CLASS
CLIMATE LINKED ATLANTIC SECTOR SCIENCE

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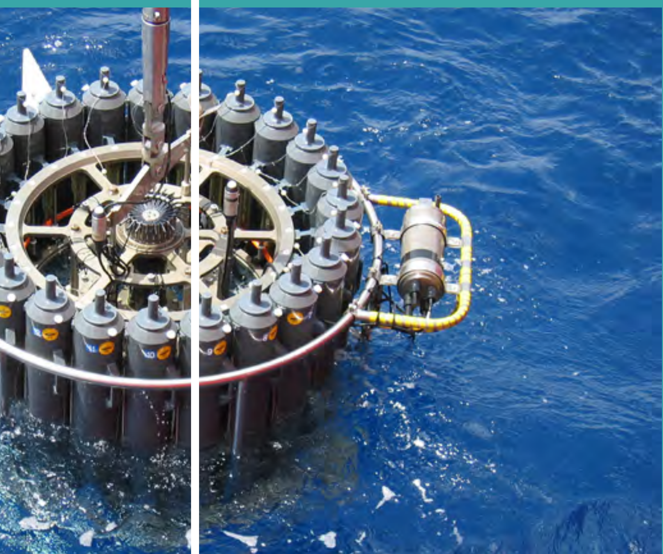
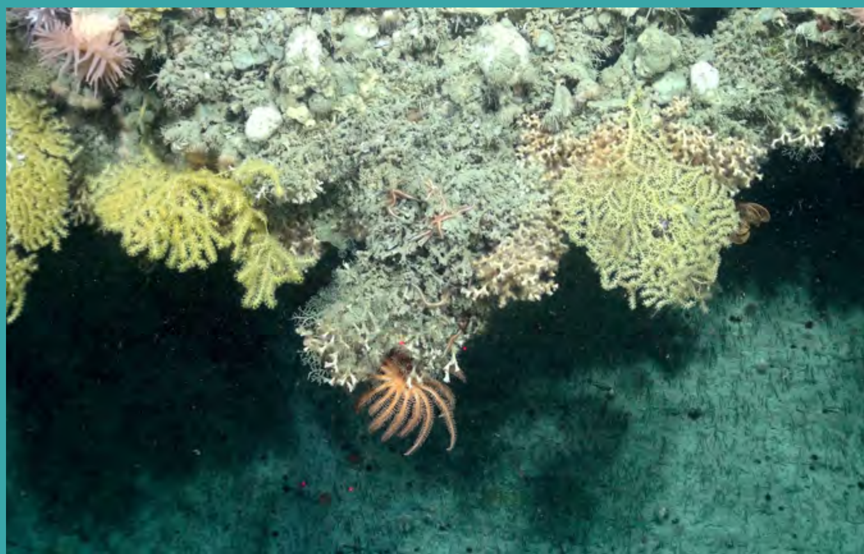
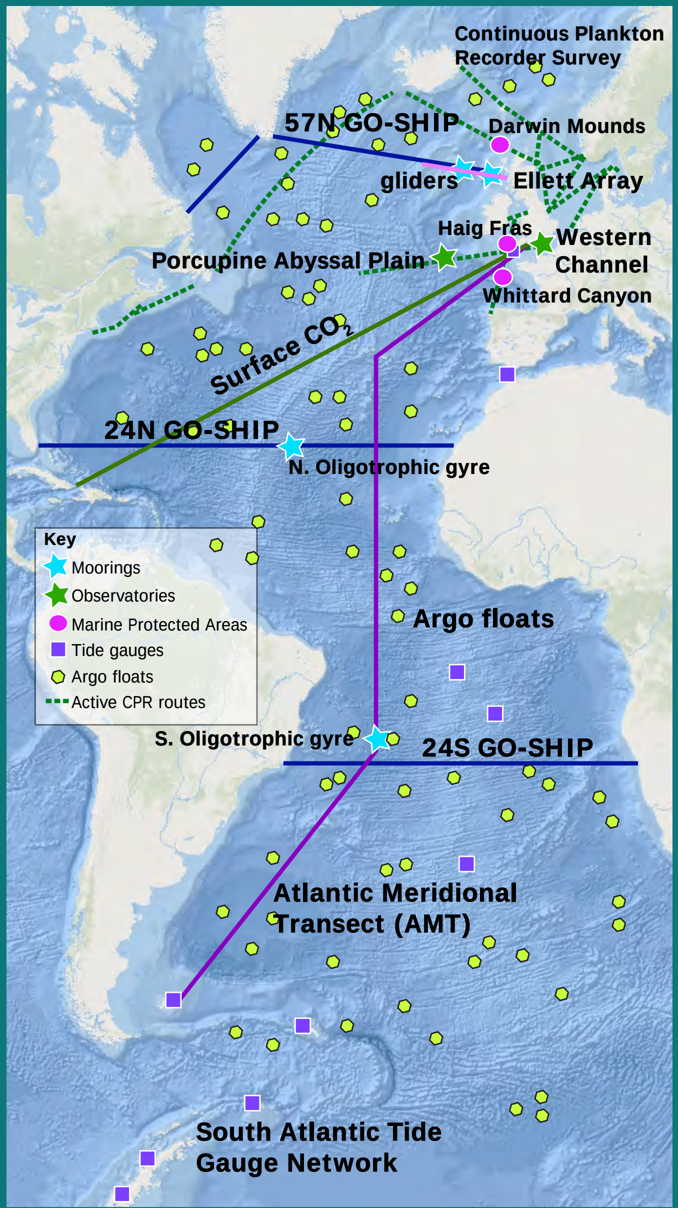
REPORT 2024

Providing a summary of research into climate and ecosystem change in the Atlantic Ocean and how they impact society





KEY MESSAGES
2024



CLASS Atlantic observing system. CLASS data available at bodc.ac.uk

Climate Linked Atlantic Sector Science (CLASS, 2018-2024) was a long-term, basin-scale, UK National Capability programme providing knowledge for research and societal needs

CLASS research explains how changes in the Atlantic Ocean have profound effects on marine ecosystems and people in the UK

The CLASS Atlantic Ocean observing system underpins world-leading research and climate and ecosystem assessments

UK Met Office ocean and climate predictive systems depend on CLASS ocean models and data

Through development of new sensors and platforms, CLASS has enhanced our ability to characterise the changing global ocean

5 UK MARINE SCIENCE CENTRES

600 PAPERS PUBLISHED

34 PAPERS PUBLISHED IN HIGH IMPACT NATURE AND SCIENCE JOURNALS

15,000+ CITATIONS

17 OPEN OCEAN RESEARCH EXPEDITIONS

483 DATASETS EXPECTED TO BE SUBMITTED TO BODC

104,000+ KILOMETRES SAILED

~40,000 SAMPLES COLLECTED

357 VISITS TO THE WESTERN CHANNEL OBSERVATORY NEAR PLYMOUTH

10,000+ NAUTICAL MILES PER MONTH SAMPLED – CONTINUOUS PLANKTON RECORDER

50 COMMERCIAL SHIPS VOLUNTARILY COLLECTING DATA FOR CLASS

~15,800 DOWNLOADS OF CLASS DATA FROM BODC FROM ACROSS THE WORLD

73 STUDENTS FROM 29 UNIVERSITIES COLLECTED DATA AND SAMPLES ON CLASS EXPEDITIONS

10 EARLY CAREER RESEARCHERS RECEIVED CLASS FUNDING FOR FIELD AND LABORATORY WORK TO SUPPORT THEIR CAREER DEVELOPMENT

22 EU-FUNDED PROJECTS

60+ NERC-FUNDED PROJECTS

6 GLOBAL OCEAN OBSERVING SYSTMS (GOOS) NETWORKS

5 INTERNATIONAL DATA HUBS

7 SOCIETAL-RELEVANT MODEL CAPABILITIES DELIVERED IN COLLABORATION WITH THE MET OFFICE

170 USERS FROM 120 ORGANISATIONS ACCESS THE MET OFFICE-NOC MODEL DATASETS EVERY MONTH

10,000 TERABYTES OF MET OFFICE-NOC MODEL DATA DOWNLOADED EVERY MONTH

MAJOR SCIENTIFIC ADVANCES IN HOW CHANGE IN THE ATLANTIC OCEAN AFFECTS CLIMATE AND ECOSYSTEMS

Drivers of the Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) is the product of series of flows and currents that move warm, salty and light surface water northward, and cold, fresh and dense deep water southward. The AMOC modifies global climate by removing from the atmosphere some of the excess heat and carbon dioxide caused by anthropogenic greenhouse gas emissions. The AMOC affects weather over Europe through its influence on the sea surface temperature in the North Atlantic. Through CLASS we have established a better understanding of the processes that underpin the AMOC, in particular the conversion of warm and light water into colder and denser water. We have found that heat loss from the ocean to the atmosphere provides some initial cooling. However, the final properties of dense water are ultimately determined by turbulent mixing that further cools and freshens deep water in a few key regions of the Atlantic Ocean near Iceland and Greenland. The importance of this new understanding lies in the ability of models used for climate projections to include the effects of mixing and therefore increase confidence in the magnitude and impacts of future climate scenarios.

Turbulent mixing is key for the formation of deep water in the subpolar North Atlantic

North Atlantic carbon accumulation is a sensitive interplay between circulation and biology

The North Atlantic plays a critical role in slowing the onset of climate change by absorbing and storing carbon dioxide (CO_2) derived from human activities away from the surface ocean on climatically-important timescales. The CO_2 is transported to the North Atlantic from outside the region, and is also taken up locally. Transfer of CO_2 from the air to sea happens through a combination of cooling of surface waters and through intense biological activity that is sustained by the subsurface nutrient supply from the Gulf Stream. CLASS research has shown that less CO_2 than expected has been delivered to the North Atlantic over the last decade by the AMOC, and that there have been opposing trends in biological productivity between the subpolar and subtropical regions. Furthermore, our research has identified that the magnitude of the North Atlantic CO_2 sink is highly sensitive to the efficiency and community composition of the biological carbon pump. The research shows that the way the Atlantic Ocean takes up anthropogenic CO_2 is changing.

Results highlight the fragility of continued carbon sequestration in the global ocean's most efficient carbon storage region

CLASS research is unravelling the direct and indirect effects of warming on Atlantic plankton

Climatic warming is the largest single factor behind large-scale shifts in plankton in the North Atlantic and fringing seas that we have witnessed over the last 60 years. Changes include partial replacement of crustacean plankton with other forms such as meroplankton, northwards range shifts and range squeezes, changing phenology and changing size structure. CLASS science is unravelling the mechanisms behind these changes, and it has revealed a dual effect. Not only is warming having direct effects on the plankton (for instance causing shifts in range or phenology), but it is also having indirect effects, through increased stratification and reduced nutrient supply, favouring tiny, low food quality picoplankton and leading to less efficient food transfer to higher trophic levels. Observational and model evidence suggest that a decline in food web efficiency will have major implications for the ability of the Atlantic Ocean to support a high biomass of fish and efficient carbon export.

Warming-induced restructuring of Atlantic plankton populations has serious implications for fisheries and for carbon sequestration

Recovery of benthic communities following seafloor disturbance

Human impacts in the marine environment are increasing and are continuing to shift into deeper waters. Activities such as bottom trawling or the installation of seafloor infrastructure have a direct mechanical impact on the benthic environment and can smother seabed fauna through large-scale sediment resuspension. CLASS research has shown that partial recovery of benthic fauna from these types of disturbance is possible, if the right management measures are taken. Individual sponges were observed to use active and passive cleaning to remove a smothering sediment cover, while cold-water coral recruits were seen to colonise artificial substrata in previously trawled areas. However, recovery trajectories are slow, taking months following sedimentation events, and decades following mechanical destruction. Hence a rigorous application of the precautionary principle, avoiding disturbance in the first place, is still the best way to protect marine benthic communities. CLASS research has provided evidence for effective restorative action and for policy decision-making

Partial recovery of cold-water coral communities following mechanical disturbance may be possible through restorative actions, but takes decades

PARTNERSHIPS AND LEADERSHIP FOR RESEARCH AND THE GLOBAL OCEAN OBSERVING SYSTEM

The CLASS observing system has provided high quality coastal to deep ocean, surface to seafloor, physical, biological and chemical data from the Atlantic Ocean. It has built on our historic legacy of many decades of UK observations, providing unique climate time series information. It is the largest component of the UK contribution to the international Global Ocean Observing System (GOOS). GOOS provides Essential Ocean Variables (EOVs) for climate and environmental assessments, operational forecasting needs, and climate and earth system research. Through CLASS the UK has taken a leading role in the coordination and governance of GOOS and its networks, as well as expert groups for intergovernmental organisations such as the World Meteorological Organisation (WMO), the Global climate Observing System (GCOS) and the International Council for the Exploration of the Sea (ICES).

CLASS has delivered research and knowledge through national and global partnerships with 26 different universities and 14 research centres. We have worked closely with UK partners such as the Joint Nature Conservancy Council (JNCC), the Centre for Environment, Fisheries and Aquaculture Science (CEFAS), the National History Museum, the Royal Navy, and the Met Office. CLASS has provided essential infrastructure for UK marine science, underpinning numerous NERC and European Union research projects.

CLASS has been a major contributor to global networks and international research, providing scientific and governance leadership as well as data, facilities and new knowledge

ENHANCING THE ACADEMIC RESEARCH ENVIRONMENT

Creating opportunities for early career researchers

CLASS placed students and other Early Career Researchers (ECRs) from universities around the world on our research expeditions. The ECRs were given the opportunity to develop their skills and collect new samples and data for their own research. During CLASS, we provided berths to 73 students from 29 different universities, supporting a very wide range of new and innovative research.

CLASS also ran a competitive Fellowship scheme that provided financial support for ECRs to extend their research through building on CLASS facilities and expeditions. Ten CLASS Fellowships were awarded to ECRs from universities in the UK, Belgium, Germany, Denmark, France and Ireland. The awards supported a wide variety of research. Several fellows tested novel sensors to study a variety of processes including coastal ocean acidification, the role of silicon in Atlantic phytoplankton growth and nitrogen cycling in sediments. Three awards were used to work on aspects of the carbon cycle: the uptake and storage of atmospheric CO_2 in the North Atlantic, the biological carbon pump, and the transport and storage of ocean carbon in seafloor sediments. Analysis of in-situ and remote data of the European Slope Current and the collection and analysis of bioturbation cores at the Porcupine Abyssal Plain were also carried out by fellows funded under the scheme.

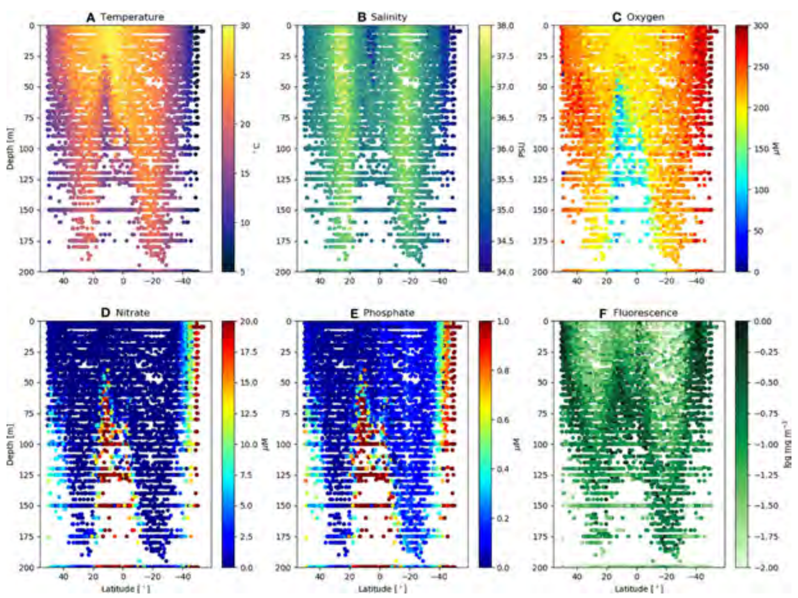
A fully funded workshop run by CLASS modelling experts gave twenty five ECRs the opportunity to learn how models can complement observational or data-based analysis and to gain familiarity with a broad range of CLASS related model simulations. These included high-resolution regional and global modelling, integrated ecological and biogeochemical processes, and simulations spanning from the near-present day to the end of the 21st century.

In 2020 the Covid-19 pandemic forced CLASS to suspend its early career researcher schemes; instead we designed a new training scheme for developing seagoing leadership skills. Since 2021 NERC research expeditions have had a Chief Scientist and co-Chief Scientist, pairing an ECR with more experienced researcher.

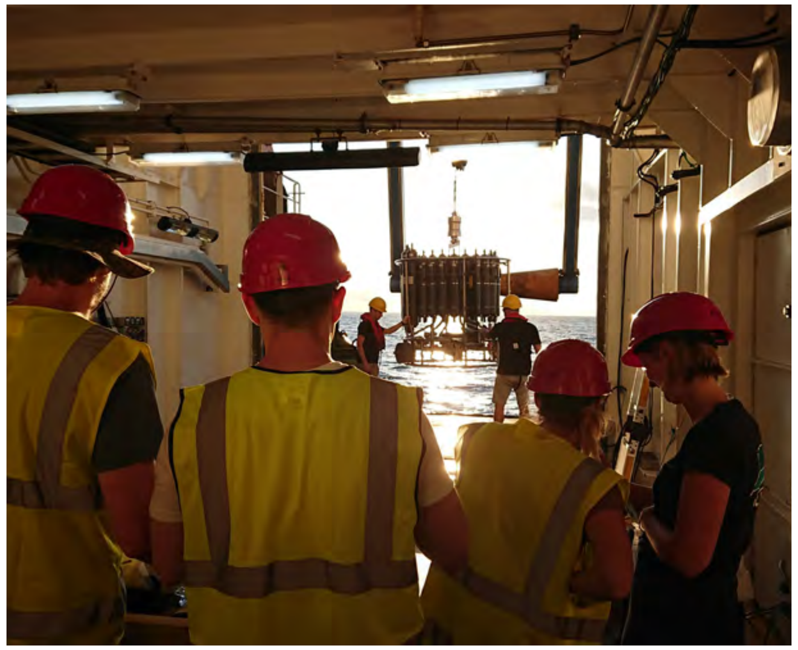
OBSERVING SYSTEM STATUS AND PROGRESS

Measurements from observatories, moorings and ships

The Atlantic Meridional Transect (AMT) programme has now achieved a 28-year time-series providing annual measurements on a route between the UK and South Atlantic. A Frontiers in Science Research Topic issue highlighted the diversity and multi-disciplinary nature of the studies enabled by the AMT programme with a collection of papers on topics ranging from bacterial biodiversity to surface ocean exchange of greenhouse gases. Three research expeditions involving 55 scientists from 23 institutes in 15 countries took place during CLASS. During the expeditions, 174 conductivity, temperature and depth (CTD) profiles were conducted and 1000s of underway measurements recorded, covering almost 100° range in latitude. A variety of techniques, sampling and measurements were used to determine distribution, abundance and characteristics of phytoplankton, zooplankton, archaea and bacteria, including net hauls and flow cytometry measurements. The data collected on AMT cruises underpin important advances in our understanding of the Atlantic. Collaboration with both the European and American space agencies (ESA and NASA) has provided additional funding and enabled improved remote satellite sensing in the Atlantic Ocean through comprehensive assessments using AMT datasets and satellite measurements.



Environmental variables from twelve AMT transects. (Smyth et al., doi:10.3389/fmars.2023.1191216)



Scientists waiting to collect water from a CTD during the trans-Atlantic hydrographic cruise JC191 (24°N GO-SHIP) between the USA and Spain

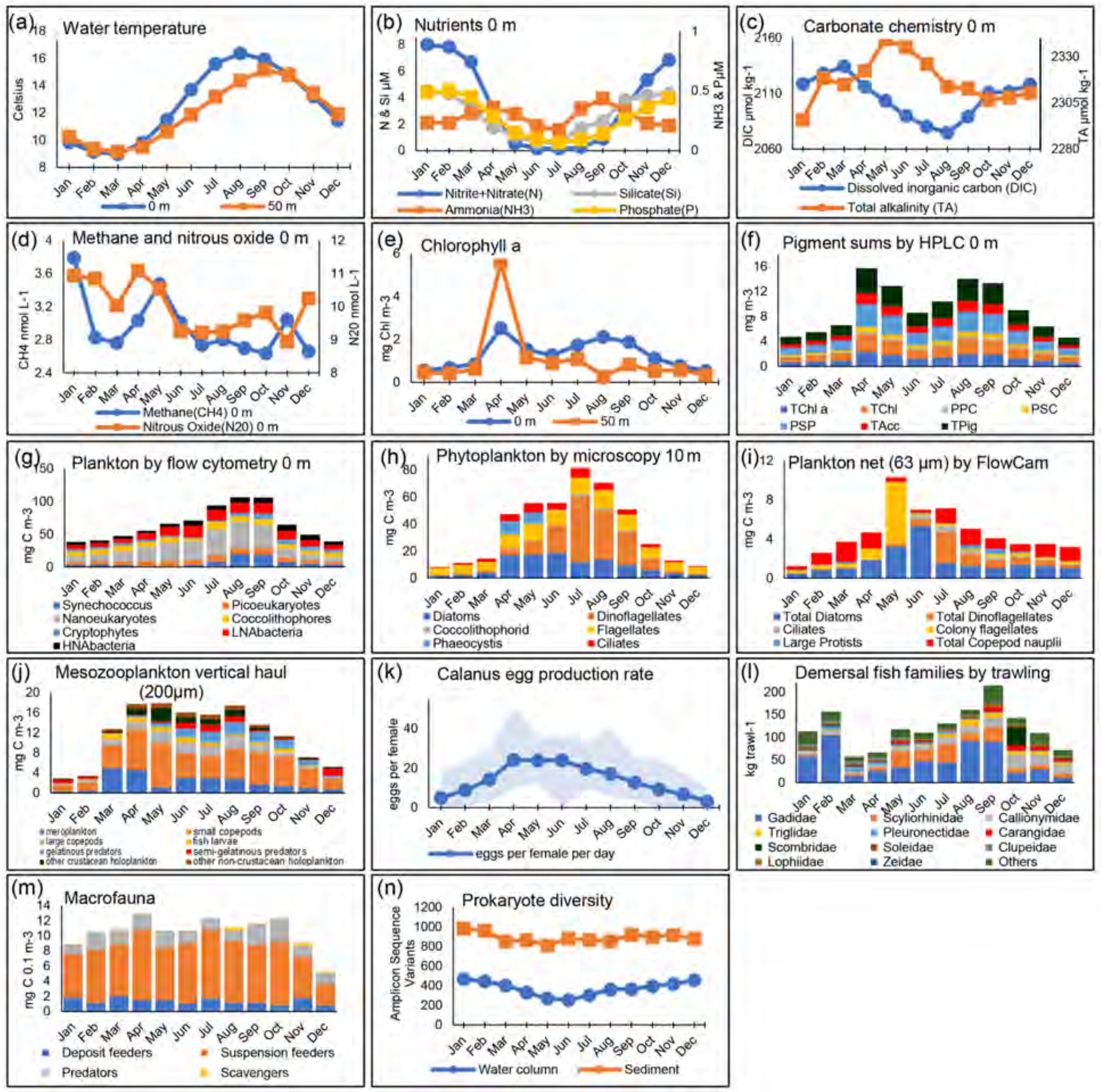
At the beginning of 2020, the eighth repeat of the 24°N GO-SHIP hydrographic section was undertaken on a research cruise from Florida, USA to Tenerife, Spain. During the cruise, 135 full depth CTD stations were completed along the transect, with measurements and sampling for physics data, carbon, oxygen and nutrients. The data from the cruise was cleaned, calibrated and sent to data centres, where it has now been incorporated into the GO-SHIP Easy Ocean atlas product. Preliminary processing has already revealed significant results in that the upper ocean part of the 24.5°N section has become warmer, saltier and higher in carbon over the last 10 years. These changes are being separated into diabatic and adiabatic, and excess and redistributed components in ongoing work that will determine why and how the ocean has warmed. Repeat measurements on the SR1b hydrographic line in the Drake Passage were conducted in 2023 and the data has been delivered to the Global Data Centre.

CLASS supported the UK-Caribbean SOOP (Ships of Opportunity) route in 2018-2019. The GEEST Line route has been providing sea surface CO_2, temperature, salinity and nutrient data since 2002. Recorded increases in atmospheric CO_2 are not mirrored in the sea surface CO_2, however increasing variability, particularly in winter is seen. On the UK-Falklands route, five trips were made across 2018 and 2019 providing sea surface CO_2 data and samples for dissolved inorganic carbon (DIC) and total alkalinity (TA) measurements. In addition to onboard sensor instrumentation, the engineers also took daily samples. Data has been used in combination with ICOS (Integrated Carbon Observation System) and SOCAT (Surface Ocean CO_2 Atlas) data to understand the processes that affect surface O_2 and CO_2,

The Continuous Plankton Recorder (CPR) Survey towed almost half a million nautical miles (nm) and analysed over 23000 samples during the CLASS project, continuing 65 years of uninterrupted monitoring in the North Atlantic. There was no break in the time series in 2020 for core regions despite the Covid-19 pandemic. With a total of 8 million nm towed

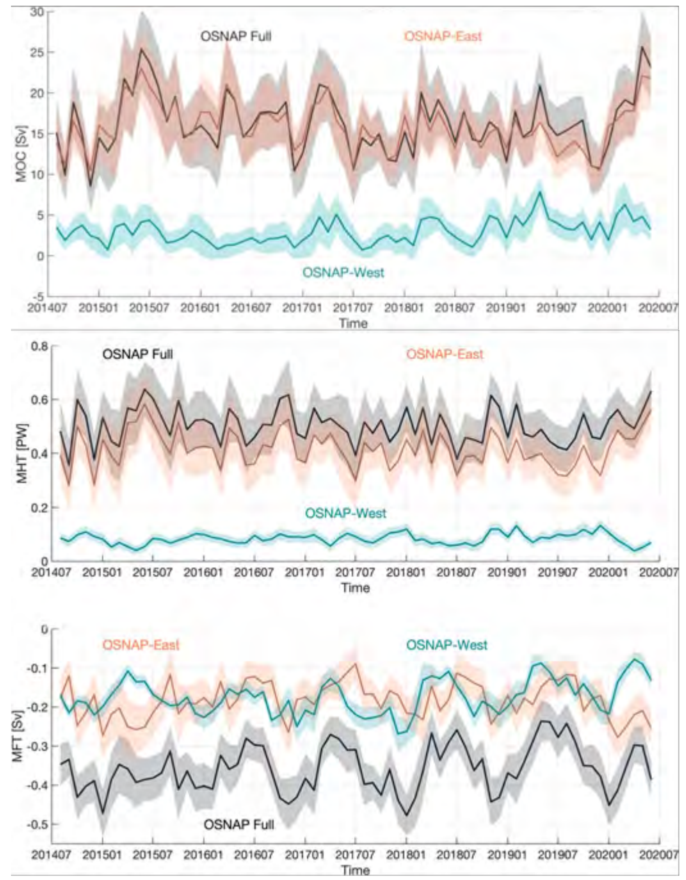
Deploying the Continuous Plankton Recorder since the start of the programme and nearly 300,000 plankton samples collected, the CPR datasets are a crucial contribution to assessing multi-decadal biological changes in the Atlantic. During CLASS some previously suspended routes have been restarted, two US operated routes have been taken over by the UK and a new route between Brazil and South Africa has been facilitated. A new integrated CPR (iCPR) includes additional sensors (for example, fluorescence), satellite geolocation and digital imaging. Survey capabilities have been expanded beyond the existing biological measurements, such as molecular methods for harmful algal blooms (HABs) and marine pathogens. New approaches have been implemented by CPR scientists to give a better understanding of biodiversity changes on ecosystem function compared to classical approaches.

Regular sampling at the Western Channel Observatory (WCO) has been maintained throughout



Seasonal patterns at station L4, Western Channel Observatory (McEvoy et al., doi: 10.5194/essd-2023-311)

the project at both the E1 open shelf station (fortnightly) and the L4 coastal station (weekly), even during the 2020 Covid-19 lockdown. Sampling at E1 started in 1903, making it one of the longest oceanographic time series in existence. It provides important data to ICOS and contributes to publications such as the ICES Report on Ocean Climate. Data from the L4 station has formed part of the 2023 OSPAR Commission's Quality Status Report which assesses the environmental status of the North East Atlantic. While WCO observations in their own right provide important insights into the changing marine ecosystem, they are even more powerful when coupled with other datasets. Combining WCO data with time series from CPR survey transects and coastal/inshore sampling programmes revealed a change in the state of pelagic habitats across the North-West European shelf. Knowledge about changes in plankton communities is crucial to enable policymakers to make effective decisions regarding the management of marine ecosystems. Integration of WCO data with CPR survey data, satellite chlorophyll data and Celtic Sea sampling data has also allowed researchers to determine how nutrient stress drives food web structure. These combined datasets, alongside other UK plankton datasets, are also being used in the UK Marine Strategy and, via the OSPAR Commission, in the EU Marine Framework Strategic Directive.



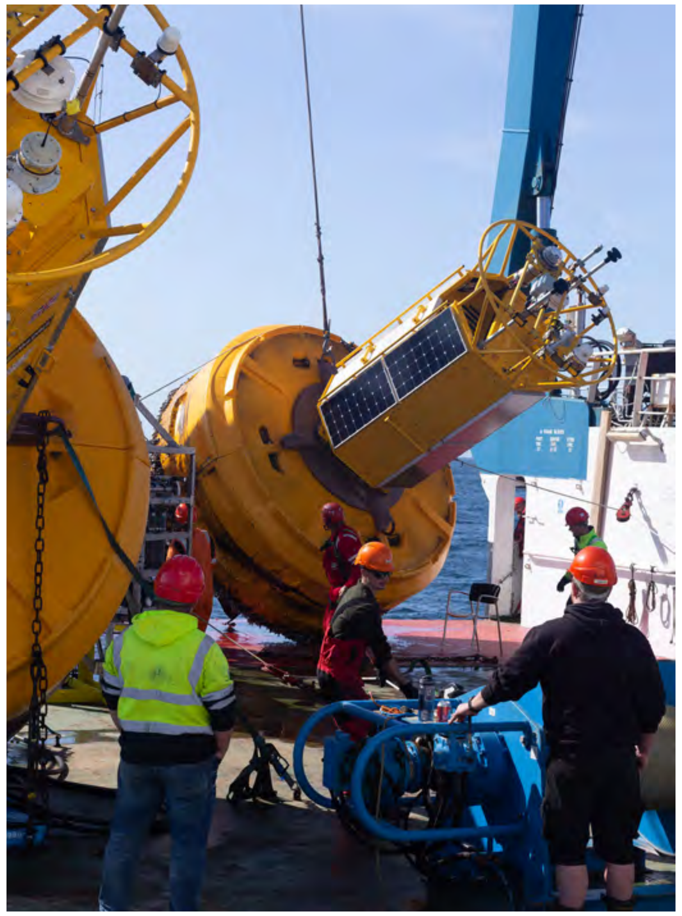
Top, monthly Meridional Overturning Circulation (MOC) time series; middle, monthly meridional heat transport (MHT); bottom, monthly meridional freshwater transport (MFT). All shown across the full OSNAP array (black), OSNAP East (orange), and OSNAP West (cyan). Shading indicates the monthly uncertainty estimated using a Monte Carlo analysis (Fu et al., doi: 10.1038/s43247-023-00848-9)

A major objective for CLASS was to maintain the Ellett Array moorings in the Rockall Trough. Three cruises took place successfully in 2018, 2020 and 2022 to service the moorings and collect CTD profile data. The latest cruise data, where ~60 full depth CTD profiles were conducted, has enabled the extension of the time-series of volume, heat and freshwater transport in the Rockall Trough to eight years. Continuous measurements (10-day means) of ocean volume, temperature and salinity transports through the Rockall Trough were delivered. Analysis of the data has revealed large variability in the eastern North Atlantic circulation due to changes in the North Atlantic Current. The Ellett Array continuous time series is allowing new types of analysis, including seasonal signals that have much greater size than was previously detectable. The Ellett Array forms the eastern end of the international programme OSNAP (Overturning in the Subpolar North Atlantic Program) to measure the subpolar AMOC, leading to new knowledge about AMOC processes. As part of a programme to test new methodologies for detecting

AMOC change alongside existing approaches, new ambient-zero-ambient (AZA) bottom pressure recorders (BPR) were deployed at the Ellett Array. The new BPRs will remain in the water for 10 years to measure changes in the speed and strength of the AMOC and the heat it transports. Data can be retrieved acoustically from the BPRs, and in a test trial the first data retrieval via an autonomous surface vehicle was successful in summer 2023.

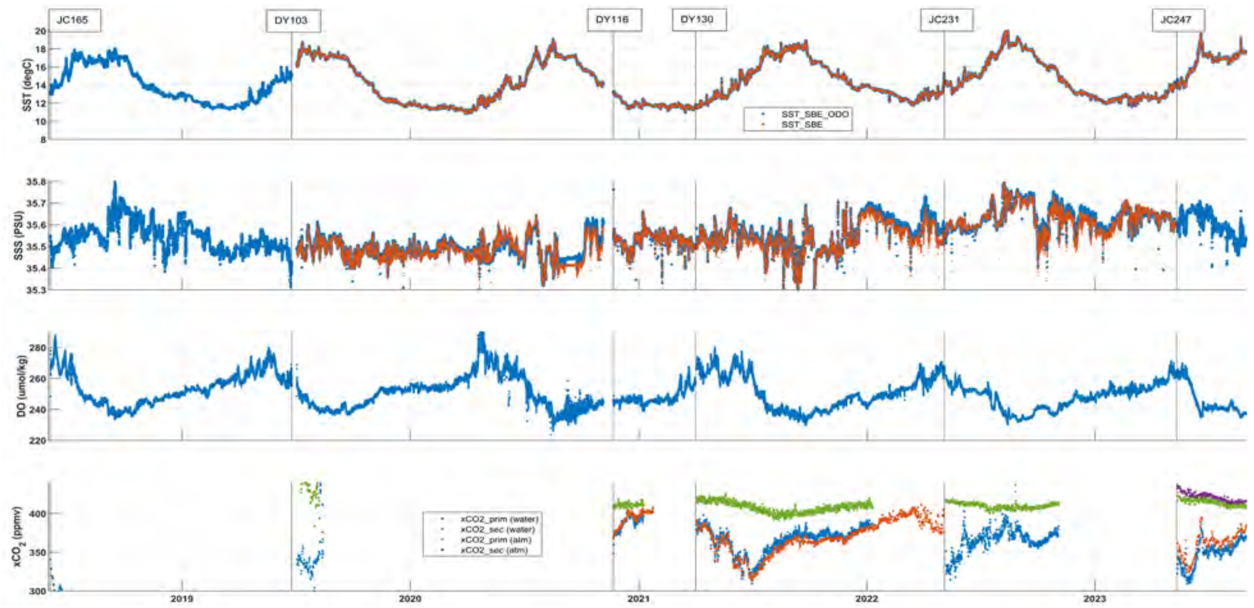
A total of eight summer and winter glider missions have been conducted, increasing the spatial coverage of the Ellett Array moorings by measuring the shelf edge current. The shelf current is an important pathway for AMOC transport, but has proved impossible to measure using moorings due to the intensity of fishing activity. Data from 110 glider transects allowed the characterisation of the current, quantifying the seasonal variability and revealing a year-round southward countercurrent at depth.

The Porcupine Abyssal Plain Sustained Observatory (PAP-SO) is the UK's open ocean ICOS station. The time series data for sea surface CO_2, pH, benthic biota and many other Essential Ocean Variables has continued under CLASS, delivered through a combination of surface and subsurface instruments and sensors, deep sediment traps and seabed cameras. During the project, seven cruises visited the site to service the mooring and instruments and to conduct sampling and surveys. Some datasets are still being processed as calibration samples are analysed. However, some data from all the cruises have already been submitted to BODC with CO_2 related data also submitted to ICOS, SOCAT, OceanSITES and the Met Office.



Met Office buoy deployment at PAP-SO

The combination of long-term physical, biogeochemical and biological time series data from PAP-SO provides a powerful tool in understanding the changes occurring in the Atlantic. This knowledge enables the connections between the atmosphere, surface water, water column and deep ocean processes to be understood. Changes in ocean climate and the corresponding effects on the ecosystem can be ascertained. For example, an increasing Atlantic Multidecadal Oscillation and reducing North Atlantic freshwater anomaly in the mid-1990s correspond with a change in seafloor biological communities. Without this comprehensive suite of data, the events would not necessarily be linked and understood. A special issue of the journal Progress in Oceanography brought together a suite of papers highlighting the unique strengths of the PAP-SO including data that spans the base of the atmosphere and sea



Examples of PAP-SO time series

surface down to the abyssal seafloor, measurement of multiple Essential Climate, Essential Ocean and Essential Ocean Ecosystem Variables and the promotion of data storage, sharing and reuse.

The South Atlantic Tidal Gauge Network (SATGN) was established in 1985. A network of nine tidal gauges from Gibraltar to Antarctica provide an important time series of sea level, water temperature and air pressure which is crucial to understanding sea level variability and ocean current fluctuations (particularly the Antarctic Circumpolar Current) and to enable 'ground truthing' of satellite altimetry data. In addition, these measurements allow the evaluation of storm surges and tides, which is vital for coastal protection and port operations. The tidal gauges have been refurbished and significantly improved during the project. Upgrades include support for operational monitoring of coastal hazards such as tsunamis, the installation of Global Navigation Satellite System (GNSS) receivers at four sites to monitor vertical land motion and the inclusion of new sensors. Sampling frequency has been increased and near real-time data delivery has been implemented.

CLASS brought together several long-term programmes to form an extensive Atlantic Ocean observing system. The combination of ship-based measurements from repeat transects with data from floats and fixed instrumentation (moorings, observatories, tidal gauges) has provided a comprehensive set of data for evaluating the impact of climate change on the Atlantic ecosystem. This in turn provides key evidence for policy advice related to our use, protection and restoration of the ocean.

Assessing human impact in the marine environment

A crucial tool in assessing the impact of human activity in the marine environment, and distinguishing between natural and anthropogenic influences, is the use of repeat surveys and monitoring at specific sites. CLASS undertook repeat fieldwork at three key Marine Protected Areas (MPAs), the Haig Fras Marine Conservation Zone (MCZ), the Darwin Mounds Special Area of Conservation (SAC) and the Whittard Canyon MCZ.

Haig Fras MCZ, the only rocky reef in the Celtic Sea, was surveyed using the Autosub autonomous underwater vehicle (AUV) in 2018 and 2022 to obtain acoustic (sidescan sonar) and image data. This has provided valuable repeat data to add to the 2012 and 2015 surveys and expanded the study of this area with a comparison of daytime and night-time benthic communities. Image analysis from these surveys has shown distinct benthic communities on different seafloor substratum. The sidescan data and machine learning techniques have been used to map where these communities occur and then show the changes of habitat over time. Imagery datasets were submitted to the CEDA (Centre for Environmental Data Analysis) archive for the first time, using data from the Haig Fras surveys. The process involved designing a new procedure for data preparation and submission, which will now be used for other CLASS and future datasets.

The Darwin Mounds were re-mapped in 2019 (adding to the first mapping data in 1998-2000 and repeat mapping in 2011) using Autosub6000 to conduct six sidescan sonar and BioCam photography surveys. HyBIS video transects were also conducted, sediment samples collected and settlement experiments recovered. There was little change in the morphology of the cold water coral mounds which were previously impacted by bottom trawling; in other words there had been negligible natural recovery despite protection for nearly 20 years. No new trawl marks were discovered but there were considerable amounts of litter, especially fishing equipment. Observations and analysis of the settlement experiments suggest that placing artificial substrata on the seabed is an efficient way to promote recovery of the cold water corals. Analysis has been ongoing, including a ‘human vs computer’ test to see whether machine learning technology or humans are quickest at estimating the amount of coral cover in images.

The Whittard Canyon MCZ was last surveyed in 2015. After a suspension of the cruise program due to Covid-19, the Whittard Canyon MCZ was finally revisited in 2022 to conduct fieldwork and repeat surveys. Prior to this, the collaborative power of the CLASS program enabled a mooring to be deployed and later serviced during the PAP cruises in 2019 and 2020. Remotely operated vehicle (ROV) video surveys, specimen and sediment samples, and AUV acoustic and image data were also collected during the Haig Fras cruise. The main Whittard Canyon expedition revisited key habitats and locations to monitor biological and geological change using photogrammetry and AUV mapping. Sediment transport dynamics in the canyon, including the transport of organic carbon and microplastics, were investigated using mapping, current measurements, and sediment and water sampling. Analysis of data is ongoing.

Images of Whittard Canyon

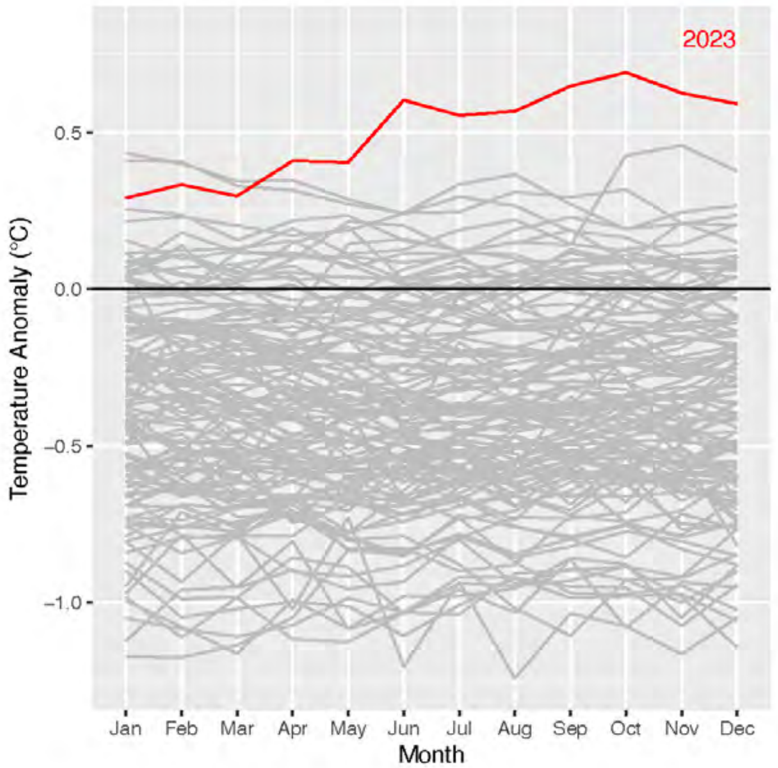
Although mapping of the Darwin Mounds did not find evidence of new coral growth, settlement experiments show that there are coral larvae in the area and therefore the potential for new cold-water coral colonies exists.

Essential novel datasets for characterizing climate change

A new dataset (CLASSnmat) has been developed that provides monthly mean, gridded values of Night Marine Air Temperature back to 1880 across global ocean regions. CLASSnmat complements the more widely used sea-surface temperature datasets as an indicator of global temperature change and serves as a reference dataset for the evaluation and reanalysis of modelled data. The dataset is updated annually, is used in a yearly contribution to the American Meteorological Society's State of the Climate report and has been used in a new global surface air temperature dataset that extends back to the 1790s.

The CLASS global upper ocean heat content product (derived from Argo float data) contributed to a new, international review of Earth's energy imbalance. The oceans continue to absorb more than 90% of global warming heat. The analysis played a central role in informing and advising policy through the Intergovernmental Panel on Climate Change (IPCC) and other channels.

In addition to datasets, tools such as the AirSeaFluxCode python package have also been developed. For the first time, ten bulk formulae have been brought together in one package to enable the calculation of air-sea surface fluxes of momentum, heat and moisture and to enable the estimation of uncertainties in flux calculations.



Monthly, global average marine air temperature anomalies (relative to a 1991-2020 base period) from the CLASSnmat dataset. Each line represents a year of data, with the unprecedented values for the year 2023 highlighted in red

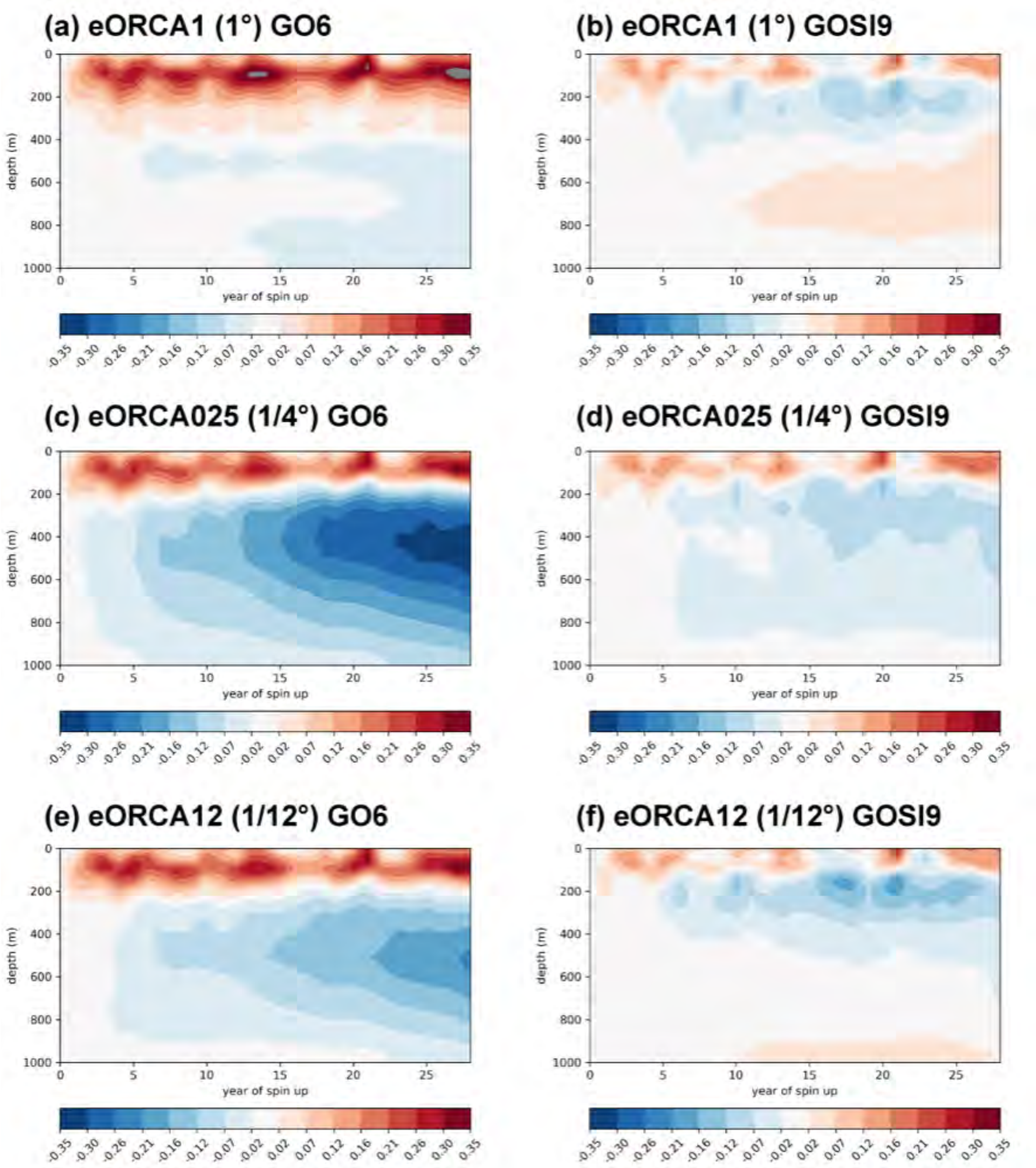
OCEAN AND CLIMATE PREDICTIVE SYSTEMS DEVELOPMENTS AND IMPACT

Key global model configurations underpinning the UK's capability in ocean prediction for climate change and operational oceanography

CLASS scientists improved the representation of physical processes in the NEMO ocean-ice model and enhanced its computational efficiency through NOC's membership of the international NEMO Consortium. Rigorously tested global model configurations for UK prediction systems (weather forecasting, including short-term ocean "weather" forecasts, seasonal/decadal climate predictions, and century-scale climate projections) have been constructed. These configurations are delivered in collaboration with the Met Office and UK academic research institutions via the Joint Marine Modelling Programme (JMMP).

NEMO's computational efficiency has been significantly enhanced by improving treatment of model grid points that lie at the boundaries of the individual computer processors and large portions of the code have been rewritten to accommodate a new, more accurate time-stepping scheme. A major improvement to the physics is the inclusion of a more realistic treatment of sea ice deformation and flow, break up via wave-ice interaction, and surface melt ponds. CLASS has also supported the adaptation of NEMO to improve performance in shelf and coastal regions without detriment to large scale circulation. This Shelf-Enabled NEMO (SE-NEMO) includes tidal forcing, tidally-generated internal wave drag and more realistic river inputs.

Two configurations of NEMO for use in UK forecasting systems have been developed with the Met Office through JMMP, GO8 (Global Ocean configuration #8) and GOSI9 (Global Ocean and Sea Ice configuration #9), They have been extensively tested under CLASS and feature a new sea ice scheme, SI3; reduced spurious numerical mixing due to inclusion of a more accurate advection scheme; a new equation of state based on latest theory and observations; and a new cutting-edge ocean surface boundary layer scheme (OSMOSIS). Tidal forcing and hybrid vertical coordinates were added and a new approach to modelling overflows of deep-water masses through critical sills, such as the Denmark Strait and the Greenland-Scotland ridge was also developed and included.



Improvement in the GOSI9 ocean/sea ice configuration compared to the previous generation of the model. Ideally a gentle warming in the upper ocean should be seen, resulting from the general warming trend: the latest model is much closer to that, and doesn't show the strong, spurious interior cooling

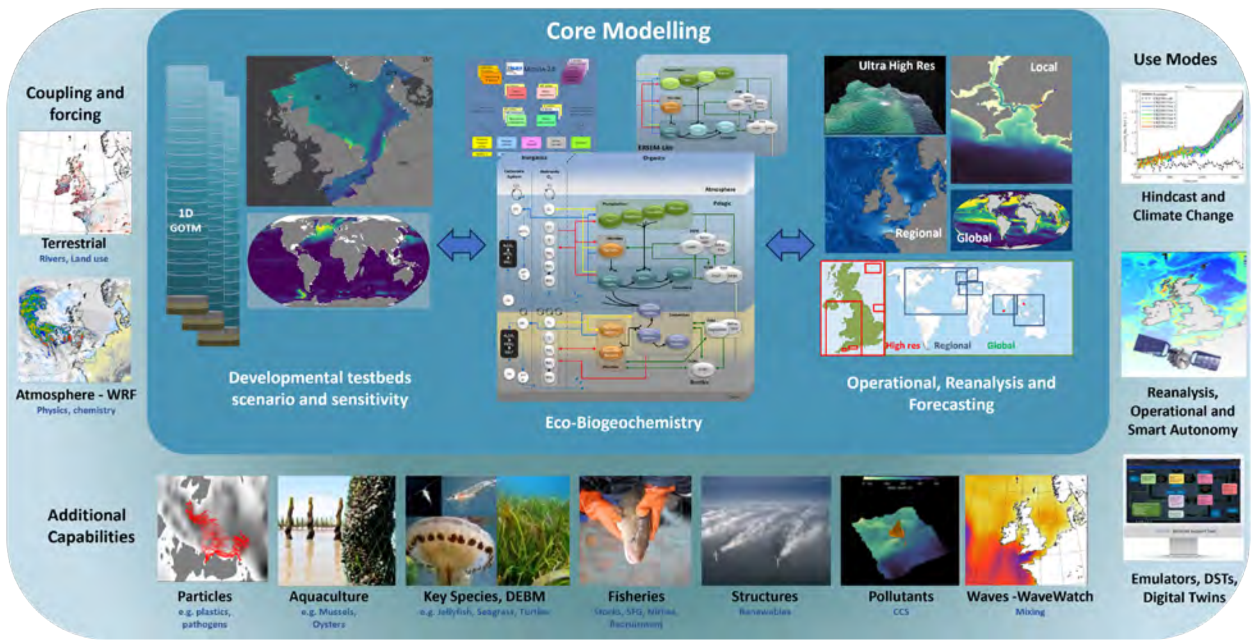
The MEDUSA model, a marine biogeochemistry component used in the global models, has been improved with dynamic C:N stoichiometry which removes potential errors in future C-cycle fluxes that can arise from fixed stoichiometry. Zooplankton ecophysiology has been improved and some development on open biogeochemical cycles, e.g. riverine input has been completed. The benthic ecosystem is represented more accurately to capture the full seafloor ecosystem from bacteria to fish using BORIS, a benthic biomass model.

Key shelf sea model configurations underpinning the UK's capability in shelf sea prediction for NW European waters and beyond.

The NEMO Atlantic Margin Model (AMM) vertical coordinate setup was revised to give better results on shelf slopes where there is very steep topography (to minimise, for example, horizontal pressure gradient errors). Wetting and drying processes (representing a mobile coastal water line) and improved Baltic boundary conditions were also incorporated.

The ERSEM ecosystem model code (ERSEM 20.10) publicly released in 2020, included harmonised formulations and updated documentation. An updated version (ERSEM 22.11) was made available in 2022. Improvements included parameterisation of pelagic production and air-sea exchange of nitrous oxide, the addition of pelagic denitrification and improved terrestrial coupling. New and updated tutorials were also released and there are now ~300 registered users worldwide. In the NEMO-ERSEM AMM7 model, the definition of river inputs and boundary conditions was improved. The flexible coupling of external model systems to ERSEM via FABM has been advanced, for example a model suite that uses PyLag particle tracking, ShellSim for aquaculture, embedded in ERSEM with physics driven by FVCOM, was used to examine the impacts and interactions between microplastics and mussel culture.

New functionality was added to COAsT, a tool for examining kilometric scale regional models. For example, arbitrary vertical slices can be selected and the properties (e.g. velocities, transports) of these sections can be plotted. This facilitates the comparison between observations and model simulations to assess model performance.



PML's coupled marine system

Other advances in modelling and analysis capabilities include further development of nctoolkit (a Python package for analysis of netCDF files), a new Python package 'ecoval', providing full automation for the validation of ecosystem models such as NEMO-ERSEM, and a new Python implementation of the GETM model to provide a quick 3D testbed for model analysis and calibration.

Glossary

ACSIS
North Atlantic Climate System Integrated Study

BORIS
Benthic Organisms Resolved in Size

COAsT
Coastal Ocean Assessment Toolbox

CMIP
Coupled Model Intercomparison Project

ERSEM
European Regional Seas Ecosystem Model

FABM
Framework for Aquatic Biogeochemical Model (Connects a hydrodynamic model with multiple biogeochemical models)

FVCOM
Finite Volume Community Ocean Model (Provides 3D simulations of ocean's physical properties)

MEDUSA
Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification

NEMO
Nucleus for European Modelling of the Ocean (A modelling framework developed by a European consortium for research and forecasting in ocean and climate sciences)

ORCA
A series of global ocean configurations used when running some models

OSMOSIS
Ocean Surface Mixing, Ocean Sub-mesoscale Interaction Study

PRIMAVERA
PRocess-based climate sIMulation: AdVances in high resolution modelling and European climate Risk Assessment (European Union funded project)

PyLag
A Python Lagrangian particle tracking framework

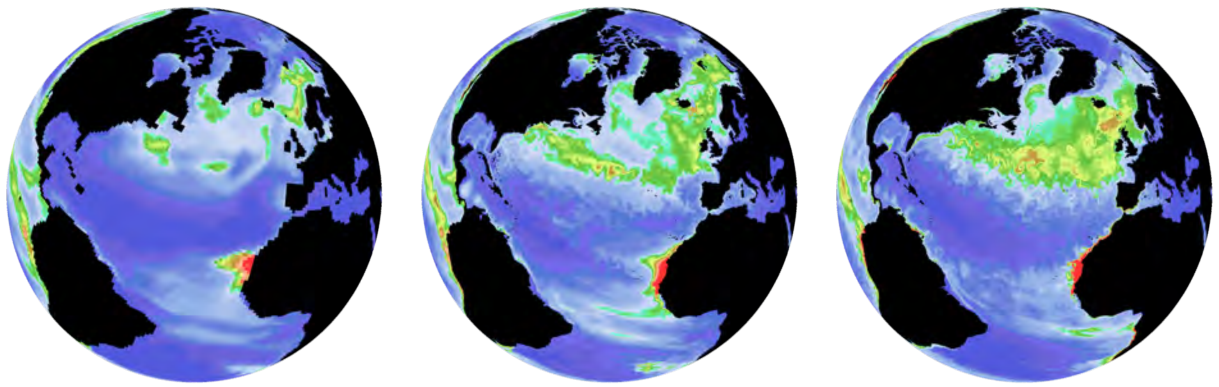
ShellSIM
Model that simulates shellfish growth and population dynamics

Global and regional simulations to investigate the impacts of climate change on the marine environment

Model simulations provide valuable data for studying the influence of climate change on the marine environment and ecosystems, and ocean feedbacks on weather and climate. Understanding potential impacts enables mitigation measures to be put in place and appropriate management of, for example, coastal areas, fisheries and Marine Conservation Zones.

Simulations can also be used to test observation strategies, enabling better targeting of resources, or to put limited observations into a longer-term context. For example, a relationship observed in the first years of the OSNAP array suggested that much of the variability of the subpolar AMOC was found in the eastern part of the North Atlantic while the western part played a much lesser role. This is also seen in ocean simulations but over a longer time period, suggesting this is not just a short-term feature.

CLASS has completed two coupled model simulations in collaboration with the ACSIS and PRIMAVERA projects. To assess the impact of model resolution, coupled ORCA-MEDUSA simulations with CMIP6 forcing (SSP370) at three resolutions (1, 1/4 and 1/12 degrees) have been completed for the period 1880 to 2100. These simulations will run to the end of this century at increasing resolutions. Analysis of simulations at different resolutions can reveal processes that might not be apparent from only one simulation. The suite of ORCA-MEDUSA simulations suggest that an abrupt change in subpolar convection and biological activity could occur in the coming decades. However, the abrupt subpolar changes do not coincide with a similar change in the strength of the Atlantic meridional overturning circulation, suggesting a highly non-linear response to a warming climate.



ORCA12-MEDUSA simulations at increasing resolution showing biological production

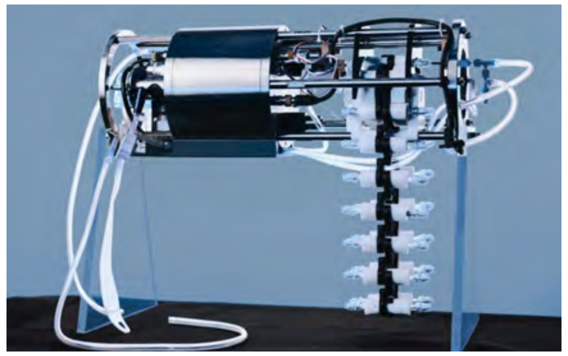
The work in CLASS feeds into a vast array of other projects and programmes. The ocean models at the heart of CLASS were not developed in isolation over the space of a couple of years, but are the result of decades of underpinning work!

ENHANCEMENTS IN CHARACTERISING OUR CHANGING OCEAN THROUGH INNOVATION

Chemical and biological sensor development

In situ lab-on-chip sensors for measurement of the ocean carbonate system have been successfully deployed in a range of environments on various platforms. As part of an offshore CO_2 release experiment, total alkalinity (TA) and pH sensors were used on landers and ROVs, while trials in Loch Ness allowed testing on an AUV. TA sensors also operated successfully for four months on a mooring in the Weddell Sea while the deep ocean capability of the pH sensor was proven during a cruise to the PAP observatory site with several successful deep (~4820m) deployments. A new version of the TA sensor using reduced sample volumes and with decreased analysis times was developed and tested. TA sensors are being used in a wide variety of contexts and applications from quantifying coral reef calcification rates to carbon capture and storage (CCS) monitoring.

Further improvement of the sensors is ongoing with integration of TA and dissolved inorganic carbon (DIC) sensors onto a single device to increase performance and reduce power usage.



RoCSI (Robotic Cartridge Sampling Instrument)

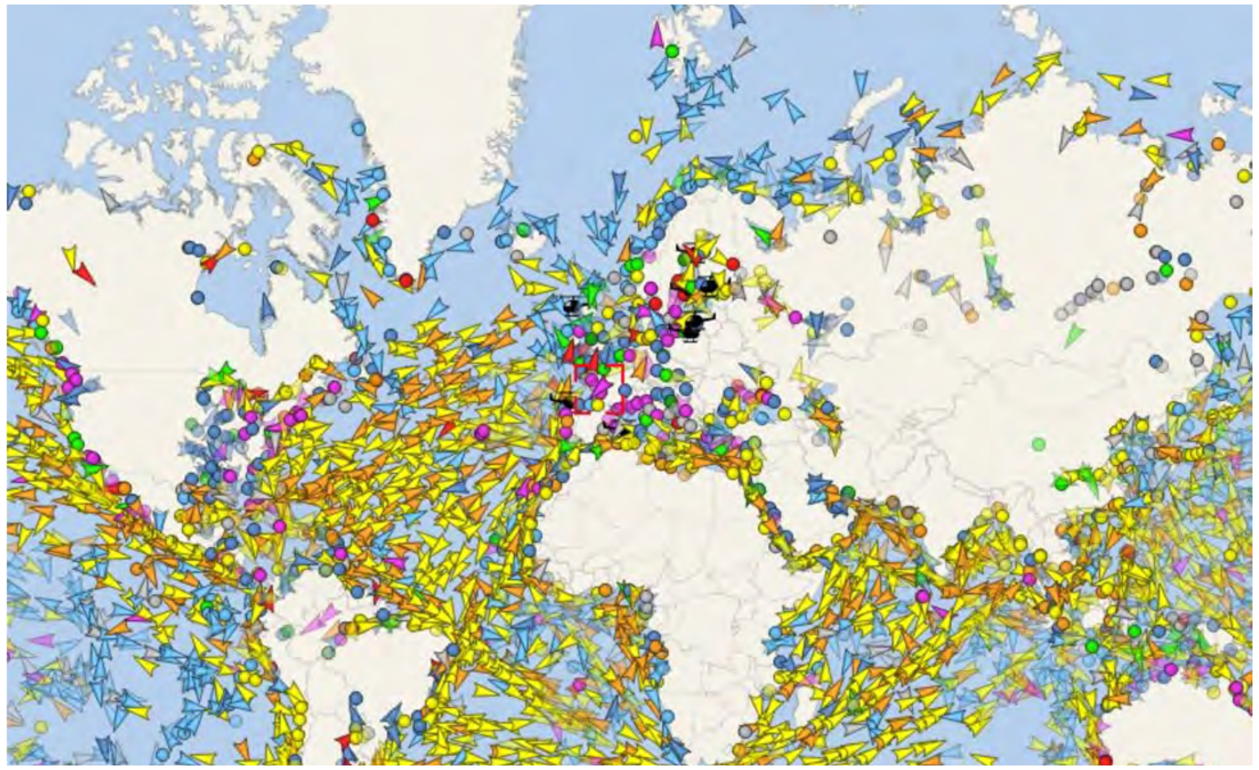
Biological sensor development included RoCSI (Robotic Cartridge Sampling Instrument), an autonomous particle sampler to target microbiology and eDNA, Cytochip, a microcytometer for shallow water work and Amplitron, an in situ genomic analyser (DNA and RNA detection). RoCSI was completely redesigned in the early stages of CLASS and after extensive testing and deployment was successfully commercialised and is now available worldwide under licence from McLane Labs Inc. (USA). Following the successful benchtop version of Cytochip which was used to generate unique cytometric profiles for harmful algal blooms (HABs), redesign work improved portability and robustness ready for in situ deployments. A prototype was built and deployed at shallow depths; deeper testing and integration with an AUV will take place in the near future.

Power and communications

To fully capitalise on sensor technologies and platforms, improved power and communications are vital as these will enable longer uninterrupted time series, fewer site visits and immediate access to data. CLASS has investigated energy harvesting and more efficient data transfer to avoid reliance on increasing numbers of batteries.

A prototype wave energy harvesting system and a supercapacitor storage prototype (for wave and solar energy) was shown to work in the laboratory and is awaiting field trials. Using supercapacitors rather than traditional rechargeable batteries potentially reduces the size, weight and hazard for deployments. Demonstration of CTD sampling driven by wave energy has shown promise but will require adaptive sampling based on power availability. A high efficiency prototype solar energy harvesting system, also using supercapacitor storage, has been deployed in the field for a year. This has been used to monitor tidal water levels and wave heights in the Severn Estuary by collecting GNSS (Global Navigation Satellite System) interferometry data.

Data transfer using the Satellite Automatic Information System (S-AIS) allows small bursts of data to be sent from AIS transponders (used on ships for vessel traffic monitoring) and relayed via satellite at a fraction of the cost of the Iridium network. There are no transmission limits and it can be powered by harvested or renewable energy. However, transmitting VHF signals via satellite is complex; not every message sent is guaranteed to be received. Work is ongoing to investigate transmission success rates and patterns to ensure optimum data transfer.



The AIS (automatic identification system) is an automatic tracking system that uses transceivers on ships, plot shows snapshot of global marine traffic

Novel remote and autonomous platforms

Measurements of air-sea interactions from oceanographic research vessels can be contaminated by the presence of the vessel itself. For example, disruption of wind flow around the vessel can cause turbulent fluxes, and the shadow of the vessel can affect observed scattered light. While modelling allows some correction of these effects, a better solution is to use remotely piloted aircraft systems (RPAS) and autonomous surface vehicles (ASVs) away from the ship.

RPAS and ASVs were successfully deployed from shore and ship. An acoustic weather station deployed on an ImpYak, a robotic impeller driven kayak, was used to obtain near-surface meteorology, and an Acoustic Doppler Current Profiler (ADCP) mounted through-hull was also used to obtain upper-level ocean velocity profiles. Geo-stationary capability of the ImpYak has been proven and these units are being used for field campaigns in the UK and Antarctica.

Water-landable RPAS have been used to successfully measure upper-boundary-layer winds. The measurements are derived from the full onboard avionics instrumentation which enable accurate determination of velocity, position and altitude. Further testing including mapping in conjunction with modelling to compare results was undertaken.

The measurement of air-sea fluxes of trace gases and heat using an array of autonomous mobile platforms has been trialled. A stack of small autonomous aircraft (drones) equipped with miniature tracer sensors are flown at constant altitude while maintaining their positioning relative to an ASV fitted with eddy covariance. The method is promising and work continues.

Increasing use of in situ and remote technologies to provide measurements and monitoring of the Atlantic Ocean is vital if we are to fully understand this ecosystem and our impact on it, without also inadvertently impacting it ourselves. Ship-based measurements will always have their place and access to ocean observatories for servicing will be needed. However, in situ and remote technologies can provide measurements over much larger areas, on much longer timescales and in areas that would otherwise be inaccessible due to geography (e.g. under sea ice) or weather conditions.

ImpYak underway during work with FAAM airborne laboratory

Impacts of COVID-19

CLASS has of course not been immune to the impacts of Covid-19. The most obvious consequence was the suspension of the National Marine Facilities cruise programme in March 2020. This affected two major CLASS cruises originally scheduled for the summer to carry out operations at Ellett Array (Rockall Trough), the Darwin Mounds and Whittard Canyon Marine Protected Areas (MPA), and the Porcupine Abyssal Plain (PAP). The cruise programme resumed in September 2020 and both expeditions were completed successfully, albeit with reduced numbers of scientists on board and a necessarily reduced scientific programme. The impacts of Covid-19 on the cruise programme continued with pressure on available ship time affecting CLASS into 2021 and 2022.

Inevitably, the delays to fieldwork and loss of productivity due to laboratory and office closures, had a knock-on effect to the completion of some CLASS deliverables. However, risks to the programme were closely monitored and the CLASS participants all worked hard to adapt to the circumstances and minimise disruption to the science programme.

Images helpfully provided courtesy of PML, MBA and CLASS project participants

UKRI Natural Environment Research Council

National Oceanography Centre

PML Plymouth Marine Laboratory

SAMS Scottish Association for Marine Science

Marine Biological Association

Sea Mammal Research Unit

projects.noc.ac.uk/class