluxes and feedbacks at interfaces and the role of turbulent mixing: the nature of communication between atmosphere and thermocline, seafloor and water column and implications for measuring temporal changes in biology (where currently still reliant on periodic physical sampling).
- Resolving biological and chemical processes.

- Measuring states verses rates – including measuring rates and gradients over small scales.
- Targeting data collection in areas of most uncertainty, and/or areas changing rapidly in space/time.
- Requirement for full ocean-depth observations and in areas of major gap (e.g. under ice).

10.4 The Marine System: Multidisciplinary System Science

Commented [AS7]: Agree the ocean needs to be studied as a system, but as above, this could be widened out to other aspects (e.g. earth, atmosphere) of the whole system that we study using marine vessels and equipment. CO2 removal is mentioned here but this is also relevant to seafloor and sub-seafloor environments.

There is a growing trend towards the development of truly multidisciplinary programmes (section 2.3) which will likely continue. This challenges both our observational and digital technologies, in terms of expanding capability for measuring a growing range of coincident variables, managing and interrogating diverse data, and understanding complex processes and feedbacks.

The uptake, fate and storage of carbon in the ocean is an example of how physics, chemistry and biology intersect in the ocean in a way that brings particular challenges for observation and prediction. In addition, given the growing interest in the potential for marine Carbon Dioxide Removal (mCDR), there is an increasing need to understand the processes that govern carbon uptake and storage in the ocean and how they might be changing, as well as the potential need for a mechanism for evaluating the efficacy of mCDR – both pilot projects and their ability to scale against the background of an ocean whose ability to uptake carbon is changing. Ultimately, a greater understanding of the mechanisms that govern ocean carbon uptake, feedbacks and storage will be required to improve predictions of the ocean's changing ability to uptake carbon.

Commented [AS8]: A key area here will be the impacts of mCDR on biodiversity and ecosystem function.

Physical-Chemical interactions – it is thought that the uptake of anthropogenic carbon is a physically driven process linked to the formation of mode and intermediate waters. However, there are mechanistic aspects, including small-scale biophysical interactions and mixing processes, which still require characterising. The interplay between ocean carbon and oxygen chemistry needs to be considered, particularly changes in stratification affecting carbon uptake along with the expansion of Oxygen Minimum Zones (OMZs) impacting the balance between photosynthesis and respiration in the ocean.

The role of biological processes in characterising ocean carbon uptake is the focus of the BioCarbon programme. The flux of carbon from microbes to higher trophic levels is yet to be understood, and changes in ocean heat, circulation and acidification are also changing functional groups and carbon flow. This underlines the need to be able to measure states, rates and processes in the ocean. BIO-Carbon presents a unique opportunity to consider use of state-of-the-art technologies and approaches as it is a programme where observations of physics, chemistry and biology, combined with an understanding of underlying processes and state of the art modelling need to be brought together at scale to address the questions. Given BIO-Carbon creates a useful test environment for our research infrastructure, FMRI has also partnered with BIO-Carbon to conduct technology demonstrator activities.

Similarly, the BioPole programme is focused on biogeochemical processes and ecosystem function in polar ecosystems (figure 10.1). Programmes such as BIO-Carbon and BioPole lay down the gauntlet for our research in terms of our ability to measure coincident physics, chemistry and biology observations at a range of spatial and temporal scales, and also model complex physical, chemical and biological processes and their interactions (see section 6.3 for more details).

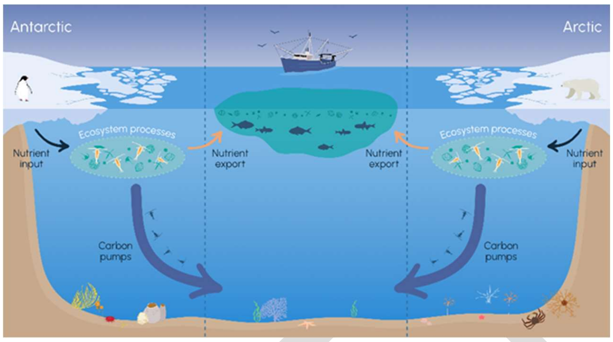

Figure 10.1: Ecosystem processes drive nutrient and carbon cycles in the polar regions with global consequences to ocean productivity and carbon sequestration. (Source: BioPole Programme)

The role of shelf seas in characterising ocean carbon uptake remains a critical gap in understanding. Shelf systems are regions of the ocean that are changing fast, under a range of environmental and human pressures, and are important regions connecting coasts and river catchments to the open ocean. They are also often gaps in observing systems for organisational reasons (see more in section 6.5.3 below).

10.5 Ecosystem Connectivity

<Alex/Julie to write>

Commented [AS9]: For example, connections between the shallow and deep ocean, important in carbon cycles, likewise connections between the shelves and deep sea.

Commented [KH10]: @Julie Robidart