5. The Role of the Ocean in a Changing Climate

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5.1. Scope and Context

The maritime industry, linked economies and societies rely on a safe, predictable ocean and climate system. Globally, 3.2 billion people rely on seafood for protein (FAO, 2024) which demands that commercially viable fish stocks are sustainable. Climate change is challenging the safety, predictability and sustainability of the ocean and climate system.

The ocean is critical for regulating climate by absorbing heat and greenhouse gases such as carbon dioxide. Over the past decades, the ocean has absorbed about 30% of the anthropogenic carbon dioxide (Friedlingstein et al., 2022) and has warmed by an average of 0.3°C per decade over the last 40 years (Cornes et al., 2023). Between 1955 and 2010, the ocean is estimated to have absorbed 90% of excess heat in the atmosphere. Without this atmosphere-ocean interaction, the atmosphere would have warmed by 36°C (Whitmarsh et al. (2015). However, absorption of excess heat and carbon by the ocean, alongside a warmer climate, has far-reaching consequences on the physics, chemistry and biology of our ocean, as well as the feedbacks that are critical in regulating the ocean and climate system.

Warming is altering how the ocean circulates by perturbing the ocean density which dictates how the ocean transports mass, heat, carbon and nutrients, with consequences for the storage of these key variables and maintenance of biological productivity. In the high latitude ocean, warming is shrinking the cryosphere, including mass loss from ice sheets and glaciers, loss of Arctic sea ice and increased permafrost melt. Freshwater discharge from the melting ice sheets and glaciers in the northern American (groundwater contribution to streamflow increase of 0.7–0.9% yr^{-1} between 1949-2005, Walvoord and Striegl, 2007) and Eurasian Arctic (23% increase in minimum flow or 8% in mean flow when averaged across all months between 1936-1999, Smith et al., 2007) has increased over the last century, with consequences for sea level. The IMBIE Team (2020) report a mean sea level rise of 10.8 ± 0.9 mm due to accelerated ice loss from the Greenland Ice Sheet between 1992 and 2018.

Ocean chemistry is being altered by warming waters altering the solubility of gases, such as oxygen. This has caused global dissolved oxygen to decrease by more than 2% (4.8 ± 2.1 petamoles [1E+15 moles]) since 1960 (Schmidtko et al., 2017), termed ‘deoxygenation’. Uptake of excess carbon dioxide has reduced the pH of the ocean by more than 0.1 since the pre-industrial average of pH 8.17 (Pörtner et al., 2014). This is known as ‘ocean acidification’, with consequences for mineral-producing plankton and coral reefs. Marine organisms live within optimal thermal limits, but ocean warming is causing organisms to reach or exceed their thermal limits driving poleward migration, termed ‘borealisation’, with unknown consequences for biodiversity and ecosystems, especially in polar regions (Genner et al 2017).

The ocean also affects the climate through interaction and feedbacks. A warmer ocean generates stronger and more frequent storms, with consequences for ocean safety and coastal communities (Field et al., 2012). Feedbacks within the ocean system are critical to maintain steady state of elements and processes (Katavouta and Williams, 2021) but climate change is altering these feedbacks and the consequences are poorly understood.

Major international efforts are being made to document and assess the impact and complexity of climate change on oceans (e.g. International Panel on Climate Change [IPCC]). The evidence collated is a key source of scientific information and guidance used by the United Nations Framework Convention on Climate Change and Paris Agreement to establish agreements and policies for carbon emission targets. The IPCC commissioned a Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; IPCC, 2019), which highlighted the impact of climate change on all facets of the marine environments, from the tropics to the poles, and coast to deep sea (Figure 5.1.). There is established international guidance on sustained observation requirements for climate; the UN Global Climate Observing System (GCOS) sets requirements for observation of Essential Climate Variables (ECVs). The GCOS Implementation Plan is presented to UNFCCC and is an authoritative guide for observing climate. A subset of the Essential Ocean Variables (EOVs) are also ECVs. A GOOS Supplement highlights the ocean actions (GCOS, 2022). GCOS also provides authoritative guidance such as the Climate Monitoring Principles[1].

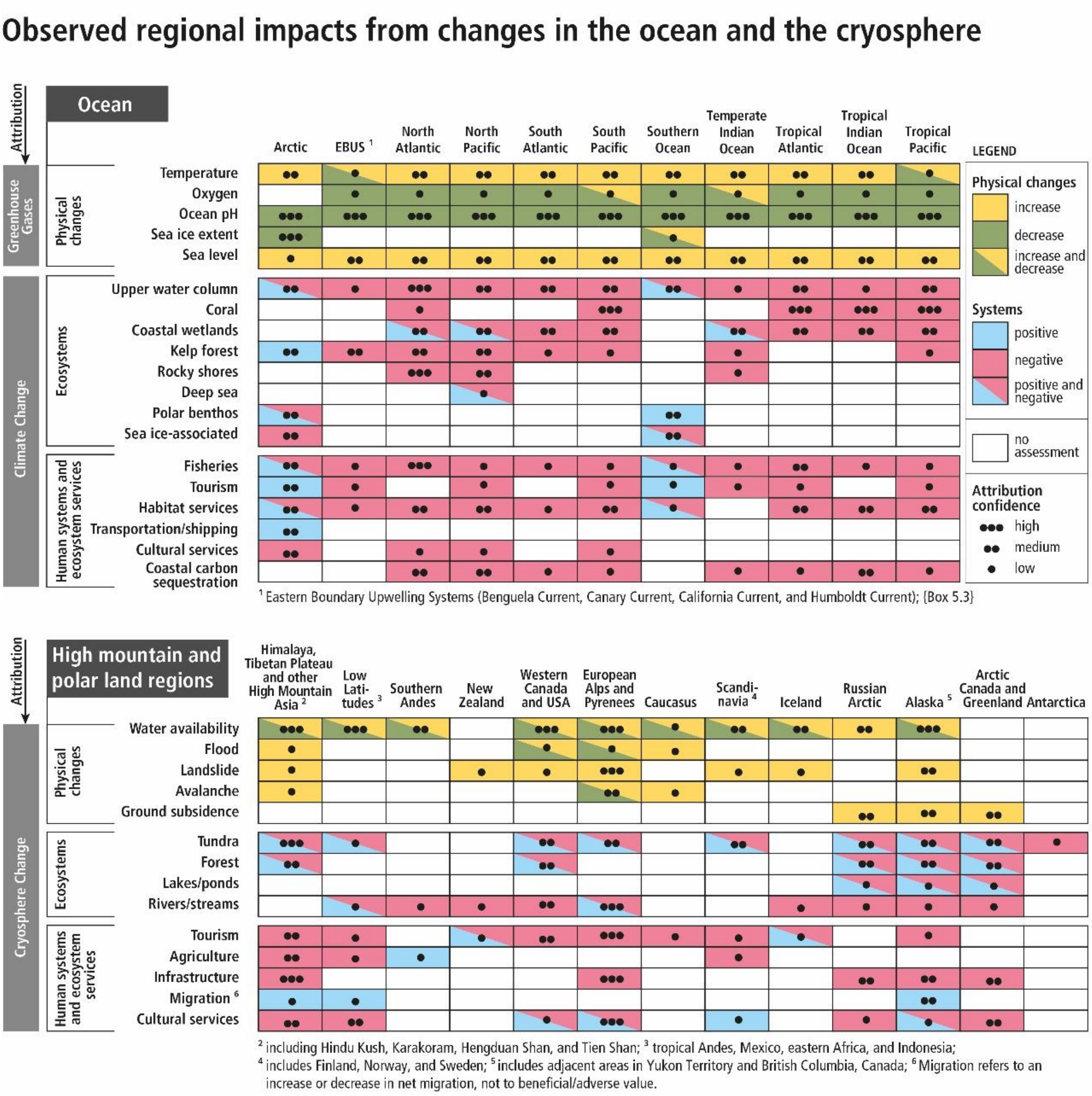
The UK provides support to the World Climate Research Program (WCRP) by funding and carrying out research that aligns with WCRP goals, collaboration through participation in committees and working groups, engaging in policy decision-making processes through the government to integrate the latest scientific findings into negotiations and agreements, and building research capacity through training initiatives and resource sharing throughout the WCRP network. UK climate research initiatives cover topics including, but not limited to, modelling, climate impacts, and ocean-atmosphere and ocean-cryosphere interactions. Notably, WCRP Lighthouse Activities are in development to address critical objectives by rapidly advancing technologies and frameworks to mitigate climate change impacts to society through transdisciplinary collaborations across and outside the WCRP community. These activities focus on developing new insights into the Earth's climate system, improving predictions of its short-term variability and long-term trends, and leveraging new technologies to create a digital "twin" of the Earth for more accurate simulations.

In UK context, the UK National Climate Science Partnership (UKNCSP) has developed a world-leading strategic partnership by combining capability in climate observing and prediction via

[1]GCOS Monitoring Principles https://gcos.wmo.int/sites/default/files/GCOS_flyer_MonitoringPrinciplesECVs.pdf?_rC3WSvDRgdehwsFphV0EewYT1AUEMlC

investment in science and computing. UKNCSP works with public and private sectors to ensure decision-makers and businesses have access to climate information to build resilience and adaptation strategies. The Marine Climate Change Impacts Partnership (MCCIP) is the primary independent source of evidence and advice for how climate change is affecting the UK marine and coastal environments. As well as providing evidence headlines, MCCIP also works with a range of stakeholders, including industry, to assess risk and build solutions to marine climate change impacts in the UK.

Figure 5.1. Synthesis of observed regional hazards and impacts in ocean (top) and high mountain and polar land regions (bottom) assessed in SROCC (IPCC, 2019).



5.2. Anticipated scientific developments by 2040

Produce more accurate weather forecast predictions and early warnings for extreme events (storms, marine heatwaves, ocean acidification, sea-ice changes, sea level). Collect more near-real time data globally but also in difficult to access regions, while maintaining measurements calibrated to climate standards. Better sample 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. Perhaps also need to mention that to improve predictions, we need to improve models and to improve models, we need to improve representation of fundamental processes in models, thus need mechanistic understanding of underlying processes and well as better representation on feedbacks between processes?

Understand how ecosystems are sustained as the ocean warms and implications for food security? **Food security and ecosystem health by maintaining a safe and sustainable ocean.** Improve forecasting of ocean productivity and prediction of marine ecosystem changes. Establish the effects of ocean warming, pollution, acidification, oxygen depletion on ecosystems.

Understanding the effects of the rapidly changing polar regions on our climate through their role on the large-scale atmospheric and oceanic circulations. Better sample the fluxes and distribution of freshwater in polar/subpolar regions. Quantify the uptake and transport of anthropogenic carbon and oxygen. Understand ice-ocean interactions through novel under ice and ice-shelves measurements, which will improve ice-sheet model development and sea level rise predictions.

Understanding risks and effectiveness of marine CO_2 removal (mCDR). Marine CDR is rapidly becoming a global scientific priority. By 2040 an increasing number of trial mCDR projects is expected. A key scientific priority will be to assess the risks and effectiveness of proposed mCDR efforts, such as alkalinity enhancement and stimulation of the biological carbon pump. Technology and theory able to measure and track ocean carbon uptake and storage and its associated risks and impacts at local scales will be critical.

Interpretation and QC of large new data streams. Advances in autonomy and sensor technology are creating vast new datasets. Machine learning is increasingly used to interpret and further extend these and other datasets. However, careful quality control and interpretation is needed use these new types of data for climate studies.

5.3. Key Science Questions, knowledge gaps and uncertainties

AMOC: We need to understand the driving processes behind and future evolution of the Atlantic Meridional Overturning Circulation (AMOC) and its associated tipping points. The AMOC affects the Earth's climate by redistributing excess tropical ocean heat to higher latitudes and by regulating the transport of carbon dioxide and oxygen. A changing AMOC has repercussions on our weather, extreme events, storm intensity, sea level rise, and fisheries. Due to a lack of agreement between modelled and observed AMOC evolutions, which results from a poor understanding of the processes driving AMOC changes, there is low confidence in the magnitude of the predicted AMOC decline and whether it will be abrupt or gradual.

Heat: We also need to observe processes of heat uptake broader than the AMOC, for example, what the role the ocean plays in setting the mean state and variability of ocean sea surface temperature and other upper ocean properties. Then, how these are impacted by changing ocean dynamics and boundary forcing, i.e., from a warming atmosphere and melting cryosphere, how these changes impact climate sensitivity, e.g., through cloud feedbacks and the pattern effect, and overall, what are the fundamental dynamics that set ocean heat uptake efficiency?

Carbon: Improved estimates of global ocean carbon uptake, particularly in undersampled regions and seasons, are needed to better constrain and partition the present-day global carbon budget. Improved quantification and mechanistic understanding of the Biological Carbon Pump (BCP) and its interactions with CO_2 solubility and ocean circulation at both local and global scale are needed to improve models of future ocean carbon uptake and deoxygenation and to assess marine CO_2 removal efforts.

Biological productivity: In addition to its role in ocean carbon storage, biological productivity is the foundation of ocean ecosystems and fisheries. Productivity is projected to decrease as the ocean warms, but the magnitude of decrease is highly uncertain. Over the next decades it will be critical to measure whether such a decrease indeed occurs and understand the potential drivers, including changes macro and micro nutrient supplies, stratification, nitrogen fixation, light, O_2, metabolism, and plankton community in a warmer ocean.

Sustained observations in air-sea fluxes of heat and carbon and upper ocean dynamics can reduce uncertainties. 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. Uncertainties also remain in the drivers and future evolution of the mixed layer depth and stratification under a changing climate. This future evolution will affect the sequestration of anthropogenic heat and carbon, and biological productivity (primary production).

To be expanded upon:

- *Understanding how change in the physical ocean climate results in impacts that affect marine species and management of marine environment (resource management and conservation management)*
- *How important are biogeochemical feedbacks in regulating the response of key ocean features (deoxygenation, carbon storage, productivity) to climate change?*
- *Does biodiversity matter in the response of ocean biogeochemical cycles to climate change or are physical changes most important?*
- *Two key regions emerged. High latitudes are:*
- *Where ice-ocean occurs, as well as the majority of ocean-atmosphere exchange, notably heat/carbon exchange, and nutrient export to wider ocean.*
- *Thermal limits exist here, cold water organisms have nowhere to go if it warms.*

- *Ocean productivity in the tropics/subtropics -this is where the globe gets its protein - and where weather systems get energy from.*
- *Presently there is a lack of useful forecasting for these regions and marine ecosystem changes, even to NPP levels are not usefully modelled...we struggle to even know the sign of future change.*
- *Thermal limits here too.*

5.4. Observation/Product Requirements

Table 5.2. Current list of Essential Ocean Variables and pilot variables for reference. Potential additions are listed in Annex 5A (Table 5A.1).

Physics	Biochemistry	Biology and Ecosystems
Sea state Ocean surface stress Sea ice Sea surface height Sea surface temperature Subsurface temperature Surface currents Subsurface currents Sea surface salinity Subsurface salinity Ocean surface heat flux Ocean bottom pressure Turbulent diapycnal fluxes (*pilot)	Oxygen Nutrients Inorganic carbon Transient tracers Particulate matter Nitrous oxide Stable carbon isotopes Dissolved organic carbon	Phytoplankton biomass and diversity Zooplankton biomass and diversity Fish abundance and distribution Marine turtles, birds, mammals abundance and distribution Hard coral cover and composition Seagrass cover and composition Macroalgal canopy cover and composition Mangrove cover and composition Microbe biomass and diversity (*pilot) Invertebrate abundance and distribution (*pilot)

5.4.1. Variables:

In addition to the internationally recognised ocean EOVs, several other key state and rate measurements will be extremely valuable for addressing the above science questions. Additional **state variables** include trace metal concentrations and bioavailability (productivity drivers), particle size (key to ecosystems and biological carbon pump), and inherent optical properties (controls light penetration and global-scale proxies for biomass, community, and productivity). Key **rate variables** include biological uptake/production of key elements and organic and inorganic compounds listed in EOVs (e.g. O2, organic C, calcification, nitrogen fixation, biogenic silica production), remineralisation (of carbon and other elements and compounds), Ingestion/grazing, Egestion/faecal pellet production, Biological Growth, and physical fluxes of key EOVs, including active fluxes, sinking fluxes, and mixing and advective fluxes. Key **experimental variables** include maximum rates (growth, feeding, etc.), minimum rates (e.g. baseline respiration), and dependence of rates on key EOVs (e.g., T, O2, nutrients, light, particle concentration). Finally, continued collection of paleo-oceanographic proxies is critical to estimate key EOVs and rates from the past and their connection with past climate.

5.4.2. Space/time scales:

There is an over-arching need for flexibility in spatiotemporal scales. Infrastructure must allow measurement of ocean at scales ranging from microscopic to global, sub-second to multi-decadal. Paleo proxies must allow estimates of past ocean states and processes from centuries to millions of years. For sustained observations in support of climate science, year-round multi-decadal timeseries are critical. Global, continuous coverage of as many climate-linked variables as possible is a key priority. Areas of particular challenge and importance include sea ice and harsh winter conditions, the mesopelagic and bathypelagic, the air-sea interface, the seafloor sediment-water interface, and pelagic/shelf/coastal interfaces. For targeted, experimental observations, capability of measuring a range of physical and temporal scales from mesoscale to microscale is essential.

5.4.3. Accuracy

Accuracy requirements for any given variable are highly dependent on the science question they are used for. Detection of climate-driven changes requires accuracy better than the magnitude of the long-term trend, or in the worst case a bias that is consistent over time.

5.4.4. Products

The **ability to take water samples from autonomy** would significantly open the ranges of variables that can be measured. Autonomy will expand the spatial coverage and temporal resolution.

To be expanded upon:

- *Sample below 2000m and under ice.*

5.5. General description of key capabilities

5.5.1. Observational Infrastructure

Sustained observations

For sustained global, continuous coverage of climate-linked variables, the international constellation of earth-observing satellites, the Argo float network, and the global drifter programme remain critical infrastructure. Satellites provide a wealth of physical parameters at the ocean surface, as well as optical properties that are used to derive an array of biological parameters with varying levels of accuracy. The Argo network is currently expanding coverage to the full ocean depth and under sea ice, and is expanding scope to cover six biogeochemical EOVs, again with varying levels of accuracy. Both satellites and Argo provide irreplaceable global coverage. Recent extensions will address key knowledge gaps, and continuation of existing measurements will increase our capacity to distinguish global climate change from other variability. However, these networks' ability to address climate science requirements also depends on sustained, widespread, high-accuracy calibration and validation measurements, often possible only with ship-based sampling. For climate variables not measured by global-scale networks, local sustained timeseries provided by moorings and/or repeat ship visits provide critical sustained coverage.

Targeted observations
The ability to make targeted, accurate measurements of any of the above key climate variables in any part of the oceans is key to maximising the potential of the UK oceanographic community to improve mechanistic understanding of the climate system.

To be expanded upon:

- *Flexibility in sampling.*
- *Exploratory science (for example in the early days of Argo).*
- *Direct large funding sources into developing more global instruments.*
- *SSOOP Ocean Observing Prioritisation report [COMMS1358 SSOOP REPORT V13.pdf (ocean-observations.uk)]*

5.5.2. People, Skills and Partnerships

To be developed.

- *The expected large datasets resulting from more autonomous and satellites measurements should come with better training to deal with large datasets and to process outputs.*
- *More links between scientists and engineers.*

5.5.3. Digital Infrastructure

To be developed.

- *ALR to gliders to Argo: resources are needed to have common data processing pathways and more flexibility*
- *A high volume of data is difficult to deal with but good for process studies*

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Annex 5A

Table 5A.1. Proposed additional EOVs

Physics	Biochemistry	Biology and Ecosystems
Additional Key State Variables		
	Trace metal concentrations Particle size Inherent Optical Properties	
Additional Rates and Fluxes		
Radiance/Irradiance (spectral, angular resolved)	Biological uptake/production of key elements and organic and inorganic compounds listed in EOVs (e.g. O2, organic C, calcification, nitrogen fixation, biogenic silica production) Remineralisation (of carbon and other elements/compounds) Fluxes of key EOVs	Biological Growth Ingestion/grazing Egestion/faecal pellet production
Experimental Parameters		
	Maximum rates (growth, feeding, etc.) Minimum rates (e.g. baseline respiration) Dependence of rates on key EOVs (e.g., T, O2, nutrients, light, particle concentration)	
Paleo Proxies		
	Proxies for key EOVs and rates from the paleo record	