Expanding the functionality of integrated ocean observing systems to address marine ecosystem change

Toshio Suga, Advanced Institute for Marine Ecosystem Change (WPI-AIMEC), Tohoku University, and Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan; Fumio Inagaki, Advanced Institute for Marine Ecosystem Change (WPI-AIMEC), Tohoku University, and Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan; Kentaro Ando, Advanced Institute for Marine Ecosystem Change (WPI-AIMEC), Tohoku University, and Japan Agency for Marine-Earth Science and Technology (JAMSTEC); and Motoko Kotani, Tohoku University, Japan

Abstract

Fluctuating dynamics of the marine environment, concordant with climate change, increasingly magnify the instability of habitats and ecosystems, particularly in coastal areas where ocean currents and human activities are most influential. Marine ecosystem change has a direct impact on the economy, food security, and culture of societies reliant on marine ecosystem services. However, current observing systems lack the functionality and data network capability sufficient for systematically decoding the intertwined climate-ocean-ecosystem complex. This is partly due to spatiotemporal data resolution, which varies significantly among the factors influencing climate, ocean circulation, and ecology. While current observation stations capture the physical characteristics of the upper ocean, they lack the capability to acquire data on spatiotemporal phenomena characterizing the mid-to-deep oceanic layers down to the seafloor. Additionally, without well-defined optimal revisit periods, it is debatable whether intermittent observation stations can provide representative spatiotemporal resolution sufficient to assess the complexity of coastal environments globally. Compared to terrestrial ecosystems observational data on marine ecosystem change is particularly scarce, presenting a major obstacle to modeling forward and reverse nonlinear predictors of the latter. Increasingly, the application of artificial intelligence (AI) approaches to merge high-resolution spatiotemporal data with data of low granularity has led to new insights and predictions. Furthermore, imminent technological advancements in automated systems to facilitate serial sampling of environmental DNA (eDNA) and collection of genomic data in situ offer to dramatically resolve data discrepancies when probing biological interactions relevant to marine ecosystem change. Here, we highlight a science and technology perspective with the potential to overcome the differences in spatiotemporal resolution of observational data between different disciplines. The innovation of profiling float technology has made it possible to simultaneously acquire physical and biogeochemical (BGC) data from the ocean environment. Accordingly, "OneArgo," encompassing the BGC Argo initiative to deploy this multi-functional observation system around the globe, has been endorsed as a UN Ocean Decade Project and is currently underway, led by the International Argo Program. Floats and similar observation technologies could be extended as a comprehensive all-in-one system for data acquisition related to physical oceanography, biogeochemistry, ecology, imagery, eDNA, and data corresponding to specific biomarkers as proxies. By integrating revolutionized four-dimensional marine ecosystem observations into high-resolution Earth system models (ESMs) and optimizing AI and computational power, we will be able to establish relevant aspects and better predictions of marine ecosystem change, thereby promoting sustainable development in the ocean environment.

The ocean is a significant determinant of climate variability, climate change, and their interlinkages. With its especially high heat capacity estimated at 1,000 times greater than that of the atmosphere, the ocean stores about 50 times more carbon proportionately. Thus, the ocean constitutes a major sink of anthropogenically released greenhouse gases.

In 2023, global temperature records were broken, with many cities experiencing unprecedented heat waves and reaching record high sea surface temperatures. Such phenomena accompanied by extensive ocean acidification and hypoxia (deoxygenation) are deviations from the Earth's normal seasonal cycles and serve as alarms announcing that global warming is profoundly changing marine ecosystems. Given that most of the oxygen we breathe is produced through photosynthesis in the ocean, particularly by "sea plants" or phytoplankton, the feedback from marine ecosystem changes threaten to also impact living organisms and environments on land.

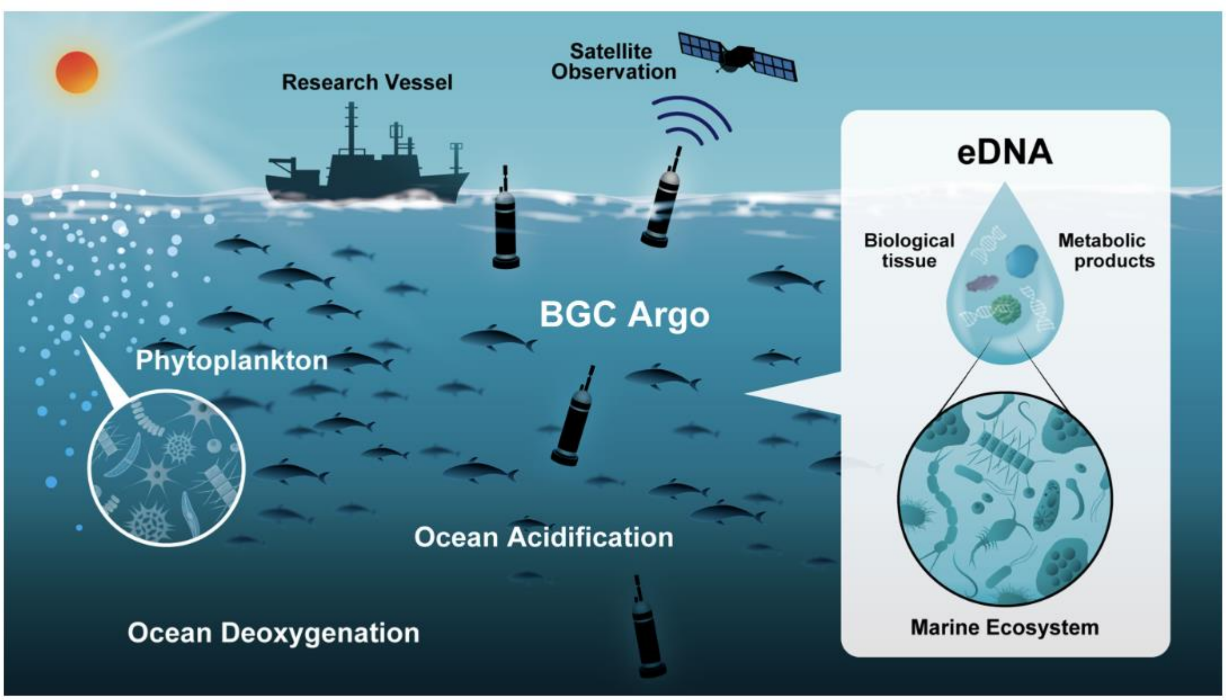
A key to understanding global warming impacts on ecosystems and achieving a sustainable Earth system lies in understanding how climate, oceans, and ecosystems, including human societies, are linked at different spatiotemporal scales. Accordingly, an insightful grasp of how marine ecosystems respond to global warming is required to forecast and mitigate this crisis. However, it is not easy to integrate the many physical, chemical, and biological processes because the spatiotemporal scales, quantity, and quality of observational data differ by orders of magnitude among different systems and disciplines. For example, satellite observations monitor the surface of the world's oceans at all times; in contrast, on-the-spot observations are necessary to observe the interior of the oceans. Compared to the field of physics, where sensor-based observations of water temperature and salinity were introduced early on, data from the biogeochemical and ecological fields, which require sample collection, are overwhelmingly scarce. Consequently, multilateral science-policy leverage is required to solve this problem.

OneArgo: A new era of the integrated ocean observations

To elucidate the mechanisms of marine ecosystem change, it is essential to significantly reduce the observational data imbalance present among marine physics, biogeochemistry, and ecology. UNESCO-IOC has supported the Argo Program for more than 20 years. The program operates approximately 4,000 profiling floats that continuously measure temperature and salinity, exhibiting almost no bias in time and space while generating a vast amount of data in real-time. The success of the Argo Program has led to a movement to expand the observation network to the BGC Argo by installing biogeochemical (BGC) sensors, such as for oxygen, chlorophyll-a, and nitrate on floats, from the sea surface to ~2,000 m depth in the ocean. The proposed advanced initiative "OneArgo" was endorsed as a project of the UN Ocean Decade (UNESCO- IOC, 2022) to replace the conventional Argo array with an expanded new array integrating traditional Core Argo floats, BGC Argo floats, and Deep Argo floats measuring temperature and salinity down to ~6,000 m below sea-surface. These advanced Argo floats will dramatically improve the quantity and quality of physical and biogeochemical data.

Another breakthrough in oceanographic observation is monitoring marine ecosystems with environmental DNA (eDNA). By collecting a small sample volume of living environment including cellular or extracellular (free) DNA, without the need to collect the whole organism, scientists can estimate the biodiversity and population structure and the interactions between species in an ecosystem in time and space. The comprehensive analysis of eDNA (i.e., meta-barcoding or -genomics) and other biomolecules (e.g., lipids and expressed proteins) enables us to evaluate ecosystem change patterns in response to inter-species interactions, potential genomic functions, and physicochemical changes in their habitat. Applying an integrative approach with eDNA-based ecology data and OneArgo data is crucial for addressing various questions of marine ecosystem change (Fig. 1).

Figure 1. Elucidating the mechanisms of marine ecosystem change requires matching the quality and spatiotemporal coverage of data corresponding to the physics, biogeochemistry and ecology.



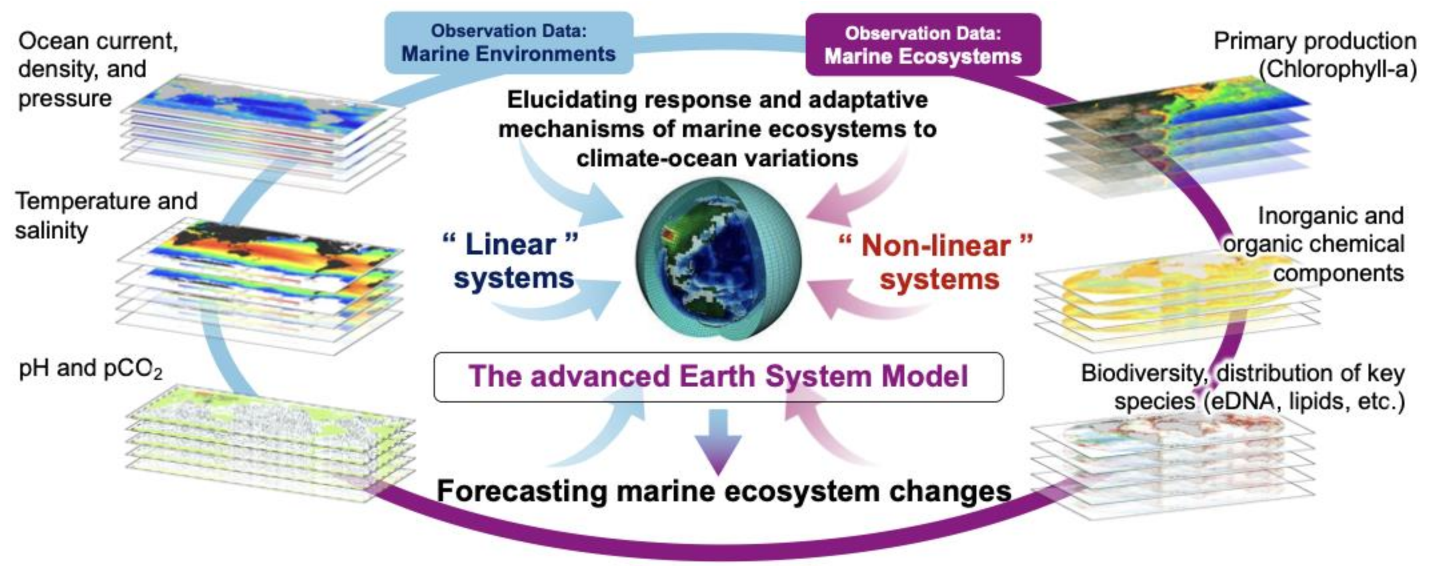
Forecasting marine ecosystem changes

Forecasting marine ecosystem changes in response to Earth system dynamics is vital for creating sustainability. Over the past decades, remarkable advances have been made in general circulation models of oceans and atmosphere-ocean integrative models that reproduce their physical environments. Model predictions will be further advanced by combining innovative observational techniques and data science from coastal areas to the open ocean. However, meeting the goal of maintenance and restoration of marine ecosystems requires systematic understanding and prediction of how they are affected by physical disturbances, such as annual reoccurrences and intensification of mesoscale eddies, typhoons, marine heat waves, and other phenomena known to have dramatic impacts on climate variability.

We envision coupling wide-area temporal observations, including data on physical ocean circulation, biogeochemical sensor records, and eDNA sampling, with analog (simulation) laboratory experiments, to improve our comprehensive understanding of the connectivity, stability, and adaptability of the climate-ocean-ecosystem complex. By incorporating four-dimensional marine ecosystem observations into high-resolution ocean general circulation models coupled with atmospheric models, a more integrated understanding and prediction of the mechanisms of marine ecosystem change is anticipated with ESMs (Fig. 2). However, many challenges must be overcome for a model to be of sufficient quality and reproducibility.

Even today's state-of-the-art models are at a stage where further performance improvement is wanting, especially with respect to ecosystem components. One promising solution for new insights is the application of AI in the assimilation and integration of high-resolution spatiotemporal data with other data of lower granularity. Constructing predictive models of change in marine ecosystems applicable on a global scale requires the incorporation of transformations that use neural networks (deep learning) in big data assimilation and integrative analyses of physical and ecological data.

Figure 2. Combining various observation data on marine ecosystems to forecast marine ecosystem changes requires the spatiotemporal expansion of observation data coverage and the advanced Earth system model.



Science-policy recommendations for addressing marine ecosystem change

Global warming due to human activities is not only associated with climate change but it also alters climate variability which together propel the ongoing ecosystem degradation and biodiversity crisis. Considering the immense significance of oceans and coastal regions for both local and global economies, we propose basic research and dissemination goals as a rigorous strategy to address SDGs laid out in the Agenda 2030 "Plan of Action for People, Planet and Prosperity" (UN, Transforming our world: the 2030 Agenda for Sustainable Development, 2015) with a particular focus on SDG14 (Life below water).

Currently, there is a considerable spatiotemporal gap between time-series studies of physical dynamics and marine ecosystem changes. This disconnect makes it difficult to understand and predict the internal and external regulation of changeable ecosystem functions, including their connectivity, stability, and adaptability defined by principles in interdisciplinary research. In turn, these challenges affect accurate predictions of marine ecosystem change, recovery, and restoration. Satellite observations and conventional Argo floats environmental parameter data for the ocean surface and the upper layer do not cover the middle-to-deep layers of the ocean and, thus, cannot fully capture three-dimensional ocean circulation and associated biogeochemical transport. Predicting the underlying physical processes depends on time and spatial scales from basin-wide gyres with strong and narrow western boundary currents. Such gyres include the Kuroshio current, ocean mesoscale eddies and fronts, submesoscale ocean waves, and three-dimensional turbulence. Likewise, ecosystems are dynamic systems propelled by condition-dependent interactions that are non-linear and involve countless interlinking biotic and abiotic elements. To predict how ecosystems adapt and respond to changing environments, it is crucial to understand fully the relevant mechanisms at the individual, population, and community levels and their interrelationships. Consequently, a model-free approach that does not presuppose the existence of a priori equations should be applied to big data (large-scale data of high quality and in large quantity) to elucidate both their intricacy and plasticity.

Taken together, new observation technologies will improve data acquisition for the current ocean system and our understanding of marine ecosystem change. Improved modeling performance will follow a renewal of the research domain based on improvements in interactive AI and computational power. New ocean observation missions, long-term station time series, and expansion and new developments of robotic platforms, such as BGC Argo and eDNA sampling devices, will reveal processes at unprecedented scales and cover new variables. The anticipated vast and wide-ranging data set though challenging to characterize, understand, and interpret will present opportunities for cross-disciplinary and transdisciplinary collaborations. These efforts are devoted to fulfilling a significant gap in the scientific community regarding basic sciences, applications that address changing coasts, and educational and training opportunities for the next generations.

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