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PERSPECTIVE

The essential role of large research vessels in marine ecosystem observations and ocean sustainability

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Abstract

Our understanding of marine ecosystems and ability to manage them sustainably has come from multidisciplinary observations made repeatedly over long periods of time. These long-term ecosystem observations depend on the capabilities of large research vessels, which play an essential role in the collection of global ocean observations. Research vessels serve as large, stable platforms for collecting high volume samples from the surface to the seafloor that provide uniquely valuable in situ marine ecosystem information. Additionally, they serve as mobile laboratories enabling the collection, preservation, processing, and analysis of unique samples and data, such as chemical, biogeochemical, and biological parameters. Given their capacity for, and repeated use in, collecting comprehensive marine ecosystem observations—across geology, physics, chemistry, and biology—large research vessels provide insight into long-term regional ecosystem dynamics. They also act as platforms-of-opportunity for testing, refining, and comparing technologies, enabling innovation and the evolution of the observing system. High-quality observations from large research vessels serve as the backbone for many other components of the global ocean observing system through their use in calibrating autonomous sensors and predictive modeling. Moreover, large research vessels function as mobile, experiential training and exploration platforms that facilitate discovery, education, and collaboration. An effective, modular marine ecosystem observing system will depend on large research vessels to sustain and augment existing observing programs and to deploy, service, and validate the growing array of autonomous platforms that contribute to it. Achieving this vision will likely require maintaining and upgrading ship-based infrastructure and personnel, integrating emerging technologies, leveraging the unique capabilities of large research vessels in conjunction with other platforms, strengthening collaborative partnerships, and building social capital for marine ecosystem observations through training, knowledge sharing, and effective governance.

Importance of long-term marine ecosystem observations to sustainability

Marine ecosystems are a critical frontier for scientific discoveries, climate solutions, and economic development (Jouffray et al. 2020; Lemoine and Kapnick 2024; Rayner et al. 2019). The importance of marine ecosystem observations is evident across numerous sectors of society, including research, management/policy (encompassing environmental protection, maritime safety, and the regulation of human

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activities), and industry (Lemoine and Kapnick 2024; Rayner et al. 2019; Estes et al. 2021a; Estes et al. 2021b). Sustained, interdisciplinary ocean observations are essential for generating the time-series data needed to characterize and understand complex ocean and marine-ecosystem dynamics and improve predictive ocean models (Henson 2014; Ducklow et al. 2009; Dickey and Bidigare 2005; Edwards et al. 2010). Through long-term ocean observing efforts, it is possible to differentiate natural ecosystem variability (Gonzalez et al. 2023) from secular changes caused by human activities (Benway et al. 2019; Asch 2015; Mori 2020).

Many ocean resources are dynamic, common-pool resources that require sustained monitoring to inform policy, regulatory, and management decisions needed to ensure their health, persistence, and equitable use (Ostrom 2008; Bennett et al. 2021). Such observations help to establish baseline conditions, assess impacts, evaluate effective responses to mitigate impacts, and to track ongoing trends (Evans et al. 2019). Long-term marine ecosystem observations are recognized as being vital to the viability of many marine commercial sectors, such as aquaculture and fisheries (Schmidt et al. 2019; Hilborn et al. 2020; Schwing 2023; Goethel et al. 2023), deep sea mining (Smith et al. 2019), marine shipping, renewable energy, and coastal tourism (Hermes et al. 2022). These industries rely on sustained ocean observations to inform how they manage risk, support safe and efficient operations, and maintain regulatory compliance (Rayner et al. 2019). The value of marine ecosystem observations will continue to increase as efforts to expand the Blue Economy lead to infrastructure and industry development (e.g., Cross et al. 2023). Additionally, under changing climate conditions, requirements for corporate Environmental, Social and Governance reporting may continue to grow (e.g., Rapach et al. 2024; Markopoulos et al. 2020). How the global ocean observing system is optimized to balance 21st century development with its associated impacts will likely have long lasting effects on marine ecosystems (Nowicki et al. 2022).

The role and evolution of large oceanographic research vessels in ocean observing

Large oceanographic research vessels, which have historically been foundational in collecting surface and subsurface marine ecosystem observations, continue to be essential tools for studying marine ecosystems (Smith et al. 2019; Schwing 2023). The modern research vessel traces its origins back to early exploration voyages, such as the Challenger expedition of 1872–1876 (Adler 2014). Historically, very few large ships were designed for scientific exploration, but rather were converted to include basic research facilities that allowed for sampling and measurements when the need arose (Treadwell et al. 1989). As oceanographic research grew more complex and multidisciplinary (e.g., physical, chemical, and biological oceanography, marine geology, ocean engineering, and atmospheric science), the practice of converting existing ships into research vessels became less practical, so dedicated research vessels were designed and built (National Research Council 2009).

Today, large research vessels are the backbone of ocean observing systems, supporting a wide range of observing technologies and on-board facilities (e.g., laboratories and berths). In the context of this paper, we use the term "large research vessels" to encompass Global and Ocean Class vessels, which are often greater than 55 m (~ 180 ft; Prince 2001) and are capable of performing a wide range of tasks and accessing nearly all parts of the global ocean (National Ocean Council 2013; Nieuwejaar et al. 2019). The capacity of large research vessels to navigate throughout the global ocean enables the observation of characteristics, processes, and ecology occurring within the deep, pelagic, and polar regions which are the largest and least observed marine regions globally (Satterthwaite et al. 2021). For example, large research vessels equipped with icebreaking capabilities are essential for accessing remote, ice-covered polar regions to observe critical processes such as ice dynamics, the role of the polar oceans in the global climate and carbon systems, and dynamics of polar marine ecosystems (Dunbar et al. 2012). These extensive, multi-disciplinary observations provide a unique multidecadal record of ocean conditions and marine life.

Exploration of the value and future of marine ecosystem observations

Ship-based observations have been examined in the context of global ocean, weather, and climate observing systems (Smith et al. 2019) and the essential value of interdisciplinary, marine ecosystem observations to marine science and sustainable management has been described (Dickey and Bidigare 2005). Future visions for ocean observing have been explored in the context of in situ observations (Gould et al. 2013; Legler et al. 2015; Lin and Yang 2020), biogeochemical time series (Church et al. 2013), climate-fisheries-marine ecosystems (Schmidt et al. 2019), as well as intelligent (Lermusiaux et al. 2017) and autonomous (Whitt et al. 2020) systems. Here, we build upon these existing studies to examine the role of large research vessels in supporting long-term marine ecosystem observations and propose future priorities for ensuring sustained collection of comprehensive, in situ marine ecosystem observations in support of ocean sustainability. We use the term "marine ecosystem" in this context to describe comprehensive ocean observations across all facets of the ocean ecosystem, including geological, physical, chemical, and biological parameters. This encompasses all trophic levels—from primary producers to top predators, including fish, marine mammals, and seabirds—across the entire food web for a more comprehensive understanding of marine ecosystems (Doney 2013). The longest-running marine ecosystem observing program in the world, the California Cooperative Oceanic Fisheries Investigations (CalCOFI), started in 1949, is used herein as a case study to explore the sustainability and future of large ship-based observing programs (Bograd et al. 2003; Rebstock 2003; Ohman and Venrick 2015; CalCOFI 2025). In honor of over 75 years of marine ecosystem observations by CalCOFI, we blend theoretical insights with decades of experience from CalCOFI to envision the future of comprehensive marine ecosystem observations. Our vision considers the role that large research vessels play in the future evolution of the ocean observing system.

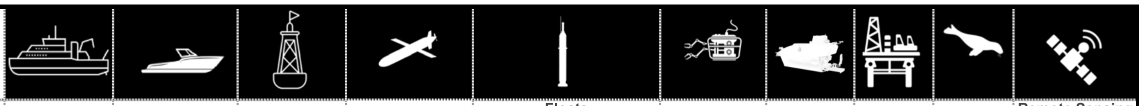
Unique benefits of large research vessels to the global ocean observing system

Stable platforms to collect uniquely valuable in situ data and large volume samples

> Deploying a 24-bottle rosette equipped with 10 L bottles at 10 stations during a CalCOFI cruise (normally taking ~ 2 d) would equate to approximately 2400 1 L autonomous collector robots.

Large research vessels are sizable platforms that can handle simultaneous deployment of multiple instruments and the significant weight and safe operation of winches, cranes, and specialized mounting and deployment systems necessary for handling and operating heavy in situ, towed, or profiling equipment deployed across a range of ocean depths (Table 1; Nieuwejaar et al. 2019). Such equipment can include large plankton nets (Box 1; e.g., MOCNESS, BongoNet), pumps (e.g., McLane Large Volume Water Transfer System [WTS-LV] pump), Remote Operated Vehicles (ROVs), towed instrument arrays (e.g., SeaSoar), trawl gear, benthic coring devices (e.g., Eckman Grabs, Multi Corers, and Push Corers), moorings, autonomous platforms, and sizeable water collection systems like Niskin and GO-Flo bottles on large CTD rosettes (Table 1; 10–36 10–12 L bottles). These instruments enable the collection of unique data and large volume samples—of water, biological specimens/material, sediment and geologic

Table 1. Capabilities of different ocean observing platforms to collect in situ marine ecosystem observations across a range of instruments/methods. "Commonly" (green) implies the instrument/method is regularly and reliably used on that platform without major limitations. "Commonly, but with limitations" (blue) implies that the platform can deploy a given instrument or use a particular method but with some limitations to the deployment (e.g., size, depth, power). "Sometimes" (yellow) indicates platforms that can deploy a given instrument or use a particular method but its only possible under some conditions, with special set-ups, or still in development. "Rarely" (red) indicates cases where it is impractical or very unlikely for a platform to deploy a given instrument or use a particular method. Table adapted and expanded from concepts in Schwing (2023).



	Large Ships/Research Vessels	Small Boats	Moorings & Buoys	Autonomous Vehicles (AUVs, ASVs) & Gliders	Floats Profiling Floats Drifters Buoyancy Engine Vehicles	Remotely Operated Vehicles (ROVs)	Human-Occupied Vehicles (HOVs)	Fixed Platforms	Marine Mammals as Observers	Remote Sensing Devices (e.g., Satellites, Aircraft, or Drones)
Specimen collection methods	commonly	commonly, but with limitations	rarely	sometimes	rarely	sometimes	sometimes	commonly	rarely	rarely
Water sample collection methods	commonly	commonly, but with limitations	sometimes	sometimes	rarely	sometimes	sometimes	commonly	rarely	rarely
Camera or visual imaging systems	commonly	commonly, but with limitations	sometimes	commonly, but with limitations	rarely	commonly	commonly	commonly	sometimes	commonly, but with limitations
Physicochemical and optical sensors	commonly	commonly	commonly	commonly	commonly	commonly	commonly	commonly	commonly	commonly
Current and flow measurement instruments	commonly	commonly, but with limitations	commonly	commonly	sometimes	sometimes	sometimes	commonly	rarely	rarely
Visual observations by humans	commonly	commonly	rarely	rarely	rarely	rarely	commonly	commonly	rarely	sometimes
Acoustic imaging instruments	commonly	commonly, but with limitations	rarely	commonly, but with limitations	rarely	commonly	rarely	sometimes	rarely	rarely
Active/passive acoustic instruments	commonly	commonly, but with limitations	commonly	commonly	sometimes	commonly	commonly	commonly	sometimes	rarely
Sediment trap	commonly	commonly, but with limitations	commonly	sometimes	sometimes	sometimes	sometimes	commonly	rarely	rarely
Benthic coring/sediment devices	commonly	commonly, but with limitations	rarely	rarely	rarely	sometimes	commonly	commonly	rarely	rarely

Box 1. Plankton sampling devices for fisheries management

From the beginnings of ocean research, Victor Hensen (1835–1924) postulated that the efficient use of fishery resources required knowledge of ocean productivity (dependent mainly on plankton) and the integration of this information into ecosystem management (Mills 2012; Berger 1990; Omori 2002). This proposal, together with Hjort's hypothesis that fish recruitment success depended fundamentally on the larval survival in their first feeding stage as part of the plankton (Hjort 1914; Schwach 2014), were the theoretical support for a large number of research projects that, in the 1960s and 1970s, addressed the relationships between the distribution and abundance of fish larvae and the environmental conditions (Omori 2002).

For these research purposes, the collection of marine organisms in their different life stages has been mainly by nets of different types, which have allowed the taxonomic analysis of the species that have been obtained, as well as the estimation of their abundance. During the first decades, plankton sampling, carried out by means of bottles and nets, was discrete and had a very limited capacity to provide continuous distributions of the abundance of organisms. This changed when Alister Hardy (1896–1985) invented the Continuous Plankton Recorder (CPR), which began operating in the North Sea in the early 1930s and has been in continuous use ever since. In the CalCOFI region, sampling was initially done with a 1 m diameter net towed with a bridle attached in front of the opening, but in 1977 it was replaced by a 71 cm diameter bongo net system without a trawl bridle (Koslow et al. 2019), which is still in use to date.

Since 1949, the use of diverse sample collection methods (Bograd et al. 2003) has resulted in a database spanning more than 75 years that, in conjunction with measurements of physical and chemical environmental variables, has been used to characterize changes in species phenology (Asch 2015) and oxygen content in the California Current (Bograd et al. 2008; Koslow et al. 2019).

New questions have been promoting the development of different collection methods, for example, the use of remotely controlled open/close net systems such as MOCNESS (Wiebe et al. 1985), BIONESS (Sameoto et al. 1980), and MultiNet (Hydro-Bios 2020) to determine the fine-scale (10–100 m) and coarse-scale (1–10 km) distribution of animals, while collecting information on the physical environment in which the captured animals inhabit. Given that net sampling still requires large research vessels, such detailed and continuous data collection is only feasible through their use, highlighting their essential role in advancing our understanding of marine ecosystems.

samples, or other "heavy" material—that can be analyzed for a broad suite of biological, chemical, and geological properties (Table 2; e.g., McClenaghan et al. 2020). For example, many investigations of the ecology of zooplankton, ichthyoplankton, or fishes and invertebrates (e.g., trawling or plankton net sampling methods) require sufficient deck space and intensive mechanical infrastructure (e.g., winches with the ability to conduct long and/or deep controlled deployments of sensors and sampling gear) for sampling large volumes of water to collect biological specimens and infer densities of organisms. Such infrastructure is required to achieve depth-stratified sampling of deep-dwelling marine communities and deep habitats (for example, MOCNESS, multinet or Tucker trawl studies, *see* Wiebe et al. 1985, Haddock and Choy 2024). Additionally, large research vessels can deploy instrumentation like McLane pumps which can collect particles to study the movement of material through the water column and associated impacts on the global carbon cycle (Nowicki et al. 2022) and the distribution of trace elements and chemicals (e.g., pollutants and toxins; Taylor and Karl 1991, Lutz et al. 2007, Collins et al. 2015, Siegel et al. 2023).

Large research vessels can be equipped with passive monitoring equipment that continuously captures environmental conditions while the ship is in transit or being used for other activities. For example, most large research vessels have an underway water collection system that is often integrated with the vessel's seawater intake system, which pumps large volumes of water continuously from a few meters depth during transit directly into onboard laboratories. Underway water and specimen collection devices can provide valuable sources of data for biogeochemical and biological parameters such as carbonate chemistry (Bakker et al. 2016; Friedlingstein et al. 2023), environmental DNA (eDNA; Jeunen et al. 2024), and larval fish or eggs (e.g., Continuous Underway Fish Egg Sampler [CUFES]; Checkley Jr et al. 1997, Zwolinski and Demer 2024). Some sampling devices such as in situ imaging systems (e.g., in situ Digital Plankton Imager, Imaging FlowCytobot) and acoustic instruments (e.g., Acoustic Doppler Current Profiler, Multibeam imaging sonar) rely on the stability and infrastructure provided by research vessels for effective operation and data quality (Smith and Rumohr 2013). For example, contemporary acoustic surveys typically need the ability to collect acoustic data from several frequencies (e.g., multibeam or multifrequency surveys), which requires a larger base to mount transducers and receivers, so smaller vessels are often less appropriate (Simmonds and MacLennan 2005; Liu et al. 2023). Additionally, having personnel with specialized experience necessary to support the maintenance and repair of instruments and ability to troubleshoot and address technical issues with data collection systems onboard and in real-time is another advantage of large research vessels. This can minimize downtime in operation and data

Table 2. Summary of in situ oceanographic instruments and methods that are deployed from large research vessels, specifying whether they provide archived samples (e.g., specimens, acoustic records, images) and which Essential Ocean Variables (EOVs; Miloslavich et al. 2018)—physical, biogeochemical, and biological or ecosystem variables—these methods sample. A shaded cell with an “X” denotes that the instrument can collect some aspect of a biological or ecosystem EOV (e.g., diversity and/or biomass). An asterisk indicates EOVs that can only be measured using environmental DNA methods. Table adapted and expanded from concepts in Schwing (2023).

		Samples collected					Essential Ocean Variables (EOVs)																		
		Physical samples collected			Information collected		Physical EOVs					Biogeochemical EOVs								Biological & Ecosystem EOVs					
	Examples	whole organisms and/or genetic material	water	sediment/ particles	digital records (images/ videos/ acoustic recordings)	numerical data points only	sea surface & subsurface temperature	sea surface & subsurface salinity	sea surface height	ocean bottom pressure	surface & subsurface currents	oxygen	nutrients	inorganic carbon	transient tracers	particulate matter	nitrous oxide	stable carbon isotopes	dissolved organic carbon	microbe biomass & diversity	phytoplankton biomass & diversity	zooplankton biomass & diversity	fish abundance & distribution	invertebrate abundance & distribution	marine turtles, birds, mammals abundance & distribution
Specimen collection methods	Plankton net tows (e.g., MOCNESS, BongoNet); Pumps (e.g., McLane pump); Underway collectors - CUFES; Trawl; Hook & Line	X																			X	X	X	X	
Water sample collection methods	Niskin bottles; GO-Flo bottles; other trace metal bottles; underway samplers	X	X	X			X	X				X	X	X	X	X	X	X	X	X	X	X	X*	X*	X*
Camera or visual imaging systems	In Situ Ichtyoplankton Imaging System, IFCB, video recorder				X																X	X	X	X	X
Physicochemical and optical sensors	temperature, conductivity, dissolved oxygen, pH, nitrate, fluorometer, backscatter sensors					X	X	X	X	X		X	X	X	X	X	X	X	X						
Current and flow measurement instruments	Acoustic Doppler Current Profiler					X					X														
Visual observations by humans	marine mammal or seabird observers				X	X																	X		X
Acoustic imaging instruments	sidescan sonar, imaging sonar, scanning sonar				X																		X		X
Active/passive acoustic instruments	Sonobuoys, hydrophones				X																X	X	X	X	X
Sediment traps		X		X										X		X		X	X	X	X	X			
Benthic coring/sediment devices	eckman grab, multi corer, push corer	X		X										X		X		X		X				X	

collection, allowing for more timely and improved quality in data acquisition.

Research vessels can also carry observers to identify organisms on or near the vessel, such as marine mammals and seabirds (Table 1; Campbell et al. 2015, Russell et al. 2023). They record species sighted, compositions, sizes, and other relevant ecological data, providing essential information for biodiversity assessments and ecosystem studies. Although some of these observations can be supplemented by drone and other aerial surveys, vessels allow for extended periods of observation since they can remain stationary or move slowly over a large areas, while gathering contextual information (e.g., in situ environmental or ecological information) or other complementary data collection (e.g., hydrophones), and may be able to reach areas where plane or drone operations may be limited or not possible (Hammond et al. 2021; Bernard et al. 2021).

Mobile laboratories that enable the collection, immediate processing, and preservation of unique geological, chemical, and biological samples and data

In addition to being able to deploy large, heavy equipment and collect large volume samples, large research vessels are often outfitted with onboard facilities that are crucial for the immediate handling, processing, analysis, preservation, and storage of samples (e.g., water or specimen samples) (Schiaparelli et al. 2016). This, coupled with the ability of large research vessels to access deep and open ocean regions, enables the collection of unique samples and information that only large research vessels can currently provide (Tables 1, 2; Hood 2009). As an example, for most adult, juvenile, or larval stages of fishes and corresponding stages of invertebrates, correct taxonomic identification is not possible without physical and visual examination or genetic sequencing of specimens. Thus, the capacity to both collect specimens and analyze (or preserve for later analysis) samples at sea is critical. Even when such taxonomic identification may be possible without physical handling (e.g., eDNA for well-studied species), demographic data from biological samples are key to many critical research products. Stock assessments and fisheries oceanography studies typically require extensive demographic information such as length, gender, and age (where the latter is obtained by otoliths, statoliths, or similar structures, Methot and Wetzel 2013, Hilborn et al. 2020), maturity state, fecundity, reproductive output, stock structure determinations (e.g., close kin mark recapture analysis, population genetics), and trophic ecology (e.g., stomach contents, stable isotopic analysis) which require whole organisms caught at sea or different types of tissue samples processed in a timely manner using a variety of preservation methods (Lowerre-Barbieri et al. 2011; Swalethorp et al. 2023).

Large volumes of water (≥ 1 L) are often required for genomic and metagenomic analyses, including microbiome, eDNA, and eRNA (Patin and Goodwin 2023; Bowers et al. 2021; Giroux et al. 2022). This is particularly true for eDNA of multicellular organisms, given limited DNA concentrations of sloughed off material, in contrast with microbes or single-celled phytoplankton which are ubiquitous and highly abundant in ocean water (Stat et al. 2017). Even larger volume samples (5–20 L) may be necessary for accurate detection of rare organisms or of organisms in turbid and deep-sea environments (Sepulveda et al. 2019; Kumar et al. 2022; Govindarajan et al. 2022). While a few autonomous vehicles currently exist that can filter water in situ (e.g., the Long-Range AUV 3rd generation environmental sample processor; LRAUV-3G-ESP; Yamahara et al. 2019), even these cutting edge instruments have limited filtering capacity. Furthermore, such in situ filtering capability is not accessible to most labs and is currently only possible at scale using oceanographic vessels equipped with Niskin rosettes or tethered AUVs (e.g., MesoBot; Govindarajan et al. 2022).

Large research vessels also allow for immediate preservation and processing, making them essential for obtaining critical information on parameters that are subject to degradation or that rapidly change, such as chemical or volatile compounds; contaminants or toxins; biological specimens, tissues or genetic material; and microbial communities. For example, conducting experiments at sea on large research vessels enables biological rate measurements (Dickey and Bidigare 2005). Biological rate measurements like primary productivity, grazing rates, calcification/dissolution, respiration, and new production often require incubation and the ability to initiate experiments promptly after collecting organisms. Such rate measurements are critical for parameterizing models, quantifying biogeochemical processes, understanding marine ecosystem function and providing foundational information for developing biogeochemical budgets of our earth system (Miller and Wheeler 2012). Additionally, discrete water samples and laboratory-based analyses are required to measure some macronutrients (e.g., dissolved phosphate and silicate) and trace metals, like iron, which are often critical to understanding ocean productivity (e.g., Boyd and Ellwood 2010). Furthermore, isotopic analysis can be performed on various samples collected from the ocean, such as water, particulate matter, or sediments to identify water mass origins, biogeochemical processes, and food web pathways, providing a comprehensive understanding of ocean biogeochemistry that cannot be achieved through remote or autonomous methods alone (Teece and Fogel 2004).

Additionally, water and net samples for microscopy can be preserved in solutions that maintain cell/body integrity (e.g., alcohol or formalin), resulting in the long-term storage and archiving of biological samples. Archiving plankton samples has proven to be especially important to emerging research, since archived samples have allowed modern technologies to be applied to specimens in ways that could not possibly have been envisioned when the sample was collected. For example, archived samples from CalCOFI have been analyzed with: state-of-the-art compound-specific stable isotope analysis to understand the trophic position of larvae fish diet (Swalethorp et al. 2023), otolith microstructure analysis to understand larval fish age and condition (Fennie et al. 2024), genetic methods to distinguish previously indistinguishable larval rockfish species (Thompson et al. 2017), metabarcoding of DNA to understand the change in fish assemblages over time (Gold et al. 2024), and visual methods to assess microplastic pollution (Gilfillan 2009).

Sources of essential high-resolution, long-term, and comprehensive ecosystem information

Large research vessels enable the collection of high-resolution, long-term, and multidisciplinary ecosystem data (Tables 1, 2; Fig. 1). Large research vessels provide a comprehensive view of marine ecosystems by enabling simultaneous collection of co-located physical, chemical, and biological measurements, from the ocean surface to seafloor (Tables 1, 2; Fig. 2; Dickey and Bidigare 2005). For example, CalCOFI provides seasonal and interannual insight into the dynamics of the California Current Ecosystem by comprehensively sampling approximately 36 different physical and chemical parameters, 2500 biological parameters, and 49,000 unique eDNA sequences within the California Current System (CCS; Box 2; CalCOFI). Given that many ecosystem observing programs are typically associated with longer-duration, continuous sampling missions, such interdisciplinary research often requires a large research vessel to accommodate diverse sampling gear and instrumentation, in addition to the crew and science party, for periods of weeks to months (Nieuwejaar et al. 2019).

Large research vessels are used to conduct process studies requiring measurements of numerous parameters on fine spatial and temporal scales (Smith et al. 2019; Siegel et al. 2021). Additionally, large research vessels are equipped with advanced dynamic positioning devices to visit the same locations across a region and maintain positioning, which allows for repeat sampling and the collection of time series data (Box 2). Repeat sampling and time series data are fundamental for tracking changes in ocean conditions, species populations, and ecological interactions, enabling retrospective analyses and providing invaluable insights into trends and long-term shifts in marine environments (Thompson et al. 2022; Clayton et al. 2022; Erickson et al. 2023).

Comprehensive and coordinated multidisciplinary ecosystem observations are increasingly important for ecosystem-based research and management (Schmidt et al. 2019). This consists of an "end-to-end" approach that involves characterizing as many levels of the ecosystem and environment as possible in order to facilitate modern marine ecosystem modeling and prediction (e.g., Gomes et al. 2024; Audzijonyte

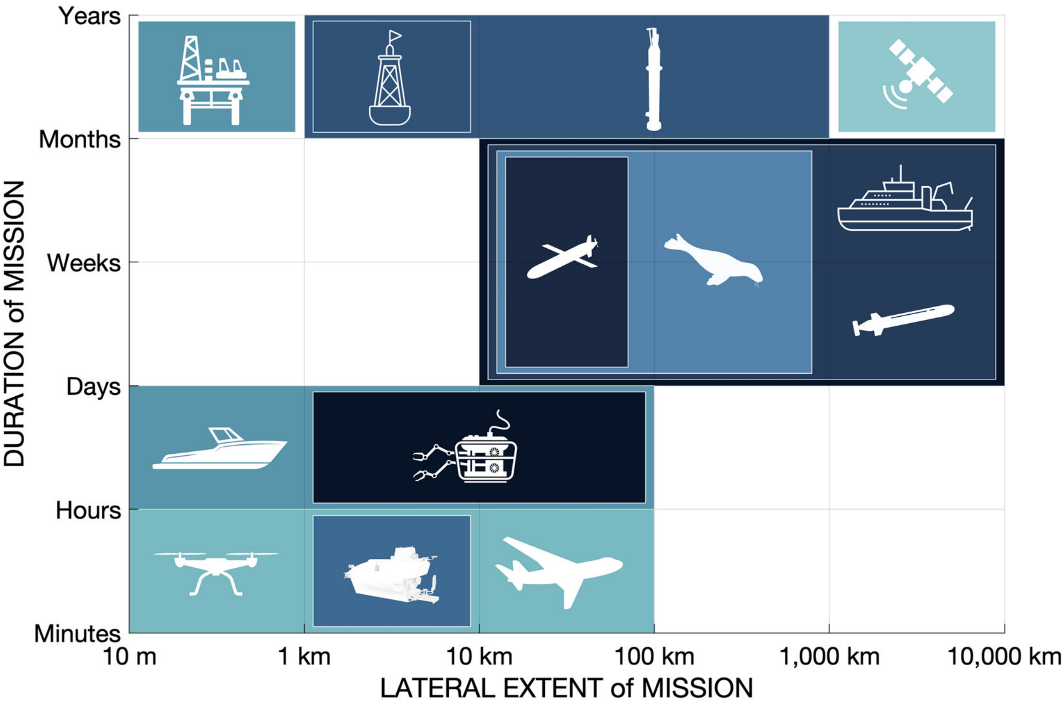


Fig. 1. A Stommel diagram (Stommel 1963) illustrating the approximate spatial and temporal scales of a single mission for various ocean observation platforms (indicated by the icon of each platform). Platforms include: large research vessels; small boats; moorings/buoys; autonomous vehicles (AUVs, ASVs); gliders; floats, profiling floats, drifters, buoyancy engine vehicles; Remotely Operated Vehicles (ROVs); Human- Occupied Vehicles (HOVs); fixed platforms; marine mammals as observers; and remote sensing devices (e.g., satellites, aircraft, drones). The different shades of blue correspond to their maximum depth as represented in Fig. 2. The x-axis represents the spatial/lateral extent of a mission, ranging from meters to thousands of kilometers, while the y-axis shows the temporal duration of a mission, from minutes to years. Figure inspired by concepts in Schwing (2023) and adapted and expanded.

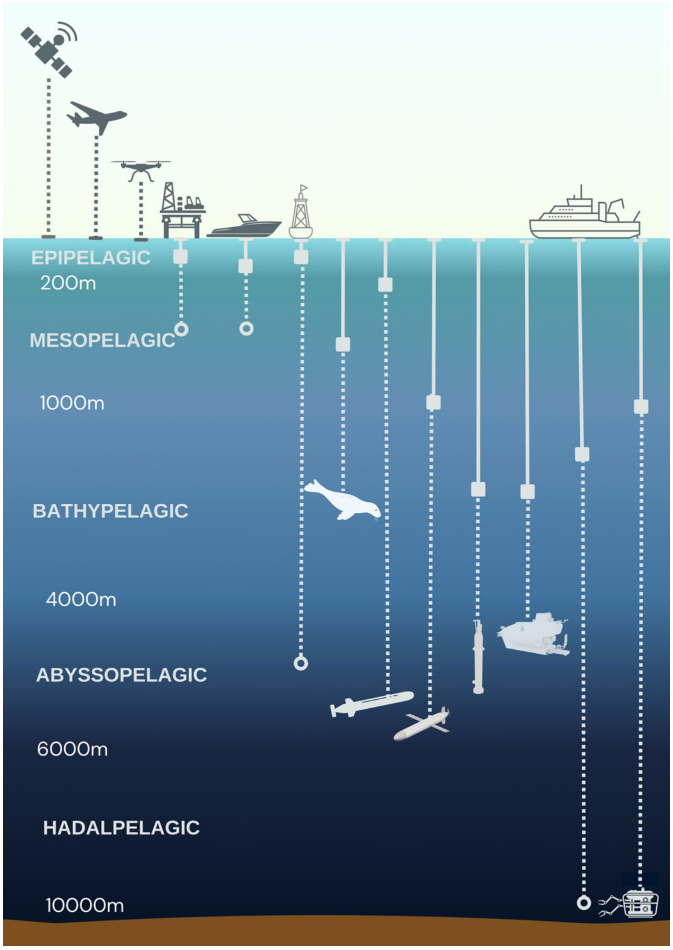


Fig. 2. Depth range (m) of various ocean observing platforms (indicated by the icon of each platform), with the usual maximum mission depth indicated by solid lines/squares and the possible maximum depth indicated by dotted lines/circles. Depths informed by Cole et al. 2003, Vasudev 2018, Javaid et al. 2014, Roemmich et al. 2019, Sward et al. 2019, McMahon et al. 2021, and BCO-DMO 2024.

et al. 2019; Marshall et al. 2017). For example, multidisciplinary studies that include an evaluation of seabirds and marine mammal predators and their prey (forage fishes and invertebrates) in the context of a dynamic physical environment require extensive seabird and marine mammal observations collected by human observers to be conducted in concert with sampling of the physical, chemical, and biological environment via water sampling, acoustics, net sampling, towed vehicles, drift arrays, and rate measurements through on-board and in situ incubations over time (e.g, Ainley et al. 2009; Santora et al. 2017). Additionally, survey methods that use approaches for estimating fish abundance like the daily egg production method (DEPM; Lasker 1985), which was first developed by the CalCOFI program to support management of the northern anchovy (*Engraulis mordax*) fishery, require the ability to deploy both small plankton nets for egg and larval data collections, large trawl nets for adult specimen collection, and CTDs to support the collection of associated oceanographic data (Lasker 1985; Hunter and Lo 1993; Stratoudakis et al. 2006).

Platforms for deploying, testing, retrieving, refining, and validating observing system technology

Large research vessels facilitate technological innovation and subsequent evolution of the ocean observing system by providing a platform and mobile laboratory for testing, ground-truthing, deploying, maintaining, recovering, cross-comparing, and validating ocean observing technologies. Large research vessels serve as "innovation incubators" by providing opportunities for open ocean field testing, system refinement, and eventual scaling of ship-integrated or autonomous oceanographic sensors and instruments (Fassbender et al. 2017). Many new ocean technologies and methods begin with testing on a research vessel after extensive shore-based research and development, as these large research vessels provide the real-world conditions necessary to evaluate the durability, performance, and accuracy of instruments and sensors before wider deployment. For example, autonomous eDNA samplers have been tested in parallel with ship-based collections to validate the resulting data quantity and quality (e.g., Truelove et al. 2022). The feedback obtained from ship-based testing helps further refine and improve technologies supporting the evolution of ocean observing system components. After sufficient testing, the instruments can be expanded to autonomous platforms or citizen-science-based data collection approaches.

Large research vessels also ensure the persistent credibility of data from commonly relied upon platforms, instruments, and methods by validating their accuracy through direct comparison (Smith et al. 2019). Even though conductivity, dissolved oxygen, and fluorescence sensors are routinely deployed during ship casts and have improved significantly in their performance over time, it is common practice to validate them with shipboard observations to ensure the highest quality data are achieved (Smith et al. 2019). This can only be done through simultaneous at-sea collection and analysis of discrete water samples (e.g., conductivity, oxygen, chlorophyll a) using laboratory instrumentation, or by optimal preservation and storage of samples (e.g., for other phytoplankton pigments, organic matter characterization and optical/spectral characteristics) by trained technicians. For example, CalCOFI cruises have been used to validate the scientific instruments on Saildrones, ensuring that measurements such as $p\mathrm{CO}_2$, water samples, and ADCP currents are consistent and accurate (Parker 2017).

The ability of large research vessels to deploy numerous types of equipment also facilitates the comparison of different observing instruments and methods. For example, researchers recently compared deep-sea eDNA data collection with MOCNESS net trawl data collection to assess the efficacy of

Box 2. The power of repeated hydrographic and ecological samples: CalCOFI as a "gold standard"

A key role of large research vessels in ocean observing is their use in global repeat hydrographic cruises, which enables the detection of ocean change over time (Hood 2009). CalCOFI exemplifies the power of repeated samples over decades. As the world's longest-running integrated marine ecosystem monitoring program, CalCOFI has conducted hundreds of surveys over a vast region of the CCS since 1949 (Bograd et al. 2003; McClatchie 2014). These cruises extend nearly 500 km offshore, sampling in waters thousands of meters deep, and collect an extensive array of physical, chemical, and biological parameters. The value of CalCOFI lies in its long multi-disciplinary time series, which provides an unparalleled record of ocean conditions and marine life over decades. The length of the CalCOFI time series is sufficient to resolve both low-frequency climate variability and secular climate change, which is rare for marine observation systems.

For example, CalCOFI's long-term, repeated hydrographic surveys are essential for capturing the spatiotemporal variability of water mass contributions to the CCS and to understand how different water masses from the subarctic, subtropical, and tropical eastern Pacific interact within the CCS and influence regional conditions and how they shift with climatic phenomena like the El Niño-Southern Oscillation (ENSO) (Bograd et al. 2015; Bograd et al. 2019). CalCOFI offers the data necessary to quantify and understand complex physical-biological interactions within the CCS, linking large-scale oceanographic changes to regional biogeochemical and ecological impacts. Additionally, the long-term repeated samples have been used to examine the effect of climate variability and change on the phenology, assemblage structure, and diversity of larval fishes (Asch 2015; Thompson et al. 2022). Finally, continuous, high-resolution data are important in understanding and predicting fisheries stock dynamics. For example, CalCOFI provides essential baseline data on sea surface temperature (SST) and other environmental factors that influence fish populations, such as small pelagic fish (e.g., Pacific sardine, *Sardinops sagax*) that are influenced by climate dynamics (Lindegren and Checkley 2013). CalCOFI helped establish a relationship between SST and Pacific sardine stock productivity, which is crucial for developing accurate forecasts and effective harvest guidelines (Tommasi et al. 2017). Continuity of CalCOFI's data is crucial for understanding the impacts of climate variability and change on marine ecosystems and developing and refining "climate-ready" fisheries and other marine resource management strategies.

each method (Dan et al. 2024). Furthermore, synoptic, simultaneous data collection enables intercalibration studies, which are crucial for developing and understanding the relationships and biases among different methods and data sources. For example, many acoustic investigations rely on trawl or large plankton net data for target validation and demographic data collection, require oceanographic data to calibrate acoustic data, and use water samples for egg, larval, or eDNA collection to enhance the value of survey information (Zwolinski et al. 2014; Benoit-Bird and Lawson 2016; Malick et al. 2024).

Additionally, large research vessels offer personnel and operational support for safely deploying and recovering observing equipment (Table 3). Large moorings, like those used in climate ocean stations, and some Autonomous Underwater Vehicles rely on support vessels for deployment and retrieval (Dickey and Bidigare 2005). Additionally, many visual survey methods (e.g., remotely operated vehicles (ROV); human-occupied vehicles (HOV); towed camera sleds (TCS); and scuba divers) rely on large research vessels as support vessels for safe and efficient operations (Yoklavich et al. 2015). Large research vessels have substantial electrical capacity that enables real-time monitoring and control of autonomous systems (e.g., ROVs) during their missions and can power advanced oceanographic instruments which capture high-resolution data (e.g., imaging or video recorders) (Petillot et al. 2019).

Contributions to algorithm development, sensor calibration, and predictive modeling

High-quality observations from research vessels are routinely used to develop and advance remote sensing algorithms, calibrate and validate the performance of autonomous sensors, and evaluate and tune the numerical models relied on for regional-to-global scale forecasts, hindcasts, and projections (Table 3; Smith et al. 2019; Sloyan et al. 2019). The quality of information sourced from satellite products, autonomous platforms, and modeling centers is foundational to our confidence in nearly all facets of marine research and management, including climate change projections, ocean currents, hurricane forecasts, species distribution modeling, ocean acidification, primary productivity, and sea state (Smith et al. 2019). Maintaining and improving the quality of ocean information provided by satellites, autonomous platforms, and models requires a commitment to sustained, high-quality, global ocean observing data.

Satellite observations, and the data products they provide, have revolutionized how we view and study the surface ocean (Le Traon et al. 2015). The development of many satellite-based products used in ecosystem research, such as chlorophyll-*a* concentration, phytoplankton groups, net primary production, and export ratio, has leaned heavily, if not entirely, on ship-based observations (e.g., Werdell and Bailey 2005; Brewin et al. 2017; Westberry et al. 2023; Henson et al. 2011). Routine vessel surveys can be especially valuable

Table 3. Frequency of deployment, retrieval, servicing, and calibration of various oceanographic platforms using large research vessel. "Common" (green)/"Sometimes" (yellow)/"Rarely" (red) indicates platforms that are commonly (green)/sometimes (yellow)/rarely (red) deployed/retrieved/serviced from large research vessels or where the data from large research vessels are used in the calibration and cross-validation. Table adapted and expanded from concepts in Nieuwejaar et al. (2019).

	Moorings and buoys	Autonomous vehicles (AUVs, ASVs) and gliders	Floats, profiling floats, drifters buoyancy engine vehicles	Remotely operated vehicles (ROVs)	Human-occupied vehicles (HOVs)	Fixed platforms	Marine mammals as observers	Remote sensing devices (e.g., satellites, aircraft, drones)
Deployed, retrieved, or serviced from large research vessels	Common	Common	Common	Common	Sometimes	Sometimes	Rarely	Rarely
Data from large research vessels used in calibration or cross validation	Common	Common	Common	Common	Common	Sometimes	Sometimes	Sometimes

to the development of remote sensing algorithms and the subsequent testing of their performance over time. For example, CalCOFI's comprehensive and high-quality bio-optical and fluorometric pigment (HPLC—high-performance liquid chromatography pigments) data have been used to develop and evaluate foundational algorithms for the SeaWiFS standard products, which are used to monitor and study ocean color (Mitchell and Kahru 1998; Valente et al. 2022).

The recent proliferation of autonomous, expendable platforms that are capable of multi-year service lifetimes has presented new challenges for sensor data quality control. For example, the biogeochemical (BGC) Argo mission is an international effort to deploy profiling floats throughout the global ocean in waters deeper than 2000 m (Claustre et al. 2020). Biogeochemical floats carry sensors that measure temperature, conductivity, pressure, oxygen, nitrate, pH, particle backscatter, chlorophyll fluorescence (chl-f), and irradiance (Johnson et al. 2022), with profile measurements collected every 10 d and often over a period of five years. Though the floats spend most time at 1000 m depth and avoid intensive bio-fouling, many years is a long time for a sensor to maintain calibration. Thus, retrieving science-quality BGC sensor information depends on the availability of high-quality ship-based data that have undergone extensive quality control analyses, largely thanks to the Global Ocean Data Analysis Project (Lauvset et al. 2024). These ship data are used to train algorithms that can estimate biogeochemical properties from other more commonly measured properties, like temperature, salinity, and oxygen (e.g., Bittig et al. 2018; Carter et al. 2021). Such algorithms are routinely used to quality control pH and nitrate sensor data (Johnson et al. 2017; Maurer et al. 2021) over the lifetime of BGC Argo floats, and they are evaluated and retrained every few years to incorporate newly available high-quality observations from ships.

High-quality data from large research vessels are required to support numerical model development, calibration, validation, parameter estimation, and improvement (Capotondi et al. 2019). This enables the development of robust predictive tools for hindcasting (e.g., DeVries et al. 2023), forecasting (e.g., Mogen et al. 2023), and projecting (e.g., Fu et al. 2022) ocean biogeochemical or ecosystem phenomena. Recently, assimilative regional ocean models have become valuable for understanding subsurface dynamics while also producing estimates of ocean state (e.g., Neveu et al. 2016; Verdy and Mazloff 2017). For example, the physical and biological response of the CCS to El Niño-Southern Oscillation (ENSO) events was investigated using a high-resolution, "eddy-scale" ocean model known as the Regional Ocean Modeling System—North Pacific Ecosystem Model for Understanding Regional Oceanography (ROMS—NEMURO; Cordero-Quirós et al. 2022). The model's accuracy was assessed by comparing nitrate profiles from the model with those from CalCOFI observations (Cordero-Quirós et al. 2022).

Mobile platforms for experiential training, discovery, education, and collaboration

Large research vessels uniquely contribute to human exploration of the ocean, workforce development, training, education, and outreach (Treadwell et al. 1989; Sloyan et al. 2019; Smith et al. 2019; Schwing 2023; National Research Council 2009). Few other platforms offer the direct engagement with the open ocean that vessels provide, making them uniquely valuable for immersive learning and practical skill-building (Kanda et al. 2023; Wescott et al. 2024; Hardy 2017). Field-based experiences provide a first-hand introduction to marine research and practical knowledge of ship-based operations, while deepening understanding and appreciation of the open ocean (Wescott et al. 2024). By offering unique and practical learning experiences, large research vessels significantly contribute to the development of ocean professionals and foster the evolution of well-rounded experimentation and innovation that only hands-on, in-field experience can provide (National Research Council 2009).

The frequent, direct, and personal engagement between the science party and crew on research vessels, problem-solving as a team, and exchanging ideas in real-time can facilitate interdisciplinary learning and collaboration, significantly contributing to the development of ocean professionals (Osiecka et al. 2022; Satterthwaite et al. 2022). Given the important role that sea-going expeditions play in ocean sciences, it is especially important to ensure that research vessels are inclusive and welcoming spaces, where the physical and emotional safety of all ocean science professionals is prioritized (Wang et al. 2024; McMonigal et al. 2023). Due to the high interactivity, close quarters, cross-disciplinary nature, and extended duration of many cruises, scientific cruises can resemble a "mini-conference" or "intensive college course" in terms of intellectual exchange and capacity building. For instance, CalCOFI cruises bring together a diverse interdisciplinary scientific team that includes physical and chemical oceanographers, acoustic ecologists, marine microbiologists, plankton ecologists, fisheries oceanographers, ecosystem oceanographers, ornithologists, and marine mammalogists, to name a few (Box 2; Gallo et al. 2019; Gallo et al. 2022). This collaborative approach since 1949 has resulted in over 10,000 scientific publications on a range of topics from ENSO dynamics to the role of upwelling in nutrient cycling to fisheries early life history to marine mammal species distributions. Such breadth of research is only possible through ship-based observations that support sampling of the full range of co-located Essential Ocean Variables measurements (Miloslavich et al. 2018).

Some vessels place strong emphasis on science communication, outreach, and diverse engagement such as with educators, communicators, and other community members. For example, the NOAA's Teacher at Sea Program offers teachers hands-on research experience aboard NOAA research vessels (NOAA Fisheries 2024). Telepresence technologies have greatly increased engagement beyond what can be achieved on a research vessel and offer excellent educational tools to inspire students and the public about ocean exploration (Stephens et al. 2016; Marlow et al. 2017). The NOAA Okeanos Explorer broadcasts their expeditions online, enabling the public to watch live and recorded footage of ocean exploration (Martinez and Keener-Chavis 2006).

Toward a vision for a modern, sustained marine ecosystem observing system

Despite the numerous benefits of and critical importance of large research vessels to ocean science and sustainability (as highlighted in Fig. 3), they are costly, and in recent years, additional challenges have impacted their availability and sustainability. Increasing operational costs (e.g., new regulations, fuel, crew salaries, and repairs), an aging fleet, and shortage of skilled maritime professionals adds strain to the current infrastructure and significantly impairs the ability to support ship-based missions (UNOLS Fleet Improvement Plan 2019; Caesar 2024).

The costs associated with large research vessels include designing them for scientific use, building them, equipping them with instrumentation, operating them (e.g., salaries, fuel, and supplies), and maintaining and upgrading them throughout their lifecycle. Research vessels can have higher initial costs than other platforms, although the longer lifespan (e.g., 30–50 years) allows for the spread of these initial costs over several decades (Nieuwejaar et al. 2019). For instance, the R/V *Sally Ride*, an Ocean Class Auxiliary General Oceanographic Research vessel designed for multidisciplinary oceanographic research worldwide, cost $89 million USD to build in 2011 (Monroe 2014), which will equate to about $1.78 million USD per year assuming the maximum operational lifespan. By comparison, earth observing satellites collect a handful of parameters, such as sea surface temperature, salinity, ocean color, currents, and sea surface height, at a high spatial and temporal resolution, but cost much more than large research vessels and have shorter lifespans. For example, the Sentinel-3 cost about €305 million to build and deploy in 2008 (European Space Agency 2008) and has a lifespan of about 7.5 years (World Meteorological Organization 2025), which equates to about €47 million per year. Other smaller platforms like autonomous vehicles (AUVs), buoys, or floats often have much lower upfront costs, shorter lifespans (e.g., 3–5 years), and tend to collect fewer variables. For example, a Core Argo float, which is equipped to measure temperature, salinity, and pressure, costs approximately $20,000 USD (Argo 2025).

Additionally, operating a research vessel is more expensive than running many other platforms, with maintenance costs increasing with the vessel's age. Crew salaries can account

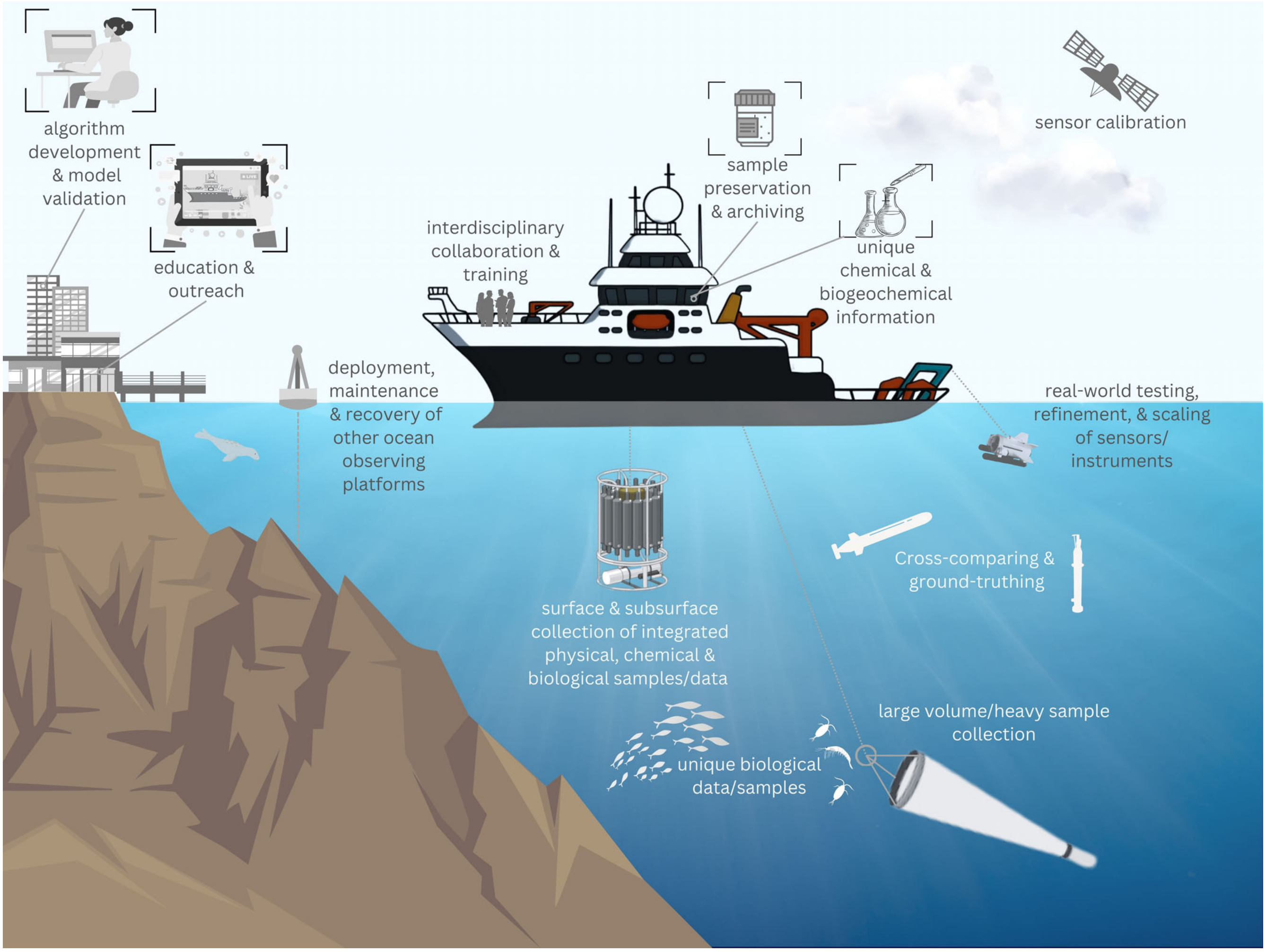


Fig. 3. The unique and essential role of large research vessels in the integrated ocean observing system.

for 40%–60% of the total operational budget, with varying costs due to crew size and national labor regulations (Nieuwejaar et al. 2019). Fuel expenses are another significant cost, ranging from 15% to 20% for open-water vessels to as much as 40% for polar research vessels. Other operational costs, including insurance, communications, harbor fees, and consumables, contribute about 25% to the total cost (Nieuwejaar et al. 2019).

Despite the lower daily costs of other platforms, research vessels can collect a diverse array of variables, which can significantly reduce the cost per variable collected. To illustrate the breadth of variables that can be collected by large research vessels, CalCOFI collects data concurrently on over 2500 unique variables—spanning physical, chemical, and biological observations—and has observed approximately 49,000 unique eDNA sequences. Other research campaigns likely capture even more information, so CalCOFI represents only a subset of the broad range of data that large research vessels can collect. For example, in 2024 the *R/V Sally Ride* supported about 17 other cruises besides CalCOFI, spanning research on ocean dynamics, geology, biogeochemistry, pelagic and deep-sea ecosystems; studies associated with instrumentation and calibration of oceanographic equipment; as well as cruises for outreach and education (UNOLS Marine Facilities Planning schedule). As an example, Saildrones cost about \$2500 USD per day to operate whereas large research vessels cost between \$30,000 and \$100,000 USD per day to operate (Voosen 2018; Cressey 2024). Assuming that Saildrones can collect about 15 variables (Saildrone 2020) and a large research vessel over 2500 variables (based on the CalCOFI cruise calculation above), the cost per variable per day comes out to \$166 USD for Saildrones compared with up to \$40 USD for large research vessels. This means that the cost per variable per day on large research vessels can be up to 75% less expensive.

Ultimately, the choice of platform and perceived cost-effectiveness depend on the specific goals, needs, uses, and types of data required. Research vessels uniquely serve as a large mobile platform for research and education and provide high-resolution, concurrent, multidisciplinary data. According to an analysis of datasets in the Biological and Chemical Oceanography Data Management Office (BCO-DMO), which houses chemical and biological measurements from publicly funded research projects, large research vessels collected 97% of all the parameters in BCO-DMO, whereas fixed stations collected 32%, buoys collected 11%, and AUVs collected 5% of all parameters in BCO-DMO (SeaDataNet p02 parameters). Additionally, 30% of the parameters in BCO-DMO are uniquely collected by large research vessels. The types of information that are unique to large research vessels support research, monitoring, and management across many fields and applications. These include water quality, ecosystem health, fisheries and ecosystem-based management, marine spatial planning, oceanography and ocean dynamics, climate variability and change, coastal and marine hazards, emergency response, pollution monitoring and mitigation, environmental impact assessments, calibration and instrumentation. However, it is important to note that BCO-DMO represents only a sub-sample of ocean data, as many other repositories serve marine ecosystem data. For example, most glider and float data are stored in other repositories, such as Argo data in the World Ocean Database.

Large research vessels can achieve numerous, unique objectives, can collect high quality data, can sample at any frequency, and can gather orders of magnitude more data types than other platforms, often simultaneously across multiple scientific domains. Thus, there is a strong desire to sustain ship-based time series to meet the growing demands for ocean information that is enabling the burgeoning blue economy (OECD 2016; Benedetti-Cecchi et al. 2018).

To ensure the sustainability and modernization of marine ecosystem observations, it will be important to address the challenges and find ways to enhance the cost effectiveness of large research vessels. This can be achieved by: maintaining and enhancing an adaptive fleet of large research vessels, embracing emerging technologies and methods for marine ecosystem data collection and analysis, leveraging the unique capabilities of large research vessels complemented by other observing platforms, strengthening collaborative partnerships, and building social capital for marine ecosystem observations through training, knowledge sharing, and effective governance.

Maintain and enhance an adaptive fleet of large research vessels to serve as the backbone for marine ecosystem observations

As current vessels age and demand grows, commitment to maintaining, retrofitting, and upgrading an updated fleet of large research vessels is vital for sustaining ship-based time series needed to advance our understanding of and to address the complexities of marine ecosystems (Weller et al. 2019). Adequately maintaining or upgrading existing large research vessels can help to minimize costs by extending their operational lifespan or expanding their operational capabilities to meet modern research needs.

Rapid advances in technology development, such as Artificial Intelligence, automation, robotics, quantum computing, genomics, nanotechnology/miniaturization, energy efficiency, and the Internet of Things, can be leveraged to enhance the capabilities and efficiency of large research vessels (Miller and Virmani 2023; Nieuwejaar et al. 2019). For example, energy-efficient technologies can help to reduce costs associated with fuel consumption and general operations. Energy-efficient vessels can include hybrid propulsion systems, in situ or renewable power sources, and advanced battery storage that can support extended missions with lower-carbon emissions (Green et al. 2019; Cavagnaro et al. 2020). For example, the American Bureau of Shipping recently approved a preliminary design of the world's first hydrogen-hybrid research vessel for UC San Diego's Scripps Institution of Oceanography that will utilize an innovative hydrogen fuel cell propulsion system (Fox and Wood 2024).

Embrace emerging technologies and methods for marine ecosystem data collection and analysis

Adopting new methods and technologies is crucial for advancing marine ecosystem data collection, analysis, management, and use (Schwing 2023). This can help to make ships more cost effective by enhancing the volume, quality, or coverage of data; decreasing the time to process or analyze data; or expanding the types of data collected. For example, recent developments in chemical and biological sensors, instruments, and genetic methods are making these tools more accessible, scalable, and cost-effective (Moore et al. 2009; Wang et al. 2019). This is advancing marine ecosystem observations by providing more detailed, efficient, and expansive monitoring of both biological and chemical processes in the ocean.

The combination of advancements in developing smaller and more efficient electronic components and improvements in battery technologies have enabled the miniaturization of sensor technologies, making it possible to deploy smaller sensors on more cost-effective platforms (Wang et al. 2019). Despite these advancements, challenges remain in enhancing sensor robustness, measuring several parameters from one sensor or platform, and further reducing costs to enable broader deployment. Many emerging sensor technologies that measure parameters previously only quantifiable in laboratory settings rely on frequent testing and calibration. As a result, both new and existing sensors, which are continually being refined or redeveloped, cannot be deployed for extended periods of time (Moore et al. 2009; Wang et al. 2019).

Additionally, eDNA sampling and analysis is an emerging technique that increases our ability to detect and quantify biodiversity in marine ecosystems (Chavez et al. 2021; Beng and

Corlett 2020). Environmental DNA enables the detection of species through genetic material in environmental samples, complementing traditional taxonomy by identifying species that are rare, cryptic, or otherwise challenging to detect. However, eDNA has some limitations including degradation and persistence of genetic material in the environment, lack of abundance information, detection bias, and limited detection rates (Beng and Corlett 2020). Environmental DNA methods were adapted from environmental microbiology, for which direct observation of small organisms (e.g., bacteria) is not possible and thus requires approaches for capturing cells on filters and extracting their DNA (Chavez et al. 2021). While microbiome sampling and analysis has had several decades of validation, recommended practices for collecting eDNA of larger organisms are actively being developed (e.g., Loeza-Quintana et al. 2020; De Brauwer et al. 2022; Shea et al. 2023); a process that relies heavily on seagoing platforms. For the past decade, CalCOFI has been advancing the field of eDNA approaches to characterize microbes, phytoplankton, zooplankton, fishes, and marine mammals and has incorporated such measurements into routine ocean observations (James et al. 2022; Dan et al. 2024; Satterthwaite et al. 2023a; Gold et al. 2024). Environmental DNA sampling can produce real-time data ("sequencing-at-sea") which can improve sampling efficiency and enhanced rapid genetics and optics-based data delivery allow for side-by-side validation with autonomous sampling (Truelove et al. 2019). Innovations in digital imaging and machine learning can assist in preliminary identifications, but the algorithms rely on taxonomists for guidance. Additionally, these tools cannot fully replace the nuanced judgments of experienced taxonomists, who are declining in number (Wägele et al. 2011; Sangster and Luksenburg 2015; Löbl et al. 2023).

Leverage the unique capabilities of large research vessels complemented by other ocean observing platforms

While large research vessels offer many unique, irreplaceable advantages that make them essential for collecting marine ecosystem observations (Fig. 3), some ship-based expenses can be reduced by augmenting or replacing certain shipboard measurements with a diverse array of more cost effective platforms (Tables 1, 2; Figs. 1, 2; Lin and Yang 2020). These platforms include vessels of opportunity (Rosa et al. 2021); smaller research vessels (Glenn et al. 2000), animal borne sensors (e.g., marine mammals as observers; McMahon et al. 2021); fixed platforms (e.g., piers, offshore structures; Glenn et al. 2000); moorings/buoys (Venkatesan et al. 2018); crewed vehicles (e.g., Human Occupied Vehicles—HOVs; Rona 1999); as well as a broad array of remotely operated and autonomous (uncrewed) vehicles (e.g., Remotely Operated Vehicles—ROVs, Autonomous Underwater/Surface Vehicles—AUVs/ASVs; Gallaudet et al. 2021) and mobile autonomous platforms (e.g., gliders, fleets or networks of floats and drifters, buoyancy engine vehicles) that operate on and within the ocean or in the air (e.g., uncrewed aerial vehicles—UAVs like aircraft, drones, satellites; Whitt et al. 2020). Such diversity of observing platforms can help to provide routine, high-resolution physical, chemical, and biological oceanographic context that supports the interpretation of sporadic ecological sampling that is often limited to ships (Figs. 1, 2; Whitt et al. 2020). For instance, gliders equipped with an array of sensors can complement ship-based sampling by conducting localized or short-term missions that do not require the extensive capabilities of a large research vessel or significant additional personnel time (e.g., Ren and Rudnick 2021). In the Arctic, estimates of krill density derived from acoustically equipped gliders were compared with ship-based surveys and demonstrated that the gliders could provide density estimates necessary to inform management (Reiss et al. 2021). Other observing platforms, such as small vessels and some autonomous vehicles, can complement large research vessels by accessing challenging or hard-to-reach areas, such as shallow water habitats, polar regions, or areas with offshore infrastructure (Whitt et al. 2020; Nieuwejaar et al. 2019; Gallaudet et al. 2021). For instance, the Argo program, initiated in 1999 (Johnson et al. 2022), maintains approximately 4000 floats throughout most of the global ocean ($\sim 3^{\circ} \times 3^{\circ}$) that are each equipped with temperature, pressure, and conductivity sensors and make vertical profile measurements every 10 d (Roemmich et al. 2019). Having a diversity of platforms is especially important in regions with growing blue economies, where diverse ocean uses, such as for fisheries, offshore energy, aquaculture, and military, can create a complex landscape of marine uses and accessibility (Rayner et al. 2019).

As some ship-based data streams are augmented or replaced entirely with other platforms or observing technologies, whether due to logistical (e.g., weather) or physical constraints (e.g., access limitations due to offshore infrastructure), financial, or other limitations, intercalibration studies are needed to sustain ship-based time series, and the data collected on different observing platforms need to be integrated to maintain comprehensive marine ecosystem observations (Hill et al. 2024).

Conduct intercalibration studies to sustain ship-based time series

As the oceans become more crowded, large research vessels may not be able to maintain the continuity of existing time series, which has the potential to introduce uncertainty and biases in survey data or could eliminate access for large research vessels in certain areas altogether (Haase et al. 2025; Hammerl et al. 2024). Intercalibration studies are essential to preserve the accuracy and reliability of long-term datasets as the ocean observing system continues to evolve toward increasing automation and novel observing components (Schwing 2023). For instance, if physical measurements from a long-term ship-based observing program are intended to be replaced by physical measurements from gliders, then contemporaneous and co-located CTD data from both the glider and the large research vessel are needed. Similar calibration concerns exist for fisheries surveys, as large research vessels may not be able to access large areas of ocean because of infrastructure development (e.g., offshore wind energy). These calibration data must be collected over sufficient spatial and temporal scales to ensure that the time series can be reliably sustained despite the transition to a new platform and data collection method. Innovations in networking capabilities between platforms, including Internet of Things-enabled devices, real-time communication, and data exchange between vessels and other ocean observing platforms, can also facilitate synoptic and coordinated measurements (Whitt et al. 2020). This proactive approach helps maintain existing, invaluable time series and ensures that transitions to alternative platforms do not compromise data quality.

Integrate data across different observing platforms to maintain comprehensive marine ecosystem observations

Effective sharing and integration of different types of marine ecosystem data from diverse platforms and instruments relies on integrated, federated data systems; standardized data formats and protocols; metadata documentation; and QA/QC (Snowden et al. 2019). Globally, such systems are managed through coordinating entities like the Regional Alliances of the Global Ocean Observing System, including EuroGOOS or the U.S. The Integrated Ocean Observing System (Révelard et al. 2022). These Regional Alliances, along with Ocean OPS and others, help to review and accredit observing system elements, to ensure they are meeting reasonable standards and practices and enable the FAIR use of data (Findable, Accessible, Interoperable, and Reusable; Tanhua et al. 2019). The Ocean Biodiversity Information System (OBIS) and the Global Biodiversity Information Facility (GBIF) are key national and international repositories for biological data. However, improved integration and interoperability are still needed to enhance accessibility and enable more comprehensive biodiversity assessments. Standardizing data formats and protocols can help to ensure compatibility and facilitate data sharing, and metadata documentation can support data integrity and traceability (Benson et al. 2018). Such practices allow for seamless integration of various data types, allowing for a holistic understanding of marine environments across space, time, depth, and ecosystem components. Further, advanced technologies, such as Artificial Intelligence and cloud computing, can enhance the processing of large, complex datasets enabling real-time access and analysis (e.g., Ditria et al. 2022).

Strengthen collaborative partnerships to share resources, infrastructure, and expertise

Creatively collaborating and bringing together different types of ocean observing resources is important to the sustainability of marine ecosystem observing systems (Révelard et al. 2022). Effective collaborative resourcing models are essential to sustain ecosystem ocean observations, which include leveraging shared financial resources from a diverse array of stakeholders for building, maintaining, operating, and updating large research vessels (Iwamoto et al. 2019; Weller et al. 2019). This can include across scales (e.g., international, national, and regional agencies), across the data value cycle (from data collectors to data users), across sectors (e.g., marine industries, government, academic, nonprofits/foundations), and across knowledge holders (e.g., tribes, Indigenous communities, citizen observers, maritime professionals) (Moltmann et al. 2019). Collaborative partnerships can make ship-based sampling more effective by pooling resources; providing access to expensive platforms, equipment, or tools that a single entity might not be able to afford alone; preventing redundant sampling efforts; increasing the value and impact of data collected by integrating data across geographies, regions, or parameters; and leveraging a variety of skills and expertise.

Programs are often sustained by a mix of government grants, private investments, and contributions from NGOs and philanthropies. For example, large ecosystem sampling programs, such as CalCOFI, have shared resources and maintained sampling through cross-organization and cross-project collaborations and diverse funding sources (Ohman and Venrick 2015). This collaboration extends to vessel use, where the CalCOFI program operates two cruises aboard ships managed by the NOAA Office of Marine and Aviation Operations and two cruises aboard the University-National Oceanographic Laboratory System vessels, such as the R/V Sally Ride. University-National Oceanographic Laboratory System is a consortium of academic, federal, and other organizations that facilitates the coordination, management, and operations of oceanographic research vessels. Additionally, the Integrated Ocean Observing System brings together a network of national and regional partnerships, across federal agencies, state and local organizations, research institutions, and private sector entities, to deliver high-quality ocean, coastal, and Great Lakes information. Integrated Ocean Observing System works closely with international initiatives like the Global Ocean Observing System which helps to coordinate ocean research efforts globally. These networks support shared infrastructure, resources, and data sharing making ocean data more comprehensive and accessible for different users and countries (Rayner 2010).

Build social capital for marine ecosystem observations through training, knowledge sharing, and effective governance

Building and sustaining social capital for marine ecosystem observing systems is necessary to increase the efficiency of ship-based research missions by fostering trust, improving coordination, facilitating knowledge sharing, and enabling effective decision-making. This is supported by training and professional development programs to keep knowledge up-to-date and enhance the capabilities of researchers, technicians, practitioners, and local community members involved in ocean observation efforts (Mori et al. 2023; Miloslavich et al. 2018). Knowledge sharing and capacity building are equally important since they promote the dissemination of best practices, methodologies, and technological innovations within the oceanographic community (Bodin and Crona 2008). Institutional frameworks and policies play a critical role in governing the operation and maintenance of ocean observing systems. These frameworks should be adaptable, responsive to evolving challenges, and capable of supporting effective governance structures (Bakker et al. 2019; Breckwoldt et al. 2021). Facilitating knowledge and data exchange among researchers, policymakers, industry stakeholders, and local communities is crucial for addressing diverse perspectives and needs and bringing value to marine ecosystem observations (Mackenzie et al. 2019). For example, bringing together information from different knowledge systems can help improve marine ecosystem management (Kaiser et al. 2019). By engaging these groups and establishing regular forums and workshops, stakeholders can discuss and shape the direction of ocean observing initiatives. Building trust, cooperation, and shared goals among these stakeholders ultimately strengthens the impact and sustainability of ocean observing systems, ensuring they effectively support informed decision-making and sustainable ocean management (Barnes-Mauthe et al. 2015).

Large vessels and small boats from various industries and private owners can serve as and carry observers for data collection, leveraging community-based observers (Schwing 2023). Some vessels, such as fishing and recreational boats, can also be outfitted or retrofitted with proper gear to deploy observing instruments akin to those on research vessels (Van Vranken et al. 2023). Sensors on vessels of opportunity and those used by recreational fishers and boaters facilitate opportunistic observations that increase data volume, even if the data are not collected systematically or over sustained periods (Rosa et al. 2021; Macdonald et al. 2024; Schmidt et al. 2019).

Because the distribution of marine resources and oceanographic processes are independent of country boundaries, international cooperation becomes a crucial part of achieving sustainable and inclusive growth on a global scale (Sampaolo et al. 2021; van Zyl and Myles 2020). For example, the IMECOCAL program (Investigaciones Mexicanas de la Corriente de California) learned from the experience of CalCOFI and started monitoring physical, chemical and biological variables in the California Current in 1997. Investigaciones Mexicanas de la Corriente de California occupies a grid of stations that were historically sampled in the early years of CalCOFI, expanding the spatial domain of the southern CCS that is currently sampled (Durazo 2003).

Conclusion

Large research vessels will likely remain at the core of any future ocean observing system, as globally distributed, high-quality ocean observations cannot be achieved without them (Fig. 3; Smith et al. 2019). They act as floating laboratories, offering a relatively stable platform for ocean exploration and the collection and preservation of large, heavy samples invaluable for in situ ecosystem data (Adler 2014). They are indispensable for simultaneous paired measurements, providing crucial physical, chemical, and biological data of high quality that cannot be adequately replicated with autonomous sampling in a manner that will preserve foundational marine time series (Hood 2009). High-resolution, long-term observations offer a unique window into marine ecosystem dynamics, but there is still a need to link these with social data to better understand the ocean as an interconnected social-ecological system (Hermes et al. 2019; Satterthwaite et al. 2023b). To maintain and enhance marine ecosystem observations, it will be essential to thoughtfully integrate new observing technologies, such as by ensuring sufficient intercalibration studies are conducted before replacing methods with new techniques (Schwing 2023). Vessels are the backbone of the ocean observing system, as many other ocean observing platforms rely on them for deployment, maintenance, and recovery (Dickey and Bidigare 2005). Beyond their technical contributions, large research vessels provide hands-on training, facilitate interdisciplinary collaboration, and foster education and outreach (National Research Council 2009). While autonomous and other platforms offer exciting possibilities for innovation and efficiency in marine ecosystem observing, they are complementary to, rather than fully able to replace, ship-based sampling (Whitt et al. 2020). As we enter an era of rapidly changing oceans and increased ocean use, large research vessels will continue to be important for ecosystem-based monitoring of the ocean and for effective management and understanding of our global ocean.

Author Contributions

Erin V. Satterthwaite and Brice Semmens conceived of the initial idea for the article. All authors contributed significantly to the revised concept and design of the article, as well as to the acquisition, analysis, and interpretation of the supporting information. Danie Kinkade and Adam Shepherd conducted the metadata analysis using datasets hosted by the Biological and Chemical Oceanography Data Management Office (BCO-DMO). Each author participated in drafting and revising the manuscript. Erin V. Satterthwaite and Andrea J. Fassbender created the figures with input of all co-authors. All authors approved the final version to be published. The final manuscript submission process and correspondence were managed by Erin V. Satterthwaite.

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Conflicts of Interest

None declared.

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