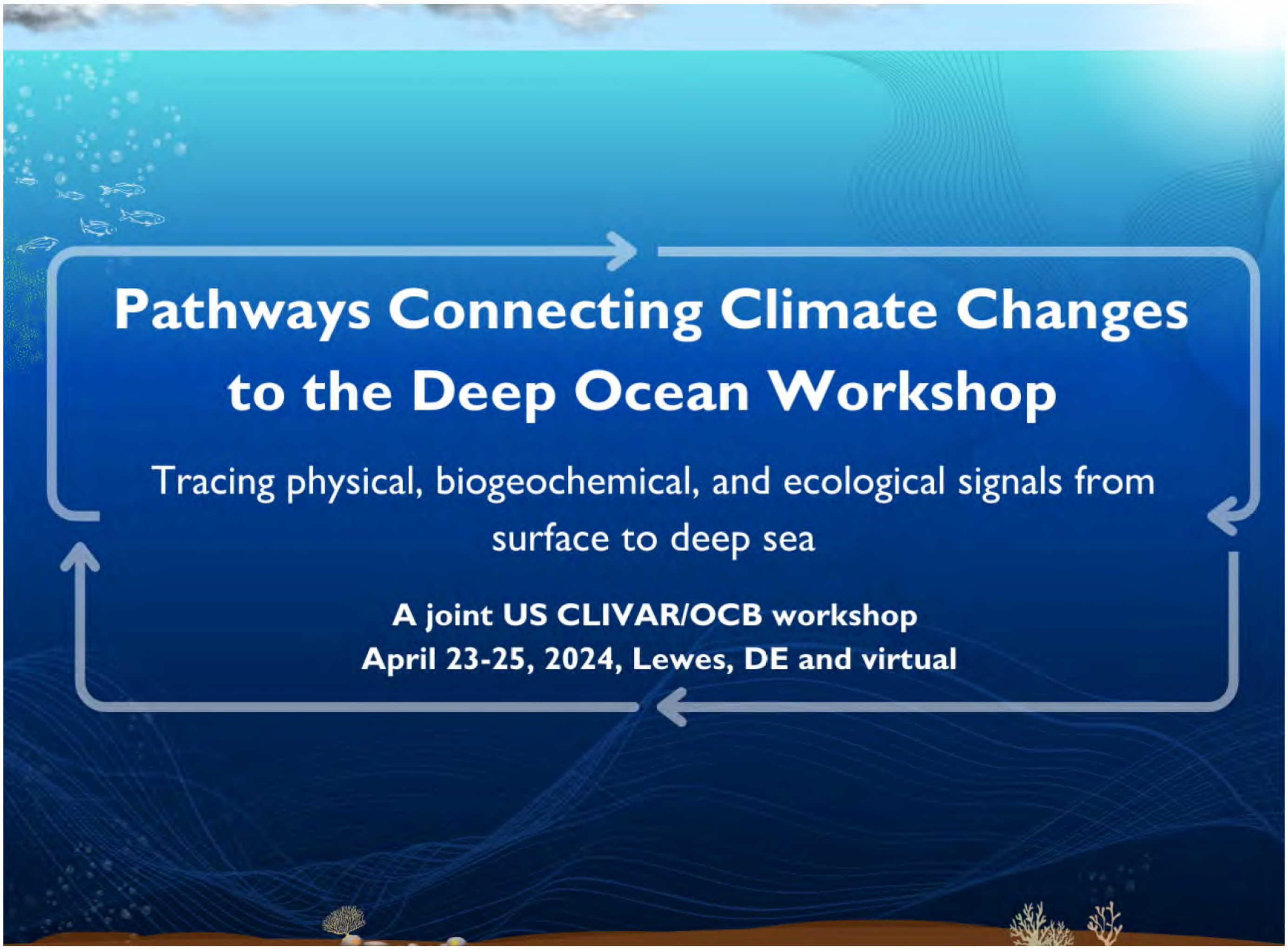

Workshop Report

OCB Ocean Carbon & Biogeochemistry · US CLIVAR · NASA · NOAA · NSF · DOOS

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Executive Summary

Background and Objectives

The deep ocean is a critical yet under-observed component of the Earth's climate system, acting as a long-term reservoir for heat, carbon, and nutrients. Over recent decades, observations have revealed significant changes in the deep ocean, including warming, freshening, deoxygenation, and acidification. However, regional patterns of change vary substantially, and the mechanisms connecting these changes to surface climate forcing remain poorly understood. To address these gaps, the joint US CLIVAR – OCB – DOOS workshop, titled "Pathways Connecting Climate Changes to the Deep Ocean: Tracing Physical, Biogeochemical, and Ecological Signals from Surface to Deep Sea," was held in April 2024. The workshop brought together observationalists and modelers from physical, biogeochemical, and ecological disciplines to improve our understanding of the pathways connecting surface climate changes to the deep ocean, as well as linkages across disciplines. The primary objectives were to assess the state of the deep ocean, identify knowledge and observational gaps, and develop recommendations for improved detection and attribution of changes in the deep ocean system.

Workshop Description

The workshop, held in Lewes, Delaware and online, brought together 47 in-person and 33 online participants. It featured 12 invited speakers who provided interdisciplinary perspectives on physical, biogeochemical, and ecological pathways, a poster session with 33 submissions, and seven virtual poster presentations.

The sessions were organized into four main themes: an overview of pathways for each discipline (physics, biogeochemistry, ecology), "fast" pathways (operating on short timescales up to a year), "slow" pathways (operating on long timescales i.e. interannual to millennial), and methods for observing and modeling these pathways.

There were three breakout sessions, each focused on a different objective. First, participants assessed the current state of the deep ocean, focusing on physical, biogeochemical, and ecological changes, as well as the pathways connecting the surface and deep oceans. Second, they reviewed existing observational and modeling tools, evaluating their adequacy for understanding deep ocean changes and identifying critical gaps in knowledge, data, and model capabilities. Third, participants developed recommendations for enhancing observational networks, improving models, and fostering interdisciplinary collaboration to better detect and attribute changes in the deep ocean.

The primary findings of the workshop are summarized here:

What we know about the pathways

Our understanding of the pathways connecting the surface to the deep ocean is built on decades of interdisciplinary research. The global overturning circulation, which includes the formation of dense water masses such as Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW), redistributes heat, carbon, and nutrients around the globe on timescales of centuries to millennia. The biological carbon pump (BCP) transfers carbon from the surface to the deep ocean through three main pathways: the gravitational pump (sinking particles), the migrant pump (zooplankton diel vertical migration), and the mixing pump (subduction and eddies). While the gravitational pump dominates carbon export, the roles of the other pathways are less understood. Observational programs, such as Argo, BGC-Argo, Deep Argo, and GO-SHIP, as well as localized time series, have been instrumental in providing critical data on physical and biogeochemical variables, thereby filling gaps in our understanding of the deep ocean. Satellite observations also play a crucial role in monitoring surface processes associated with carbon export.

What we don't know about the pathways

Despite significant progress, several key gaps hinder our ability to fully characterize and predict how the deep ocean responds to climate change. The efficiency of carbon transfer from the surface to the deep ocean, particularly through the mesopelagic zone (200-1000m), is poorly understood. Biological processes, such as zooplankton migration and bacterial remineralization, play a significant but unquantified role in modulating this transfer efficiency. Additionally, the characteristics and causes of intermittent pulses of particulate organic carbon (POC) reaching the deep ocean remain unclear. The processes controlling the formation and variability of AABW, NADW, as well as other intermediate water masses, particularly in a warming climate, are also not well-constrained, limiting our ability to predict changes in the global overturning circulation. Furthermore, the magnitude and distribution of turbulent mixing, which drives the overturning circulation and influences biogeochemical pathways, remain highly uncertain. Finally, current models struggle to accurately represent key physical and ecological processes, zooplankton behavior, and deep-sea ecosystem dynamics, leading to uncertainties in characterizing, understanding, and predicting how the deep ocean responds to climate change in terms of physics, biogeochemistry, and ecology.

Recommendations

To address these gaps, the workshop participants proposed several actionable recommendations.

First, emphasizing the need to expand and enhance observational networks. This includes fully funding and expanding One Argo (Argo, BGC-Argo, and Deep Argo) as well as re-occupying key GO-SHIP sections to provide global, continuous measurements of physical and biogeochemical variables. Increasing deep ocean observations using platforms like moorings and gliders will help monitor processes like AABW and NADW formation, as well as turbulent mixing. Sustaining long-term time series programs is also crucial for quantifying variability and detecting trends in the deep ocean, particularly in critically undersampled regions such as the Arctic and the Southern Ocean. Expanding the synchronous collection of interdisciplinary datasets is also key; significant progress can be made by identifying low-cost, high-impact add-ons to existing infrastructure.

Second, improving modeling capabilities is critical. Increasing model resolution will help capture small-scale processes, such as eddies and turbulent mixing, which are essential for accurately representing surface-to-deep ocean pathways. Developing better parameterizations of ecological processes, such as zooplankton behavior and particle remineralization, will improve predictions of carbon export and sequestration. Fostering interdisciplinary modeling efforts to integrate physical, biogeochemical, and ecological processes is also necessary.

Third, organizing targeted process studies will close key gaps. For example, in key regions like the Southern Ocean, studies will help improve our understanding of AABW formation, turbulent mixing, and the biological carbon pump. Studying high-latitude water mass transformation will enhance our understanding of the global overturning circulation. The overturning in the Subpolar North Atlantic Program (OSNAP) is beginning to unravel water mass transformation variability but still too short to infer decadal variability, let alone secular trends. Expanding successful surface-focused initiatives, like EXPORTS (EXport Processes in the Ocean from RemoTe Sensing), into the deep sea will provide valuable insights into carbon export processes and deep POC pulses.

Fourth, fostering collaboration and open data sharing across disciplines is essential. Establishing interdisciplinary working groups will facilitate the exchange of knowledge and data, ensuring that oceanographic data adhere to FAIR (Findable, Accessible, Interoperable, Reusable) principles. The work required to implement these principles at all levels (from metadata via reproducible workflow codes to federated repositories) needs to be recognized.

Finally, connecting with policymakers and emphasizing the need for long-term observations of the deep ocean is crucial. Highlighting the societal relevance of deep ocean research, particularly in the context of climate regulation, carbon sequestration, and deep ocean ecosystem health, can help garner support from policymakers and the public.

Introduction

Background

The deep ocean is a significant but under-observed part of the Earth system. This vast volume of water can store heat and carbon dioxide for hundreds to thousands of years and hosts unique and fragile ecosystems. Limited observations of the deep ocean have revealed changes in recent decades, including warming, freshening, deoxygenation, and acidification. Constraining these physical and biogeochemical long-term changes is a challenge. However, it is even more difficult to assess the associated changes in deep ocean life, as co-located ecological and biological observations are virtually non-existent.

Another unconstrained aspect is how changes in the deep ocean are connected to forcing at the ocean surface. Overturning circulation connects the surface and deep oceans over very long timescales. Mesoscale eddies, strong convection, particle sinking, mixing-induced water mass transformation, and other processes within the biological carbon pump are mechanisms that link the surface and deep oceans on much shorter timescales. The relative importance of these and other potential processes in propagating surface climate change signals to the deep ocean remains unknown.

The tight coupling between ocean circulation, biogeochemistry, and life in the deep sea necessitates an extensive exchange of data and knowledge across ocean science disciplines (Fig. 1). With deep-ocean biodiversity losses observed or anticipated in many areas, there is an urgent need for bolstering these exchanges and co-designing both observational campaigns and modeling experiments to understand, monitor, and predict deep-ocean evolution under climate change and other anthropogenic stressors.

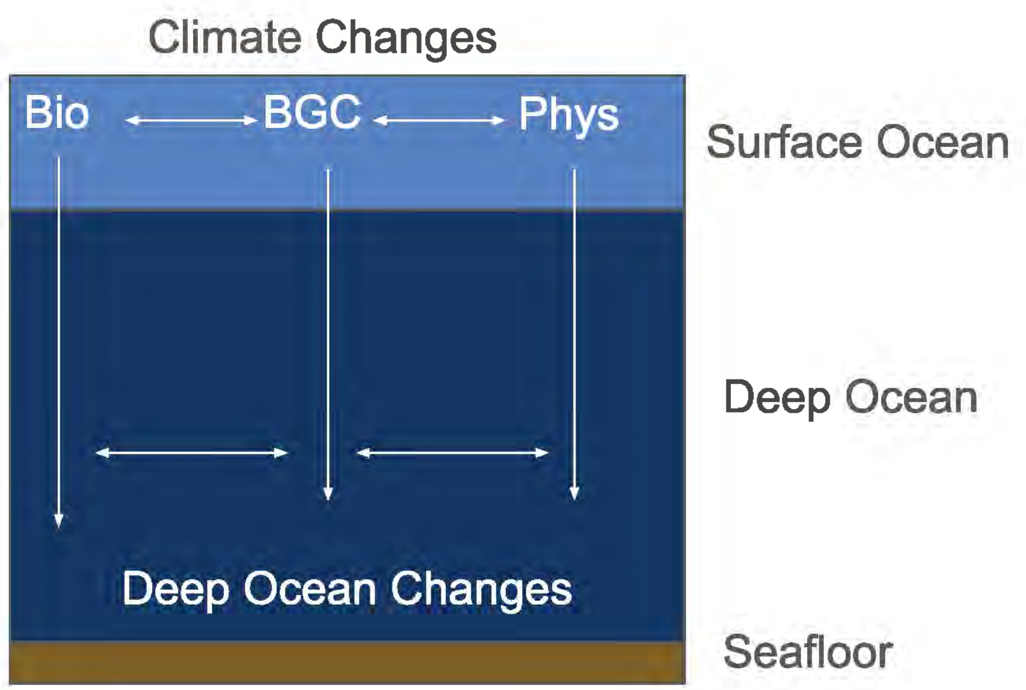


Fig. 1: Schematic highly simplified representation of the primary pathways by which surface climate changes are transferred into the deep ocean. This schematic was proposed as a "strawman" to provide a basis for discussion during breakout sessions.

The surface-to-deep ocean connection was a topic of interest at the 2021 US CLIVAR Phenomena, Observations, and Synthesis (POS) Panel summer meeting, which featured speakers across physical, biogeochemical, and ecological disciplines. A key action item identified in this meeting was to engage the Deep Ocean Observing Strategy (DOOS) and Ocean Carbon & Biogeochemistry (OCB) networks to develop an interdisciplinary dialogue and workshop on surface-to-seafloor pathways connecting climate variability and changes to the physics, biogeochemistry, and ecology of the deep ocean.

Workshop description

The joint US CLIVAR/OCB/DOOS workshop "*Pathways Connecting Climate Changes to the Deep Ocean: Tracing Physical, Biogeochemical, and Ecological Signals From Surface to Deep Sea*" was organized to bring together observational oceanographers and modelers across physical, biogeochemical, and ecological communities involved in climate research and ocean exploration to develop a collective set of requirements for improved characterization of baseline state and variability, as a prerequisite to enable detection and attribution of change in the deep ocean system.

- More specifically, the objectives of the workshop were to:
- Provide an updated comprehensive assessment of the deep ocean's state and changes across disciplines, key quantities in which these changes are expressed, and pathways and timescales connecting the surface to the seafloor
- Review existing observation and modeling tools and their adequacy for constraining, understanding, and attributing changes in the deep ocean system. Identify critical knowledge and observational data gaps and model deficiencies
- Develop a collective set of recommendations for improved detection and attribution of changes in the global deep ocean system, with a focus on better serving and supporting deep ocean science across disciplines
- Build an interdisciplinary network of ocean modelers and observers across disciplines, opening communication channels and facilitating collaborative exchange of data, knowledge, and tools across communities

The workshop took place April 23-25, 2024, in Lewes, Delaware, and virtually, bringing together 47 in-person participants and 33 online participants. Twelve invited speakers provided an overview of physical, biogeochemical, and biological pathways from an observational and modeling perspective (Session 1), fast pathways (Session 2), slow pathways (Session 3), and observing and modeling methods (Session 4). All participants were invited to present posters during two in-person and one virtual poster sessions. The workshop also included three breakout sessions focused on objectives 1 to 4.

Section 1: Overview

This session provided a broad overview of pathways, including the current state of knowledge and the associated gaps. It was organized by discipline (physics, biogeochemistry, ecology), with both observation and modeling perspectives represented for each discipline.

1.1 Physical pathways

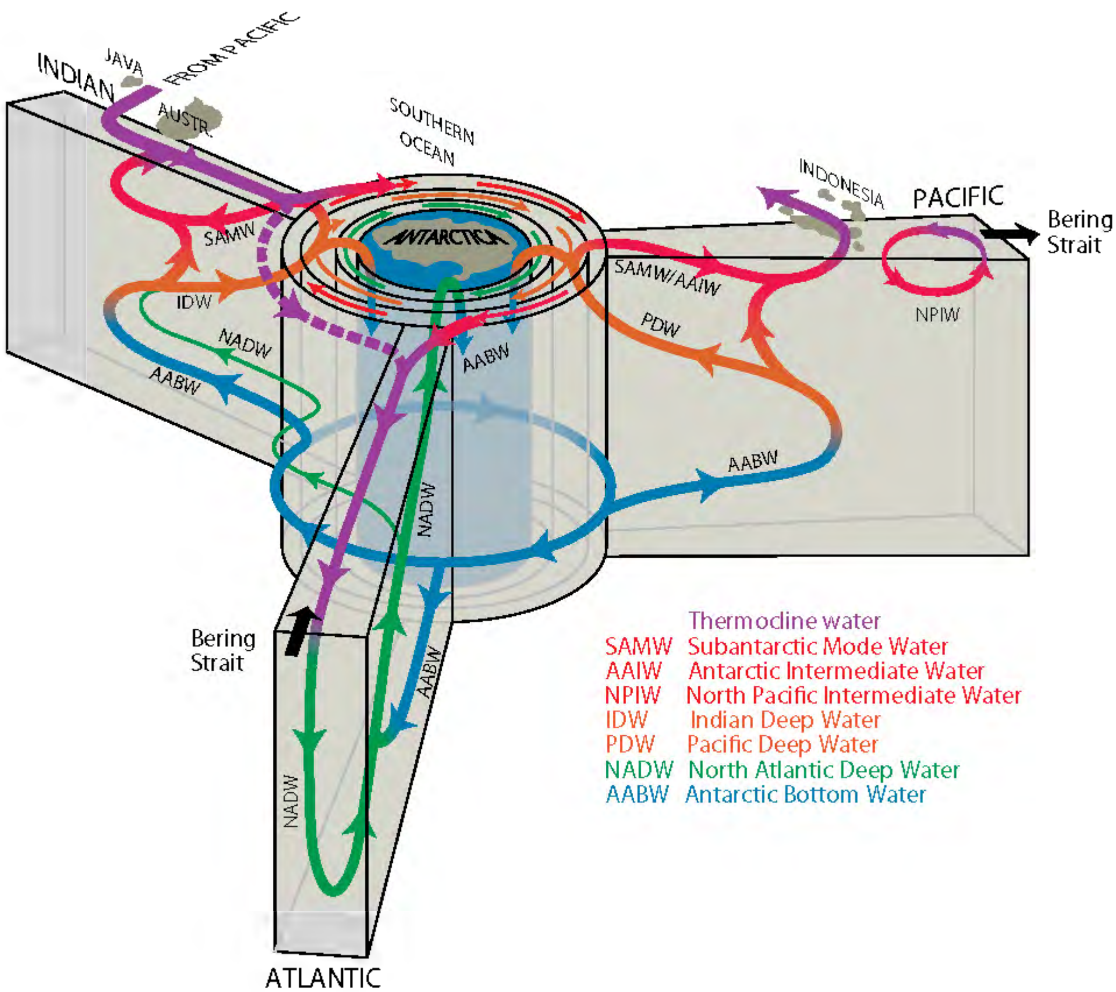


Fig. 2: Schematic of the global overturning circulation (Talley, 2013).

The overview of the physical pathways focused on the global overturning circulation (Fig. 2), a critical component of Earth's climate system and one of the key sets of mechanisms connecting the ocean surface to deep and abyssal oceans. Two water masses, the Antarctic Bottom Water (AABW) and the North Atlantic Deep Water (NADW), are major components of the overturning, filling the majority of the global deep and abyssal ocean. The formation rates and characteristics of AABW and NADW are intricately linked to surface buoyancy forces, which determine the density of surface waters, leading to their sinking and subsequent spreading into the deep ocean. Upwelling and ocean mixing also play an important role in bringing deep waters to the surface, closing the overturning. Large-scale atmospheric circulation adds to the picture by modulating the horizontal gyre circulation and its subtropical-subpolar-polar linkages.

Modeling serves as an essential tool for understanding (and predicting) the global overturning circulation and its roles in redistributing heat, carbon, nutrients, and other properties. Although progress has been made over the past decades, critical challenges remain. First, accurately modeling the global overturning circulation system requires detailed knowledge of bathymetry at multiple length scales. However, standardized methodologies for incorporating bathymetric data into ocean models are lacking, leading to inconsistencies among research groups and modeling frameworks. Second, accurate air-sea fluxes in both ice-free and ice-covered regions, skillful representation of ice-ocean interaction, and parameterization of ocean mixing, which all influence water mass transformation, are vital for model fidelity. Additionally, achieving quasi-equilibrium of the deep ocean in simulations, especially at eddy-resolving or permitting resolutions, is impractical due to the long timescales required. Consequently, many simulations must accept that the deep and abyssal oceans are unrealistically far from equilibrium. Addressing these challenges necessitates ongoing model development and improvement, extending beyond ocean models to encompass the entire Earth system.

Looking ahead, monitoring the deep ocean will become increasingly vital for understanding and predicting climate change. Continuous observations of deep ocean temperature, salinity, biogeochemical tracers, and circulation patterns will provide critical data for constraining and validating climate models, thereby enhancing projections and informing policy decisions aimed at mitigating the impacts of climate change. Due to the relative paucity of deep ocean data, expanding Deep Argo globally and adding biogeochemical sensors is one major recommendation to enhance observational capabilities and improve model constraints. Furthermore, leveraging data assimilation and machine learning techniques could improve model initialization (e.g., by accelerating spin-up, reducing drift, and ameliorating systematic biases) and improve parameterization of missing processes (e.g., by constraining uncertain parameters and supporting the discovery and validation of new schemes). Enhanced collaboration and communication between modelers and observationalists (including across disciplines) will be crucial for overcoming these challenges and seizing the opportunities they present.

1.2 Biogeochemical pathways

Biogeochemical (BGC) variables refer here to oxygen, pH, nutrients, and carbon. Observations show that oxygen has declined in the deep ocean because of climate-driven changes in solubility and ventilation (Oschlies et al., 2018). Ocean pH has also been declining, most strongly at depth (Fassbender et al., 2023), consistent with model results (Kwiatkowski et al., 2020). The primary large-scale constraint on deep ocean oxygen and pH is from BGC-Argo floats in the upper 2000m, and Deep Argo floats below 2000m (some Deep Argo floats carry oxygen sensors). BGC Argo floats have also been used to assess phytoplankton bloom timing and carbon stock (Stoer and Fennel, 2024), net community production (Su et al., 2022), carbon export (Xing et al., 2023), biogenic carbon pools (Huang et al., 2023), and phytoplankton taxonomy (Rembauville et al., 2017). These variables are all related to the biological carbon pump (BCP), by which particulate organic carbon (POC) produced within the sunlit ocean mixed layer gets transported downward, thus linking the surface and deep ocean. The BCP consists of three main pathways: (1) the mixing pump driven by large-scale subduction, eddy pumping, and changes in seasonal mixed layer depth, (2) the migrant pump driven by animal vertical migrations, and (3) the gravitational pump, driven by the sinking of detrital matter. At the global scale, a data-assimilated biological pump model was used to estimate carbon downward flux and sequestration by each pathway. The resulting budget indicates that the BCP exports ~10 GtC/yr and sequesters ~1753 GtC globally, most of it via the gravitational pump (Nowicki et al., 2022, 2024). Finally, BGC Argo-derived products are also used to validate Earth system models and constrain the ocean carbon budget (Friedlingstein et al., 2023). Within the global observing system, BGC and Deep Argo fill an important observational gap on timescales from months to multi-years, spatial scales from sub-regional to global, and vertically below the surface that cannot be monitored by other methods (Fig. 3). Thus, sustaining and expanding BGC observations in BGC and Deep Argo is crucial.

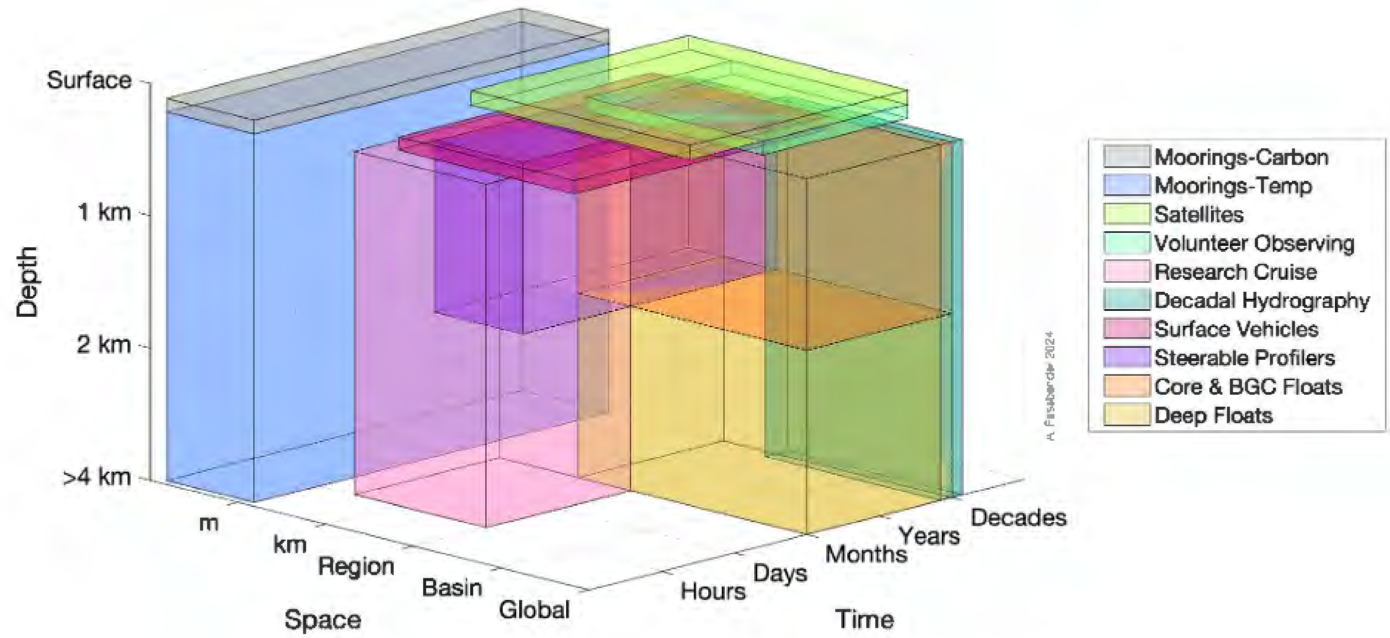


Fig. 3: Spatiotemporal coverages of the major existing ocean observing platforms, highlighting the observing gap filled by core, BGC, and Deep Argo floats. Image courtesy of Andrea Fassbender (NOAA PMEL).

1.3 Ecological pathways

From a biogeochemical and ecological standpoint, the deep sea is tightly linked to the surface via carbon export from surface waters. However, our understanding of these connections remains largely unconstrained. As an example, large POC pulses have been observed in a 3600 m deep time series, increasing in frequency and magnitude over time (Smith et al., 2018). POC flux modeled from satellite data and the Martin curve correctly represents the baseline POC flux, but the pulses remain unexplained. Processes that generate deep POC pulses include both physical processes (e.g., convergence/divergence) and biological processes (organisms that live in the mesopelagic, and bacterial communities that live on particles). These biological processes impact remineralization and transfer efficiency, which determine how much carbon is ultimately transferred to the deep ocean. From a modeling standpoint, we know more about export from the euphotic zone than transfer efficiency, although satellite-based models do not constrain export well (Clements et al., 2023). Fewer observations from deep ocean (>2000m) and benthic ecosystems make it challenging to represent key ecological processes and pathways in models. Bacterial communities (which change with depth), zooplankton diel vertical migration, particle size distribution and composition (both impacting sinking speeds), and surface phytoplankton community composition all impact transfer efficiency. Fish and other animals also play a significant role in carbon export and sequestration (Pinti et al., 2023), as they perform diel vertical migration and directly transfer carbon to depth when they die and sink. They are expected to be particularly impacted by climate change due to trophic amplification (Lotze et al., 2019; Tittensor et al., 2021); however, their role remains poorly understood. Finally, future changes in ecological processes connecting the surface and deep ocean are very poorly constrained observationally, and most processes are poorly represented in climate models (Henson et al., 2022; Fig. 4). Even today's dynamics are poorly constrained; for instance global modeled export estimates range from 4 to 12 GtC/yr in 2000 (Burd, 2024). New technologies are becoming available, providing novel information that should help constrain these ecological processes. They include the recently launched NASA Plankton, Aerosols, Clouds, ocean Ecosystem (PACE) mission, which provides hyperspectral ocean color measurements that can resolve phytoplankton functional groups and new imaging systems that can be used to observe biological communities and sinking particles.

Process	Included in CMIP6 model	Export bias without process	Future effect on export
Fragmentation (& aggregation?)	✗ 18 ✓ 1	+	?
Zooplankton vertical migration	✗ 19 ✓ 0	−	?
Temperature-dependent remineralization	✗ 8 ✓ 11	?	↓
Oxygen-dependent remineralization	✗ 9 ✓ 10	+ ?	↑ ?
Fish vertical migration	✗ 19 ✓ 0	−	?

Fig. 4: Summary of modeled export processes and their effects. Modified from Henson et al. (2022).

Section 2: Fast Pathways

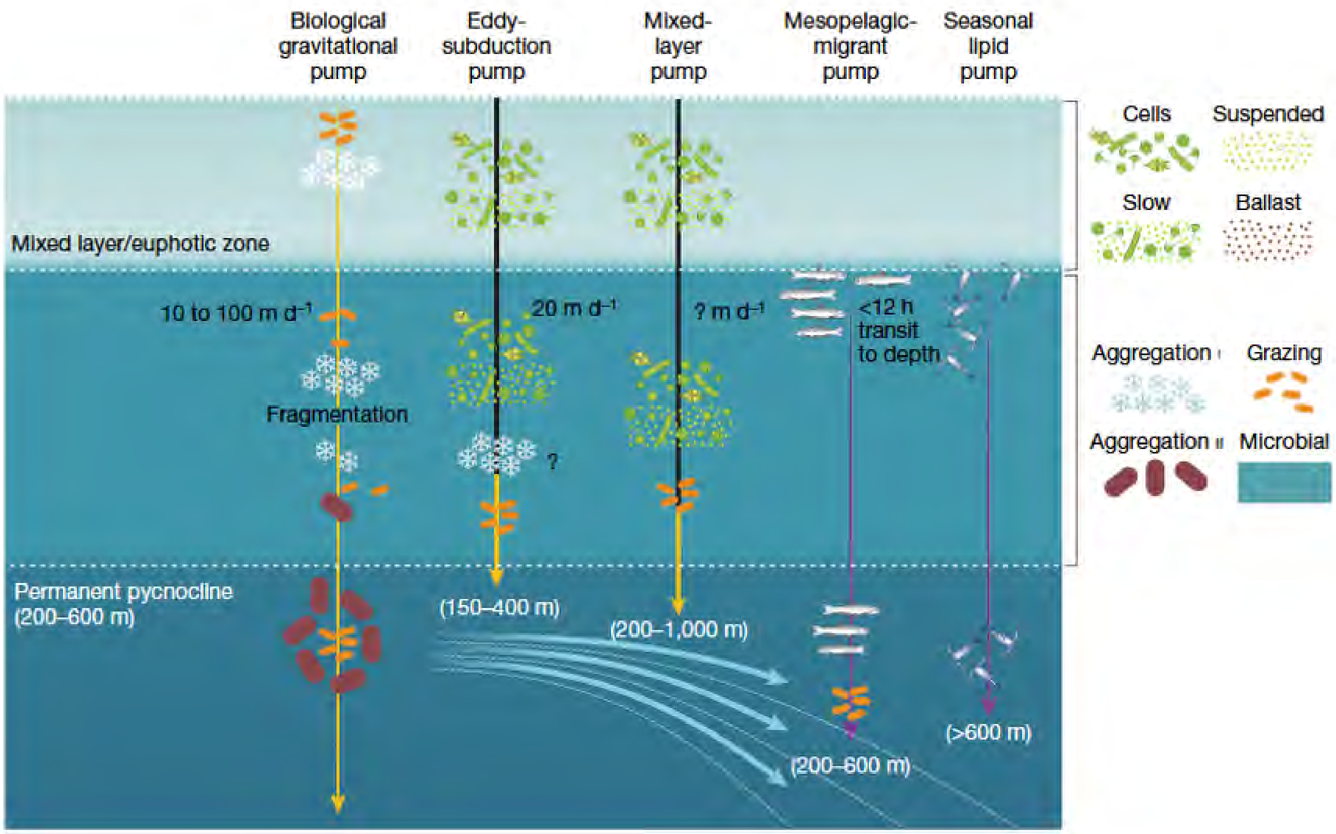


Fig 5: Particle characteristics, mode and speed of export, and delivery depth for multiple pumps comprising the biological carbon pump. Figure reproduced from Boyd et al. (2019).

Multiple mechanisms comprising the total biological pump create fast pathways connecting the surface to the deep ocean on sub-diurnal to seasonal timescales (Fig. 5). These include the gravitational pump, the eddy-subduction and mixed layer pumps, and the mesopelagic migrant and seasonal lipid pumps (Boyd et al., 2019; Baker et al., 2025). The gravitational pump–associated with particle production and sinking–dominates, with an amplitude estimated to be equal to that of the remaining pumps combined, although there are few concurrent observations. The gravitational pump within the California Current ecosystem, which explains 60% of carbon export from the euphotic zone, is an exception (Stukel et al., 2023).

Recent studies have elucidated the key species driving the gravitational pump, either directly (e.g., as dead animal or plant matter) or by generating large, fast-sinking fecal matter. Salps and krill have emerged as important contributors to the latter, suggesting particular attention should be paid to determining their response to climate change. Sediment traps provide valuable insight into dominant carbon exporters, although these results may be biased by methodological difficulties, including differing lability of various biological organisms. Flux attenuation by zooplankton and bacteria is an important target for improved constraint of the gravitational pump, but is characterized by significant complexity and strong spatial heterogeneity.

To determine the relative importance of the remaining pumps, it is also essential to consider differences in delivery depth and flux attenuation. Notably, the export flux associated with the eddy subduction pump exceeds that of the migrant pump, but is limited to the upper ~150-400m (Boyd et al., 2019), so it does not lead to long-term sequestration. The migrant pump–driven by the zooplankton diel migration and constrained by observations from acoustics and tow nets–explains ~30% of the total sinking flux and supplies ~20% of the required energy to deep ecosystems. This pump is important for contributing to carbon export, for supporting microbial diversity, and influencing oxygen minimum zones (OMZ). Specifically, migrators stop at the boundary of OMZs to avoid anoxic regions, leading to increased respiration in these boundary regions and OMZ expansion. Future predictions suggest that reduced nutrient supply with increasing stratification should weaken the migrant pump, although observations indicate increasing zooplankton biomass. Poorly constrained mortality rates at depth may be a key source of uncertainty.

The importance of eddy subduction and mixed layer pumps is revealed by the observed influence of eddy kinetic energy on oxygen variance and intermittent increases in subsurface chlorophyll and decreases in apparent oxygen utilization (AOU), producing vertical inversions in these properties. These inversions have been attributed to discrete subduction events and are a key indicator that eddies are important for export. Model-based evidence includes the strong dependence of OMZ size on model resolution. Whilst it is expected that net community production (NCP) and export production should balance at large scales, this balance is not seen in available observations, particularly in the subtropics. Properly accounting for subduction influenced by mixed layer mesoscale (geostrophic) and submesoscale (ageostrophic) frontogenetic processes may be important for closing the budget. With increasing stratification anticipated with ongoing climate change, eddy processes may provide an increasingly important mechanism for sustaining the transport of biogeochemical properties (and community structure) from the surface to the interior. On interannual to multi-decadal time scales, mode- and intermediate water formation plays a dominant role in the uptake and sequestration of excess heat from Earth's energy imbalance (Li et al., 2023).

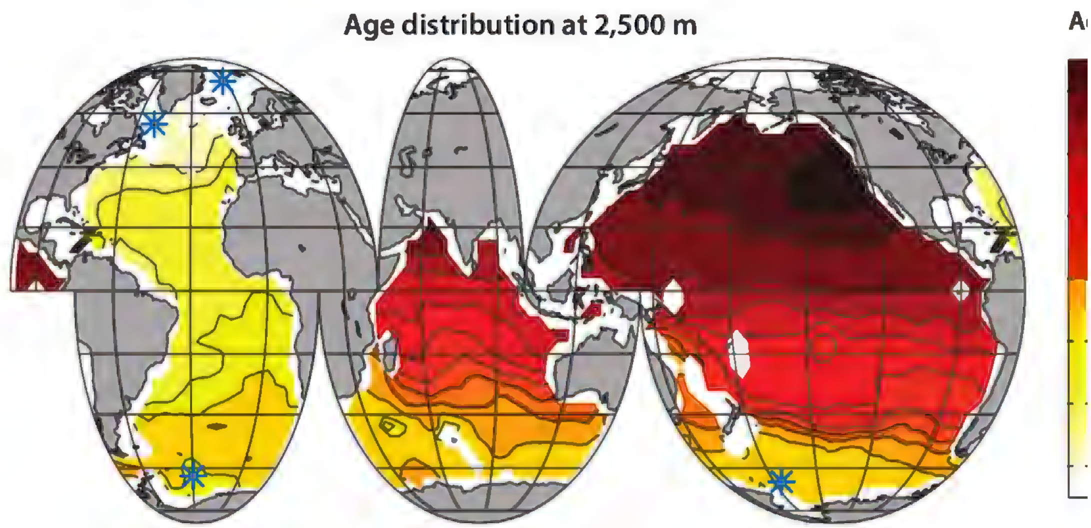
Section 3: Slow Pathways

The global overturning circulation is the primary "slow pathway" from the surface to the deep ocean. This large-scale circulation pattern moves waters from the surface to the deep in the high-latitude North Atlantic and Southern Ocean and then moves them into the deep ocean interior along multiple pathways. The time scales associated with this global circulation pattern are on the order of hundreds to thousands of years (Fig. 6; Gebbie and Huybers, 2012; Ferreira et al., 2018). Ocean tracers, which can be anything from water properties such as temperature, salinity, oxygen, and nutrients to anthropogenic tracers such as radiocarbon and chlorofluorocarbons (CFCs), have long been used as tools to constrain large-scale circulation patterns (e.g., Talley 2013). More recently, tracers have been used to determine whether the circulation has changed on long-time scales, which would be very difficult to measure directly (Gebbie and Huybers 2019; Cimoli et al. 2023). This is still a nascent field and is a critical piece for understanding how these slow surface-to-deep ocean pathways are evolving under climate change.

The global overturning circulation is thought to be driven by small-scale turbulent mixing. On this, Wunsch & Munk (1998) stated that "without deep mixing, the ocean would turn, within a few thousand years, into a stagnant pool of cold salty water…" Our understanding of how mixing drives the overturning circulation has evolved considerably in recent years. We now understand that the net upwelling that turbulent mixing provides is a balance between much larger downwelling towards topographic features and upwelling up rough topographic slopes (Ferrari et al. 2016; de Lavergne et al. 2016; Drake et al. 2022). Another important recent finding is that the magnitude of mixing, which remains highly uncertain, can significantly impact air-sea CO_2 fluxes in the Southern Ocean, a key factor in determining the efficacy of linked biogeochemical and physical surface-to-deep ocean pathways (Ellison et al. 2022).

Given the importance of ocean mixing, efforts are underway to better measure and otherwise constrain it across space and time. This presents a particular challenge due to the patchy and episodic nature of mixing events. Ongoing efforts to better constrain mixing include the development of low-cost mixing platforms, with the eventual goal of measuring mixing on Argo floats (ArgoMix, de Boyer et al. 2023). Other research avenues are to constrain mixing as a residual from observationally-constrained global ocean models, or to infer it from inverse state and parameter estimation methods (Forget et al. 2015, Trossman et al. 2022). Ideally, observations and models will be used in concert to further our understanding of turbulent mixing and how it shapes the global overturning circulation. Beyond this, future research on slow surface-to-deep ocean pathways should also consider the coupling with biogeochemistry and ecology beyond the usual "conveyor belt" schematic, which tends to see these as being carried passively in the overturning circulation, ignoring the important role of the horizontal circulation (MacGilchrist et al., 2019).

Figure 6: Ocean age, or mean time when the water was last at the surface as determined from radiocarbon data by Gebbie and Huybers 2012. Figure adapted and presented in Ferreira et al. 2018.



Section 4: Methods

Numerical models provide a crucial tool for assessing and quantifying different pathways between the surface and the deep ocean. The fundamental question is to understand the timescales and advective pathways impacting distinct water masses in different locations within the ocean. These pathways are strongly asymmetric; different mechanisms connecting the same two points in the ocean can vary in their timescales by several orders of magnitude. Broadly speaking, there are three types of numerical model analysis methods.

- Eulerian tracer methods primarily use chemically inert, passive tracers, such as CFCs (e.g., England, 1995a), or idealized, modeled tracers, such as idealized seawater age (e.g., England, 1995b), to track temporal changes in these properties throughout the ocean. Idealized tracers, such as ideal seawater age, which increases each time step and is reset to 0 when the water mass is within the mixed layer, are often the most convenient but are not directly observable. To compare with *in situ* measurements, tracers such as CFCs or similarly inert species, like radiocarbon, can be useful.

- In contrast to Eulerian methods, which consider changes in the amount of a certain tracer in a given location, Lagrangian tracer methods advect particles within a velocity field to trace advective pathways through the ocean (van Sebille et al., 2018). This method provides a direct understanding of ocean pathways. When applied to large numbers of particles, the probability distribution of the particles at future modeled timesteps can provide similar information to tracer distributions calculated through Eulerian methods. A major advantage of Lagrangian methods is that they can be calculated "offline" through saved velocity fields. However, they typically struggle to represent sub-gridscale diffusion or turbulence effects.

- A third method combines elements of both Eulerian and Lagrangian methodologies. The water mass transformation method defines a volume of water and considers the evolution of that water mass via different processes, including air-sea buoyancy fluxes, interior mixing, and advection into or out of a given domain (Groeskamp et al., 2019; Drake et al., 2025). While this method can be most directly tied to individual processes governing water mass formation and circulation, it is computationally expensive.

Cohesive global observing strategies are crucial to understanding large-scale pathways connecting the surface and deep oceans. An optimal deep ocean observing system would satisfy several requirements: global coverage below 2000 m, international in scope, free and easy data access in both near-real-time and with delayed mode quality control, contain effective and diverse partnerships between academia, government, and industry, and operate on long time horizons. Ship-based repeat hydrography programs, such as GO-SHIP, and float-based autonomous observations, such as Deep Argo, fulfill several aspects of such an optimal observing system, but cannot satisfy many of the ecosystem and biology essential ocean variables. One way *in situ* measurements are useful is to compare with modeled results to determine the verisimilitude of the numerical models. Passive tracers such as CFCs are especially useful for this; indeed, comparisons between modeled and observed CFCs have revealed significant discrepancies in large-scale ventilation pathways that help to evaluate model performance (Dutay et al., 2002). However, the utility of CFC observations to constrain deep ocean circulation timescales is limited due to the lack of CFC emissions before ~1950, meaning measurements of other tracers, such as radiocarbon or other elemental isotopes (Holzer and Primeau, 2010; Hamme et al., 2019), are necessary to understand longer-term circulation pathways. Observations of sufficient spatial and temporal coverage can also be used to, for example, close global ocean budgets for sea level rise and ocean heat content (Johnson and Purkey, 2024; Johnson et al., 2024).

Summary and Recommendations

Current understanding of the pathways

Our current understanding of the pathways connecting the surface to the deep ocean is built on decades of interdisciplinary research, combining observations, modeling, and theoretical frameworks. We know that the deep ocean is a critical component of the Earth's climate system, acting as a long-term reservoir for heat, carbon, and nutrients. We also know the primary mechanisms that connect the surface to the deep ocean, including the global overturning circulation, mesoscale eddies, convection processes, and the biological carbon pump (BCP). However, pathways operate on different timescales, from days to millennia, and involve complex interactions between physical, biogeochemical, and ecological processes that we have yet to fully understand and constrain.

The multiple elements that constitute the global overturning circulation have been studied with a widely varying degree of detail. A major component of the global overturning circulation is the formation of dense water masses such as Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW). These water masses sink in high-latitude regions and spread throughout the deep ocean, redistributing heat, carbon, and nutrients. Modeling efforts have been crucial in understanding this circulation, but challenges remain in accurately representing small-scale processes like turbulent mixing, surface buoyancy fluxes, and ice-ocean interactions, which are critical for the formation and transformation of water masses. Observations from programs like Deep Argo and GO-SHIP repeat hydrographic sections provide valuable data on temperature, salinity, nutrients, and circulation patterns, helping to validate models and improve our understanding of these slow pathways.

On shorter timescales, the biological carbon pump (BCP) plays a key role in transferring carbon from the surface to the deep ocean. The BCP consists of three main pathways: the gravitational pump (driven by sinking particles), the migrant pump (driven by zooplankton diel vertical migration), and the mixing pump (driven by subduction and eddy processes). Observations from satellites, ships, BGC-Argo floats, and sediment traps combined with modeling have shown that the gravitational pump dominates carbon export, but the relative contributions of the other pathways remain uncertain. Recent studies have highlighted the importance of species like salps and krill in generating fast-sinking fecal matter, which significantly contributes to carbon sequestration. However, the efficiency of carbon transfer and the role of biological processes in the mesopelagic zone (200-1000m) are still poorly constrained.

Ships, moorings, and autonomous floats form the crucial pieces of our deep ocean observing systems. However, they currently lack the ability to observe ecosystem and biological essential ocean variables. Long-term time series provide a long-term depiction of processes and variability in the deep-sea but remain scarce at the global scale. A new technology, Deep Argo, shows promise to fill in critical observational gaps of some ocean variables in the deep ocean. Satellite observations also play a key role in monitoring surface processes like phytoplankton blooms, which are linked to carbon export. On the modeling side, Earth System Models (ESMs) are essential for integrating physical, biogeochemical, and ecological processes, but they still struggle to accurately represent key processes like turbulent mixing, transfer efficiency, and the ecological dynamics of deep-sea ecosystems. Other modeling tools, such as inverse models, state and parameter estimation frameworks, or emulators, are showing promise in representing key processes and observed changes.

Knowledge, observation, and modeling gaps

Despite significant progress in understanding the pathways connecting the surface to the deep ocean, several key knowledge, observation, and modeling gaps remain. These deficiencies hinder our ability to fully characterize and predict how the deep ocean responds to climate change and other anthropogenic stressors.

In terms of knowledge gaps, while the gravitational pump driven by sinking particles is recognized as a major pathway, the precise role of biological processes—such as zooplankton diel vertical migration (DVM) and bacterial remineralization—in modulating transfer efficiency is poorly understood. Furthermore, the factors controlling the attenuation of carbon flux as it sinks through the mesopelagic zone, which spans from 200 to 1000 meters, remain unclear. Another area of uncertainty concerns the intermittent pulses of particulate organic carbon (POC) observed reaching the deep ocean. The causes of these pulses are not well understood, whether they are driven by physical processes like eddies and subduction, or by biological processes such as changes in surface phytoplankton communities or zooplankton behavior. This lack of clarity limits our ability to predict how carbon export might change under future climate scenarios. Additionally, our understanding of the processes controlling AABW and NADW formation and their variability, particularly in a warming climate, is incomplete, despite their significant potential impacts on global ocean circulation and climate. Turbulent mixing, a critical process driving overturning circulation and influencing biogeochemical and ecological pathways, also presents a major knowledge gap, as its magnitude and spatial distribution remain highly uncertain. This uncertainty affects our ability to accurately model ocean circulation and its role in redistributing heat, carbon, and nutrients.

Regarding observation gaps, while programs such as Argo have revolutionized our ability to observe upper ocean hydrographic properties, observations of the deep ocean below 2000 meters remain sparse. Deep Argo floats, capable of profiling to 6000 meters, are still in the early stages of deployment, and their coverage is limited. Deep Argo floats, as well as autonomous platforms in general, are also limited in the variables they can measure. This scarcity of deep ocean data hinders our ability to monitor changes in deep ocean temperature, salinity, and circulation, which are critical for understanding long-term climate trends. Similarly, although BGC-Argo floats have expanded our capacity to monitor biogeochemical variables such as oxygen, pH, and nutrients, significant gaps persist in our understanding of ecological processes in the deep ocean. For instance, observations of zooplankton DVM and deep-sea benthic ecosystems are rare, making it difficult to represent these processes accurately in models. Moreover, long-term, continuous observations are essential for quantifying variability and detecting trends in the deep ocean. However, many existing time series are short or intermittent, particularly in remote regions, especially the Southern Ocean and the Arctic Ocean. Sustained funding for long-term observational programs is therefore critical for beginning to close the many observational gaps.

Finally, modeling gaps also present challenges. Current climate models struggle to accurately represent key ecological processes, such as zooplankton behavior, particle remineralization, and the role of deep-sea ecosystems in carbon cycling. These processes are often oversimplified or omitted entirely, leading to uncertainties in predictions of carbon export and sequestration. Many models also lack the resolution needed to capture small-scale processes such as eddies, submesoscale dynamics, and turbulent mixing, all of which are critical for accurately representing surface-to-deep ocean pathways. Additionally, parameterizations of biogeochemical processes, such as the biological carbon pump, often rely on simplified assumptions that may not hold true across different regions or under changing climate conditions. While progress has been made in integrating physical, biogeochemical, and ecological processes in models, there is still a need for more interdisciplinary approaches. For example, the coupling between ocean circulation, biogeochemistry, and deep-sea ecosystems is often treated as a one-way process, whereas in reality, these systems are tightly interconnected.

Recommendations

Addressing the knowledge, observation, and modeling gaps in our understanding of the pathways connecting the surface to the deep ocean requires a multi-faceted approach. Several potential actions can help close these gaps and advance our understanding of this critical system.

A primary action involves expanding and enhancing observational networks. An expansion of the Argo program to a full array of Core, Deep, BGC, and Polar floats will close critical gaps in our understanding of physical, biogeochemical, and ecological processes in the deep ocean. To deploy these expanded observations most efficiently, continued support for global coordination and collaboration efforts, such as the Deep Ocean Observing Strategy (DOOS), across observing networks and programs is essential. Other long-term observational programs, such as repeat hydrographic sections from GO-SHIP, long-term time-series stations, and moored arrays such as OSNAP, are also crucial for detecting trends and variability in the deep ocean. These programs provide critical baseline data and help monitor changes over time. Identifying low-cost, high-impact add-ons to existing research projects, such as new sensors on autonomous platforms or new variables measured on ship-based cruises, offers a pragmatic way to enhance data collection. Furthermore, leveraging modeling tools like observing system simulation experiments will ensure observatories are designed to fill key observational gaps effectively and complement existing elements of the global ocean observing system.

Targeted process studies are essential for addressing specific regional and thematic uncertainties. The Southern Ocean, for instance, plays a critical role in global ocean circulation and carbon sequestration, yet remains under-observed. Focused studies in this region will help improve our understanding of AABW formation, turbulent mixing, and the biological carbon pump. Investigating the formation and transformation of water masses in high-latitude regions, such as the North Atlantic and Southern Ocean, will also contribute to a better understanding of the global overturning circulation and its response to climate change. As such, the OSNAP array is emerging as a key network to quantify variability of North Atlantic overturning, connect overturning with oxygen and carbon uptake, and decipher relevant processes. Opportunities exist to expand this array with BGC sensors. Similarly, field campaign initiatives like EXPORTS (EXport Processes in the Ocean from RemoTe Sensing), APERO (Assessing marine biogenic matter Production, Export and Remineralization: from the surface to the dark Ocean), and COMICS (Controls over Ocean Mesopelagic Interior Carbon Storage) provide valuable insights into carbon export processes. Expanding these studies to different regions and seasons, and coupling them with high-resolution modeling efforts, will enhance our understanding of the factors controlling carbon transfer efficiency and deep POC pulses.

Improving modeling capabilities is another key area. Current models often lack the resolution needed to capture small-scale processes like eddies, submesoscale dynamics, and turbulent mixing, which are critical for accurately representing surface-to-deep ocean pathways. Investing in high-resolution models will therefore enhance our understanding of these processes and their role in the global ocean system. This will require accurate bathymetry in a number of critical regions and consistent ways to utilize high-resolution bathymetry among different models. Also, many climate models oversimplify or omit key ecological processes, such as zooplankton behavior, particle remineralization, and deep-sea ecosystem dynamics. Developing more sophisticated parameterizations and incorporating ecological data into these models will improve predictions of carbon export and sequestration. Greater integration of physical, biogeochemical, and ecological processes within models is also needed. This includes coupling ocean circulation models with biogeochemical and ecological models to better represent the interconnected nature of these systems, a goal for which collaborative efforts between modelers and observationalists will be crucial. Furthermore, since all these models rely heavily on subgrid-scale parameterizations, formal methods for comprehensive initialization, parameter calibration, and uncertainty quantification with better utilization of observations need to be developed. This may, in part, alleviate the need for spinning up the deep ocean state over millennia.

Fostering collaboration and robust data sharing practices is fundamental to scientific progress. Establishing interdisciplinary working groups that bring together physical, biogeochemical, and ecological oceanographers can facilitate the exchange of knowledge and data across disciplines (Smith et al., 2022). These groups can collaboratively develop integrated observational and modeling frameworks to address key knowledge gaps. Ensuring that oceanographic data adhere to FAIR (Findable, Accessible, Interoperable, and Reusable) principles (Wilkinson et al., 2016) is also essential for maximizing the utility of observational data. Funding to support data sharing, quality control, and the development of standardized data products should be explicitly written into grant applications. Publishing reproducible workflows, i.e., codes, and developing federated repositories will make data more seamlessly accessible and repositories more resilient. Efforts to recover and standardize older datasets that do not currently meet FAIR standards should also be prioritized to preserve and integrate historical knowledge.

Finally, connecting with policymakers, emphasizing the need for long-term observations of the deep ocean, and ensuring deep ocean observing is responsive to societal needs is crucial (Levin et al., 2022). Highlighting the societal relevance of deep ocean research, particularly in the context of climate change, carbon sequestration, and ecosystem health, can also garner crucial support from policymakers and the public. Emphasizing the deep ocean's role in regulating global climate and supporting biodiversity will help justify the need for continued investment in ocean research.

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Appendix B: Agenda

Presentations and recordings are available on the workshop website

Tuesday, April 23, 2024		
Time (EDT)	**Agenda**	**Presenter**
7:00 AM	**Workshop registration and breakfast**	
8:10 AM	**Introduction and welcome**	
8:30 AM	**Session 1: Overview**	Chairs: Monique Messié, Leslie Smith, Xinfeng Liang
8:30 AM	**(Invited) Ventilating the Deep: Quantifying pathways of deep ocean ventilation from ocean observations***	Sarah Purkey, UCSD/SIO
8:50 AM	**(Invited) Physical modeling of the deep ocean: Challenges and opportunities**	Gokhan Danabasoglu, NCAR
9:10 AM	**Q&A**	
9:20 AM	**(Invited) Observations and tools for studying ocean biogeochemistry from the surface to the deep**	Andrea Fassbender, NOAA PMEL
9:40 AM	**(Invited) Pathways of organic carbon export and sequestration by the biological pump***	Tim Devries, UCSB
10:00 AM	**Q&A**	
10:10 AM	Break	
10:40 AM	**(Invited) Observing the biological gatekeepers of the deep sea and their responses to a changing climate**	Colleen Durkin, MBARI
11:00 AM	**(Invited) Modeling biological pathways connecting surface and deep ocean ecosystem**	Daniele Bianchi, UCLA
11:20 AM	**Q&A**	
11:30 AM	**Session 1 panel discussion**	
12:00 PM	Lunch	
1:00 PM	**Poster Session 1**	
2:00 PM	**Breakout 1 - Current understanding of vertical pathways**	
3:30 PM	**(Keynote) Bentho-pelagic coupling under climate change and other human disturbance***	Lisa Levin, USCD/SIO
4:00 PM	End of day 1 for virtual participants	
4:00-6:00 PM	**Networking event**	
Wednesday, April 24, 2024		
6:30 AM	Virtual breakout for alternate time zones	
7:00 AM	Breakfast	
8:15 AM	**Recap of breakout 1**	

9:00 AM	**Session 2: Fast Pathways**	Chairs: Helen Pillar and Cristina Schultz
9:00 AM	**(Invited) The many faces of the biological carbon pump**	Mike Stukel, FSU
9:20 AM	**(Invited) Hotspots of connectivity from the surface to mesopelagic: from eddy fluxes to climate**	Mara Freilich, Brown University
9:40 AM	**Q&A**	
9:50 AM	Break	
10:20 AM	**Session 3: Slow Pathways**	Chairs: Isabela Le Bras, Charles Stock
10:20 AM	**(Invited) Signs of disequilibrium in the deep and abyssal circulations of seawater and tracers**	Jake Gebbie, WHOI
10:40 AM	**(Invited) Fast to slow impacts of turbulent mixing***	Laura Cimoli, University of Cambridge
11:00 AM	**Q&A**	
11:10 AM	**Session 2 and 3 panel discussion**	
11:30 AM	**Virtual poster session**	
12:00 PM	Lunch	
1:00 PM	**Poster Session 2**	
2:00 PM	**Session 4: Methods**	Chairs: Patrick Heimbach and Zach Erickson
2:00 PM	**(Invited) Steps towards a global and interdisciplinary deep ocean observing system***	Nathalie Zilberman, UCSD/ SIO
2:20 PM	**(Invited) Modeling pathways and processes of deep ocean ventilation**	Henri Drake, UC-Irvine
2:40 PM	**Discussion**	
3:00 PM	Break	
3:30 PM	**Breakout Session 2: Adequacy and gaps of existing observation and modeling tools and assessing where process studies will help**	
5:00 PM	End of day 2 for virtual participants	
5:15 PM	Optional informal activity	
Thursday, April 25, 2024		
6:30 AM	Virtual breakout for alternate time zones	
7:00 AM	Breakfast	
8:15 AM	**Recap of breakout 2**	
9:00 AM	**Breakout Session 3: Recommendations**	
10:30 AM	Break	
11:00 AM	**Recap of breakout 3**	
11:30 AM	**Conclusions and future steps**	
12:00 PM	**Workshop concludes**	

Find presentations, recordings and more on the workshop website
https://usclivar.org/meetings/pathways-connecting-climate-changes-to-deep-sea