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EDITED AND REVIEWED BY
Rui Rosa,
University of Lisbon, Portugal

*CORRESPONDENCE
Patti Virtue
p.virtue@utas.edu.au

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Editorial: New techniques for providing a window into the opaque ocean

Patti Virtue[1,2]*, Paco Bustamante[3,4] and George D. Jackson[5]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Battery Point, TAS, Australia, [2]Australian Antarctic Division, Department of Climate Change, Energy, the Environment and Water, Kingston, TAS, Australia, [3]Littoral Environnement et Sociétés (LIENSs), La Rochelle Université, La Rochelle, France, [4]Institut Universitaire de France (IUF), Paris, France, [5]Department of Earth and Biological Sciences, School of Medicine, Loma Linda University, Loma Linda, CA, United States

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Editorial on the Research Topic
New techniques for providing a window into the opaque ocean

Despite remarkable advances in marine science, the ocean remains a difficult environment to access and understand. Many ecosystem responses to change, ecological processes, species distributions, and trophic interactions remain difficult to quantify. New analytical tools and techniques are beginning to illuminate these previously opaque systems, enabling the observation of ecosystem dynamics and biological patterns across spatial and temporal scales. The research assembled in this Special issue demonstrates how these techniques, monitoring programs, predictive frameworks, and molecular tools are advancing our understanding of marine ecosystems and assessing their likely responses to changing conditions.

Collectively, these manuscripts highlight the use of analytical tools to elucidate processes that are not directly observable. Combining modeling, biochemical, ecological, and molecular techniques with traditional sampling, these studies challenge existing assumptions about physiological responses, species ecology, habitat use, trophic interactions, and ecosystem change, spanning ecosystems from temperate reefs to the rapidly warming Arctic Ocean.

Shalders et al. integrated distribution modeling with physiological data to understand ecosystem response to environmental change. The authors used lipidomic and metabolomic techniques to investigate the effects of marine heat waves and ocean warming on the Australian seaweeds, *Sargassum linearifolium* and *Ecklonia radiata*. Despite finding marked differences between species, they found limited effects on nutritional quality resulting from warming.

Providing evidence for the ongoing Atlantification of the Arctic, i.e., the increasing influence of warmer waters of Atlantic origin in the Arctic Ocean, Golikov et al. analyzed an 18-year time series of cephalopod biomass data. Their results showed that the warming of Arctic waters facilitated the northward expansion of boreal-subtropical species, highlighting the rapid reorganization of Arctic marine communities. Their research reinforces the critical importance of long-term observation programs for detecting and understanding ecosystem change.

One example of the value of sustained monitoring in advancing our understanding of cryptic trophic interactions and ecosystem functioning is the use of ^{13}C-enrichment nuclear magnetic resonance spectroscopy to trace energy through the marine ecosystem (Bock et al.). An algal-

bivalve experiment was used to trace the dietary carbon from a diatom (*Phaeodactylum tricornutum*) into the king scallop (*Pecten maximus*), revealing that warming altered the assimilation of nutritional compounds. This article highlights how biochemical techniques can provide insights into the physiological pathways that drive ecosystem responses to a rapidly changing climate.

Molecular approaches are transforming biodiversity monitoring. Species-specific environmental DNA (eDNA) assays were developed by Cardeñosa for endangered hammerhead sharks (*Sphyrna corona, S. media*, and *S. vespertina*) in Uramba Bahía Málaga National Park in Colombia. This article demonstrates the potential of eDNA to detect elusive species without the challenges or potential disturbance caused by using conventional techniques.

While eDNA can reveal species diversity in marine ecosystems, epigenetics can provide insights into their physiological responses to changing environmental conditions. A review by David et al. synthesized recent advances in marine environmental epigenetics, detailing how pathways in DNA methylation, histone modification, and non-coding RNA respond to environmental perturbations, such as ocean acidification, pollution, hypoxia, and ocean warming. Including epigenetic tools as part of monitoring may provide early indicators of biological stress in marine organisms.

Using complementary biochemical tools, Lipscombe et al. explored the poorly understood trophic ecology of immature white sharks (*Carcharodon carcharias*). They used fatty acid and stable isotope analyses to characterize diet and habitat use across temporal scales in eastern Australia. This integrated analysis showed a marked seasonal shift in diet and highlighted the importance of coastal resources for these sharks. This study demonstrates the power of integrating complementary biochemical techniques to better understand marine predators, their trophic ecology, and their behavior.

The utility of stable isotope approaches was further demonstrated by Jackson et al., who used isotopic niche analysis and Bayesian mixing models to study the trophic niche differentiation and foraging plasticity in long-finned pilot whales (*Globicephala melas edwardii*) that were stranded along the Tasmanian coast. Their results revealed substantial spatial variation in habitat use and dietary flexibility. The application of biochemical approaches, as shown in this article, offers unique insights into the behavior, diet, habitat use, and ecology of marine species that are otherwise hard to access using conventional field operations.

At the community and ecosystem levels, Swieca et al. investigated the recruitment dynamics of northern anchovy (*Engraulis mordax*) in the California Current using otolith microstructure, *in situ* imaging, and oceanographic parameters. The authors demonstrated that larval growth and survival are driven by oceanographic conditions, fluctuations in prey availability, predator pressure, and upwelling dynamics. Through innovative ways of observing and measuring ecological processes, their research reveals ecological interactions that enhance our understanding of mechanistic processes operating within dynamic marine ecosystems.

The challenges of studying highly mobile species, such as whale sharks (*Rhincodon typus*), were addressed by Ahn et al., who used species distribution modeling to identify habitats at the northern edge of the species range in Korean waters. Despite limited observations, the authors used databases and an innovative pseudo-absence selection approach to improve habitat predictions. This study provides an example of how predictive modeling can be an important conservation tool in rapidly changing marine environments.

The new and emerging technologies highlighted in this Research Topic have advanced our ability to overcome historical research limitations in vast and inaccessible marine environments. The integrative approaches published in this Research Topic include long-term observations, predictive modeling, biochemical analysis, and the use of epigenetic biomarkers and environmental DNA. These contributions move beyond descriptive surveys to identify the mechanisms driving ecological responses, providing a robust foundation for prediction, conservation, and management. Together, these advances provide a window into the opaque ocean, illuminating the processes that underpin marine ecosystem dynamics and enhancing our ability to understand and anticipate ecological change.

Author contributions

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