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Monitoring ocean biogeochemistry with autonomous platforms

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Abstract | Human activities have altered the state of the ocean, leading to warming, acidification and deoxygenation. These changes impact ocean biogeochemistry and influence ecosystem functions and ocean health. The long-term global effects of these changes are difficult to predict using current satellite sensing and traditional in situ observation techniques. Autonomous platforms equipped with biogeochemical sensors allow for the observation of marine biogeochemical processes and ecosystem dynamics, covering a wide range of spatial and temporal scales. The international Biogeochemical-Argo (BGC-Argo) project is currently building a global, multidisciplinary ocean-observing network of autonomous Argo floats equipped with an extensive range of biogeochemical sensors. Other autonomous platforms, such as gliders and surface vehicles, have also incorporated such sensors, mainly operating on regional scales and near the ocean surface. Autonomous mobile assets, along with remotely sensed data, will provide the 4D information required to improve model simulations and forecasts of ocean conditions and ecosystem health.

Anthropogenic activities are rapidly changing the oceans, contributing to ocean warming, acidification, eutrophication, pollution, deoxygenation, nutrient flux reduction, vital habitat destruction, declining fishery resources and an increasing number of endangered marine species[1]. Recent observation-based estimates show that the ocean has been undergoing rapid warming over the past few decades, and that the rate of warming has increased[2]. Ocean warming has been linked to increases in rainfall intensity in tropical regions, declines in ice sheets, glaciers and ice caps in the polar regions, rising sea levels, enhancement of ocean stratification and a decrease in primary production[3]. Ocean-ecosystem health responds to anthropogenic activities in general through transforming the dynamics of marine organisms, altering the rate of the carbon cycle and changing marine-animal behaviour[4].

The upcoming United Nations (UN) Decade of Ocean Science for Sustainable Development marks a global push towards collecting comprehensive observational data for biogeochemical processes in order to encourage the sustainable development of the ocean. However, marine ecosystems and biogeochemical cycles are complex, involving a range of physical processes, such as wind-driven mixing, convective mixing, upwelling, downwelling, isopycnal mixing, diapycnal diffusion and horizontal advection, chemical processes, such as air–sea CO_2 exchange, ocean acidification and deoxygenation, and biological processes, such as primary production, phytoplankton growth and loss, and zooplankton grazing[5–8]. Many of these complex processes cannot be observed using only traditional observation platforms, such as ships and moorings.

To address the limitations of existing observation methods, new sensor technologies for conducting biological and biogeochemical measurements are being developed and equipped on novel observational platforms, such as autonomous mobile platforms[9]. Together with more traditional observation methods, these new platforms can collect data to assess the changes in biogeochemical and physical properties of the ocean on global and decadal scales[10,11].

In this Perspective, we explore the application of autonomous platforms in assessing ocean biogeochemistry and ecosystem health. We first review traditional methods used for observing ocean biogeochemistry. Then, we discuss the demand for conducting observations to resolve marine biogeochemical and ecosystem spatial and temporal variations. We present current examples of the use of multiple autonomous mobile platforms and how different platforms are used synergistically. Finally, we describe the approaches for applying 4D data to monitor and forecast ocean biogeochemistry and ecosystem health.

Traditional ocean observations and challenges

The use of observing platforms has evolved over the past century (FIG. 1). Early motivations for using such platforms were to investigate the productivity of the ocean, and fisheries in particular, to mitigate marine destructive events, such as typhoons and tsunamis, and to study geography[12]. Whereas ships and moorings were the platforms of choice to survey the ocean, recently, the application of remote sensing has greatly improved the spatial coverage of the entire ocean to near real-time. In this section, we describe existing ocean-observing platforms and their related applications and challenges.

Shipborne observations. Oceanographers historically collected data from the ocean and seafloor using ships during cruises of limited duration. This expeditionary research approach has resulted in major advances in our understanding of the global ocean. The *HMS Challenger* expedition in the 1870s pioneered the concept of a systematic global survey of the subsurface ocean, measuring the physics and chemistry of seawater and collecting biological samples at hundreds of sites. Later efforts, such as the Geochemical Ocean Sections Study (GEOSECS) in the 1970s, the World Ocean Circulation Experiment (WOCE) in the 1980s and 1990s, and the ongoing Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) (FIG. 1), have improved global coverage and included measurements of

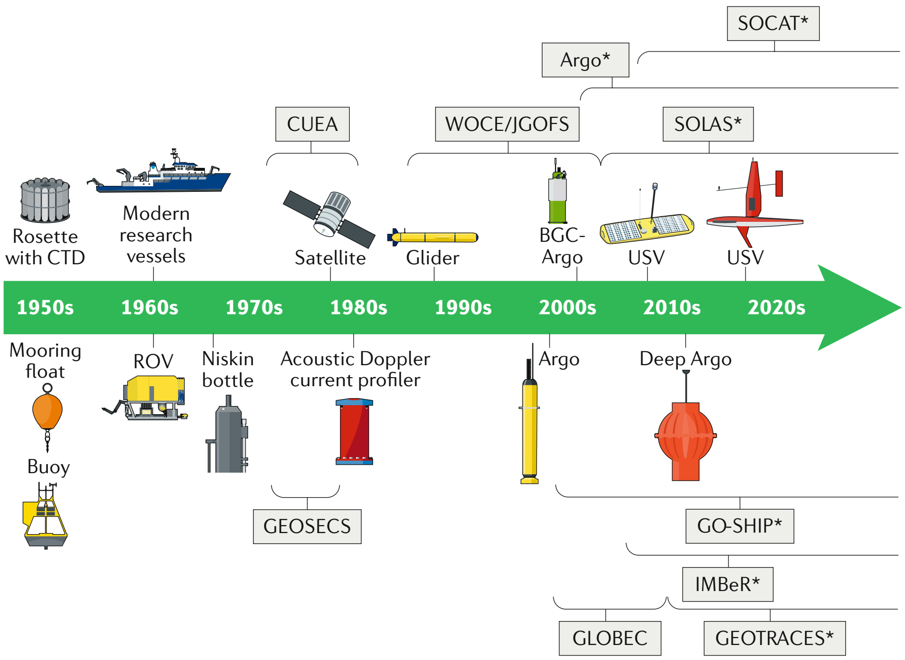

Fig. 1 | **Timeline of oceanographic observation platforms and international projects measuring marine biogeochemistry.** International project durations are indicated with brackets. Ongoing projects are denoted with an asterisk (*). BGC-Argo, Biogeochemical-Argo; CTD, conductivity, temperature and depth; CUEA, Coastal Upwelling Ecosystems Analysis; GEOSECS, Geochemical Ocean Sections Study; GLOBEC, Global Ocean Ecosystem Dynamics; GO-SHIP, Global Ocean Ship-based Hydrographic Investigations Program; IMBeR, Integrated Marine Biosphere Research; JGOFS, Joint Global Ocean Flux Study; ROV, remotely operated underwater vehicle; SOCAT, Surface Ocean CO_2 Atlas; SOLAS, Surface Ocean Lower Atmosphere Study; USV, unmanned surface vehicle; WOCE, World Ocean Circulation Experiment.

biogeochemical variables, such as nutrient concentrations and the carbonate system[13]. Research and industry partnerships have also supported networks of autonomous physical and chemical measurements on ships of opportunity, such as in the Surface Ocean CO_2 Atlas (SOCAT) since 2007 (REF.[14]). Shipborne observations have allowed the discovery of large spatial variations in productivity through the identification of phenomenon such as high-nutrient, low-chlorophyll zones[15] and the oligotrophic gyres[16]. More recently, the GEOTRACES programme has identified processes and quantified fluxes that control the distributions of key trace elements and isotopes in the oceans[17], and the Tara Oceans project has shown the enormous taxonomic diversity of photosynthetic microorganisms in the surface ocean[18].

However, ship-based observations are limited by their spatial and temporal coverage, and can be prohibitively expensive, such that only a limited number of cruises can be conducted at any given time. Cruises can also be constrained by extreme weather conditions, particularly during winter; as a result, ship-based observations can be sparse and strongly biased towards summer-season sampling.

Sustained, fixed-location observations. Modern ocean moorings have evolved from the weather stations established in the 1940s (REF.[19]). By the 1980s, moorings had become critical platforms, enabling studies into ocean biogeochemistry and the role of the ocean in influencing climate and weather[20]. Data from historical stations such as Ocean Station Papa and ALOHA revealed ecosystem responses to the El Niño–Southern Oscillation events[21], global warming[22] and ocean acidification[5]. Moorings now provide the backbone of many of the global ocean networks used for studying ocean–atmosphere interactions[23,24] and for characterizing marine-ecosystem changes[25,26], particularly in coastal waters[27]. OceanSITES, a worldwide system of open-ocean reference stations, coordinates time series of global mooring observations and serves as a global long-term network[26].

Fixed-location moorings will continue to be a key element of ocean-observing infrastructure, providing high-frequency subsurface data to supplement data collected by ships, autonomous vehicles and satellite remote sensing. A disadvantage of these systems is their high maintenance cost, which severely limits the number of systems that can be deployed. Furthermore, sensors are often located at fixed depths, and instruments near the surface are subject to biofouling. Thus, despite being an ideal platform for collecting high-resolution times series, fixed-location moorings are ineffective at providing large-scale spatial coverage or tracing the movement of different water masses.

Remote sensing. Satellites are an important innovation in oceanographic technology[28]. A range of satellite observing systems is available, including active scatterometers, microwave spectrometers, radiometers, microwave imagers, altimeters and probes for advanced gravity missions. Ocean-colour satellite observation systems started with the launch of the Coastal Zone Color Scanner (CZCS) in the late 1970s, which provided the first global view of phytoplankton distribution[29]. Global ocean-colour data have been recorded continuously since the SeaWiFS project began in 1997, sustained by the MODIS-Aqua, MERIS, VIIRS and OLCI sensors[30]. In the past four decades, satellite observations have resulted in numerous advances in our fundamental understanding of the ocean through resolving global features associated with the mesoscale circulation of physical and biological properties[30,31].

Satellite observations can be used to estimate long-term trends in marine-ecosystem change at both basin and global scales. Satellite remote sensing has shown that global chlorophyll *a* is decreasing (REF.[32]), especially in the subtropical gyres[33], and that oligotrophic areas of all oceans are expanding[34]. The response of primary producers to climatic oscillations, ranging from intraseasonal[35] to multidecadal scales[36], has been clearly shown by satellite imaging, in particular, following El Niño–Southern Oscillation[37]. Unfortunately, satellites have limited capabilities for resolving features below the ocean surface. The presence of clouds can also interfere with some satellite sensors; this is especially problematic for cloudy regions, such as high-latitude oceans, which play a predominant role in driving global biogeochemistry[38]. At high latitudes, data from ocean-colour satellites often contain large gaps in winter, owing to low sun angle and increased cloudiness[39].

Needs in ocean observation

Due to the limitations of traditional observing systems, there is a need for new systems capable of resolving complex, multiscaled biogeochemical phenomena.

Observing the ocean requires large spatial coverage, high temporal sampling frequency and capability to conduct measurements at depth with high vertical resolution.

Spatial coverage. Compared with traditional in situ observations by ships and moorings, the greatest strength of autonomous-platform networks is their capacity to conduct multiscale and cross-disciplinary measurements. Such resolution is critical, as biogeochemical processes and associated dynamics can vary largely in scales; for example, basin-scale phytoplankton growth can be influenced by the atmospheric transport and deposition of Asian dust-associated iron tens of thousands of kilometres away[40].

In recent years, mesoscale and sub-mesoscale data have been increasingly acquired by Biogeochemical-Argo (BGC-Argo) project floats, gliders and unmanned surface vehicles (USVs)[41–47] (FIG. 2). Data from such autonomous platforms have rapidly improved our understanding of relationships between physical and biogeochemical processes. This is particularly true for observations from gliders, as they are capable of adaptive sampling through eddies and fronts. Based on glider data and model interpretations, Mahadevan et al.[47] showed that mixed-layer dynamics can be driven by sub-mesoscale processes and, conversely, patchy blooms can be triggered when the mixed-layer depth is abruptly shoaled due to eddy-driven restratification. Another study combining BGC-Argo and glider observations found that sub-mesoscale physical processes are also likely to affect algal-community composition, as more diatoms appeared in the patchy bloom areas than outside them[43]. BGC-Argo float and glider data have shown that sub-mesoscale subduction induced by eddy pumping can contribute to the biological carbon pump, transferring dissolved and particulate organic matter from the surface into the mesopelagic zone[45,48]. Integration of meteorological measurements with biogeochemical measurements by USVs can also help to determine how strong atmospheric forcing and mesoscale physical processes drive ocean biogeochemistry[49].

A global array of 1,000 BGC-Argo floats can capture a snapshot of the global upper-layer biogeochemical and ecosystem state every 10 days, which is higher in sampling frequency and much less costly than ship-based surveys[50]. For example, the Global Ocean Data Analysis Project Version 2 (GLODAPv2), a ship-based survey comprised of 724 cruises between 1972 and 2013, collected data from 52,317 stations globally[51]; a global BGC-Argo array would be able to surpass this total number of temperature, salinity, chlorophyll *a*, nitrate concentration, pH and oxygen profiles in only 2 years[11].

Some high-density networks capable of wide-ranging spatiotemporal coverage are already active on a regional scale. In the Southern Ocean, 35 BGC-Argo floats have revealed discrepancies in air–sea CO_2 fluxes in various sub-provinces and during different seasons[52]. In the Mediterranean Sea, data taken from 39 BGC-Argo floats between 2012 and 2017 have improved the performance of a pre-existing regional biogeochemical model[53]. On a global scale, more than 100 BGC-Argo floats produced the first global bio-optical data set (chlorophyll *a*, particulate backscatter and spectral radiometry) in order to address differences in regional distribution in bio-optical properties[54], regional discrepancies in photoacclimation effects on phytoplankton chlorophyll-to-carbon ratios[55] and global distribution of non-algal particles[56].
The large-scale observations made by the BGC-Argo array allowed characterization of biogeochemical provinces and biomes, and potentially provides data for improving biogeochemical model performance, as well as the calibration and validation of satellite measurement systems.

Vertical coverage. As ocean satellite measurements are limited to the surface ocean, there is a need to extend biogeochemical observations throughout the water column[57]. For example, the biological carbon pump has an important role in transferring atmospheric CO_2 from the sea surface, through the water column

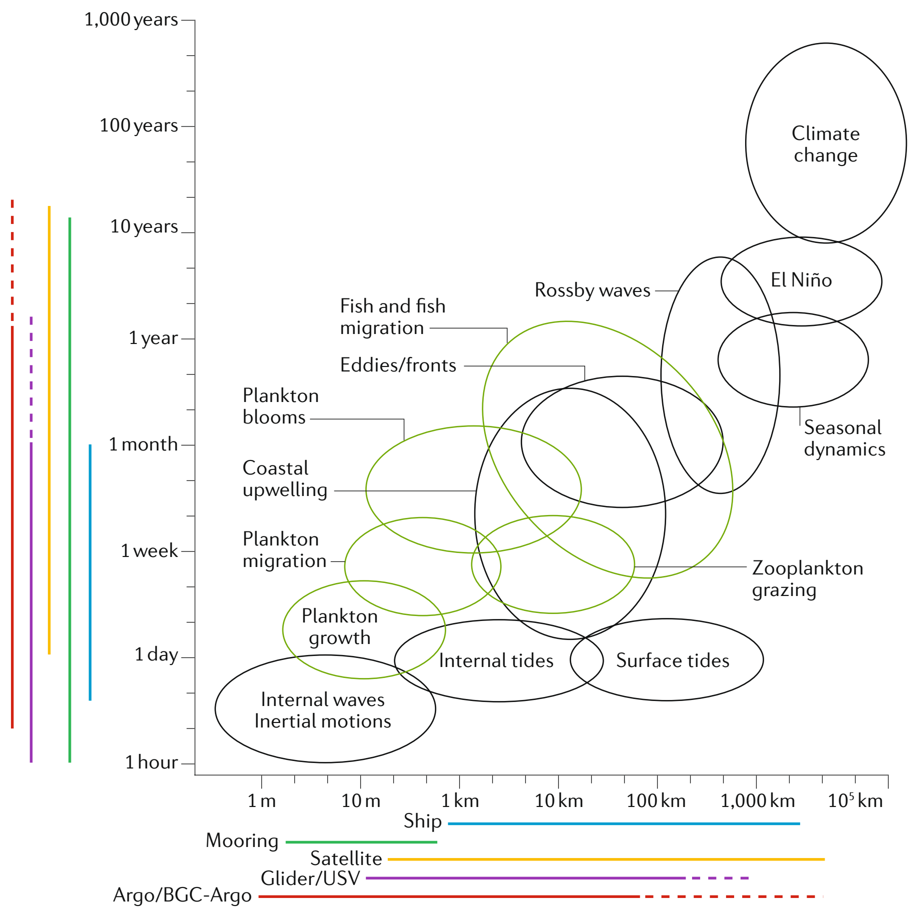

Fig. 2 | **Measuring across spatiotemporal scales in marine systems.** Spatial and temporal scales of marine dynamic and ecosystem processes, and the measurement capabilities of different observational platforms. Dynamic and/or physical processes are represented by black circles and biological and/or ecological processes by green circles. The presence of new autonomous platforms, such as Biogeochemical-Argo (BGC-Argo) floats (red line) and gliders and similar unmanned surface vehicles (USVs) (purple line), fill the cross-discipline and cross-scale observational gaps left by traditional observation methods such as remote sensing by satellite (yellow line), moorings (green line) or ship-based observations (blue line). Dashed lines indicate potential extension of an observational network. Data from REF.[179]. Adapted with permission from REF.[180], Elsevier.

and into the ocean interior, and, thus, is responsible for modulating climate change and supporting deep-ocean ecosystems. Studies on the efficiency of the pump, and related physical–biogeochemical coupling processes, now rely heavily on the observations from autonomous platforms[58–63]. BGC-Argo and gliders are excellent tools for resolving physical and biogeochemical variables in various oceanic conditions, as they are operational in both open and deep oceans (>1,000 m), and gliders can also operate in marginal seas (<1,000 m). Moreover, autonomous platforms equipped with transmissometers can operate in drifting mode as 'optical sediment traps' and can directly and accurately observe particle sedimentation on daily to weekly scales with higher frequency than traditional sediment traps that operate at monthly scales[64].

Temporal coverage. Autonomous platforms can fill some of the important temporal continuity gaps inherent with traditional platforms, improving observation frequency in the open ocean from monthly or seasonal to daily and weekly timescales. USVs such as saildrones and Wave Gliders can perform continuous observation of sea-surface biogeochemical properties, such as $p\mathrm{CO}_2$, dissolved oxygen, pH, chlorophyll *a* concentration and air–sea carbon flux[65,66]. As autonomous platforms can operate in harsh environments, even operating underneath sea ice[52,67,68], they are capable of recording continuous time series at high latitudes under all-weather conditions; these data can fill the temporal gaps seen during winter using satellite-based observations[52,69–71].

Rapid weather changes can lead to transient ecosystem responses not captured by ships or satellites. For example, a large number of BGC-Argo observations have revealed that rapid changes in mixed-layer depth could efficiently pump particles from the surface ocean into deep waters[59,60]. A BGC-Argo float in the Bay of Bengal recorded subsurface chlorophyll *a* enhancement after a tropical cyclone induced regional upwelling and turbulent mixing; the surface chlorophyll *a* bloom was attributed to the combined effect of subsurface chlorophyll *a* entrainment and nutrient injection[6].

Autonomous platforms

The presence of new autonomous platforms, such as Argo floats, gliders and USVs, fill the cross-disciplinary and cross-scale observational gaps described above, providing revolutionary insights into ocean biogeochemistry and marine ecosystems.

Argo floats. The profiling float, a modern instrument that is complementary to ship-based systems, was first used in prototype form, carrying only temperature and pressure sensors, during the WOCE[72]. Large-scale deployments with commercially prepared instruments commenced in 1999 (REF.[73]). The float uses an inflatable, oil-filled bladder to change its buoyancy, in order to vertically profile from the sea surface to depths of 1,000–2,000 m, a process that occurs over the course of ~10 days[72]. Data are reported in near real-time using a satellite link and recent versions are outfitted with conductivity, temperature and depth (CTD) instrumentation. Presently, ~4,000 profiling floats are collecting publicly available, real-time observations, providing a synoptic view of the ocean interior every few days as part of the international Argo programme[74]. Some profiling floats have also been adapted to extend observations to deeper oceans or shallower marginal seas, including deep Argo floats reaching 6,000 m (REF.[75]) and coastal Argo floats with fast observation time and anti-drift capabilities[76].

Modern versions of Argo floats (FIG. 3a) used in the BGC-Argo network are equipped with a variety of additional physical, chemical and bio-optical sensors, such as an optode for oxygen sensing, ultraviolet spectrophotometers for measuring nitrate concentrations, electrochemical sensors for pH measurements, chlorophyll *a* fluorometers, scatterometers and radiometers[77]. Throughout the ocean, including in ice-covered regions, floats can operate for between 2 and 7 years after launch, depending on battery usage[50,78]. Using a global network of sensors greatly enhances the probability of encountering transient phenomenon such as carbon export by mixed-layer pump processes during the late winter–spring transition[60,79], episodic responses of dissolved oxygen during tropical cyclones[8] and blooms induced by restratification[80]. Recently, the first observational evidence of a hydrothermal-vent-triggered bloom was captured by BGC-Argo floats in the Southern Ocean, revealing that iron from hydrothermal vents can play an important role in modulating surface primary production[7].

Profiling floats can also be used for long-term data collection. A recent study on nitrate measurements, using data collected from Ocean Station Papa in the North Pacific, demonstrated interannual changes in nitrate concentration, which lead to significant changes in ecosystem functions[81]. They enable predictions of ocean health, including fishery yields. However, Argo floats are limited by the available sensor technology[82] and by sensor offsets and drifts[77]. Moreover, unlike moorings, Argo floats drift passively and, therefore, cannot remain at a fixed location, making long-term observations of a single location difficult.

Gliders. Gliders (FIG. 3b) are similar to Argo floats and operate using similar buoyancy engines[83]. Some gliders are equipped with wings that can translate some vertical movement through the water column into horizontal movement; an adjustable weight inside the glider allows the platform to be steered automatically in order to fulfil spatial requirements for measurements. Gliders use the Iridium global telecommunications network to transmit data to shore-based servers and receive commands for future actions from shore-based personnel when at the surface[84]. Consequently, gliders can conduct uninterrupted missions for up to a year; however, most deployments are shorter in duration, as these systems generally operate continuously, whereas profiling floats sleep for up to 10 days between profiles.

With the ability to carry many diverse sensors (TABLE 1), gliders effectively collect and integrate information related to the physics, chemistry and biology of the ocean[85]. Unlike Argo networks, gliders mainly sample on continental shelves and reveal energetic features of the coastal oceans. Furthermore, their adaptive capabilities allow for sampling of subsurface ocean features that cannot be observed from satellites, such as thermoclines, nutriclines and the deep chlorophyll maximum[41]. Gliders can even collect and transmit ocean data from within hurricanes[86], making them well suited for storm research. Much of the uncertainty in storm forecasts is caused by storm-induced ocean mixing processes, which can alter the storm's intensity at landfall[86]. Given that gliders can adjust their positions dynamically, national agencies are now exploring how gliders might provide a network that can be adaptively positioned during a storm's approach to fill data gaps from traditional methods. Use of gliders in this way could allow more accurate forecasting of storm trajectory and intensity. However, operational time during deployment is limited by the glider's battery life[87].

Unmanned surface vehicles. USVs, including saildrones and Wave Gliders, are capable of basin-scale observations of meteorological variables and surface ocean conditions. A number of USVs are in various stages of development and use (FIG. 1), with the majority of testing done by the Tropical Pacific Observing System (TPOS) and Innovative Technology for Arctic Exploration (ITAE)[66].

A saildrone (FIG. 3c) is a 7-m-long USV with a 5-m-high wing, which uses wind for propulsion and solar energy for powering its sensors[44]. Meteorological sensors are mounted on the wing of the saildrone, and oceanographic sensors are present in the hull and keel. Saildrones are capable of measuring air temperature, barometric pressure, relative humidity, solar irradiance, wind speed and direction, sea-surface temperature and salinity, ocean colour, dissolved oxygen, pH, and atmospheric and seawater pCO_2, and can use active acoustics to measure currents, bathymetry and fish, and passive acoustics to measure ocean noise caused by marine mammals and subsea volcanoes. Adaptations can be made for extreme environments; the current fleet of ~70 saildrones, active since 2015, has been operating in the Arctic[49,88,89], Southern Ocean, western boundary currents and coastal waters.

New USV designs such as Wave Gliders (FIG. 3d) show promise for operating in extreme currents, wind and wave conditions in western boundary currents and high latitudes, where air–sea observations are currently undersampled[90,91]. The surface float of the Wave Gliders that hold the sensor package are 2–3 m long and are propelled by the conversion of ocean wave energy into forward thrust independent of wave direction through subsurface wings at 8 m depth tethered to the float. Wave Gliders have been utilized on several repeat observing missions[92], but, although subsurface measurements have been made on the Wave Glider's 8-m-depth wings, sampling of subsurface waters is a current limitation of surface vehicles.

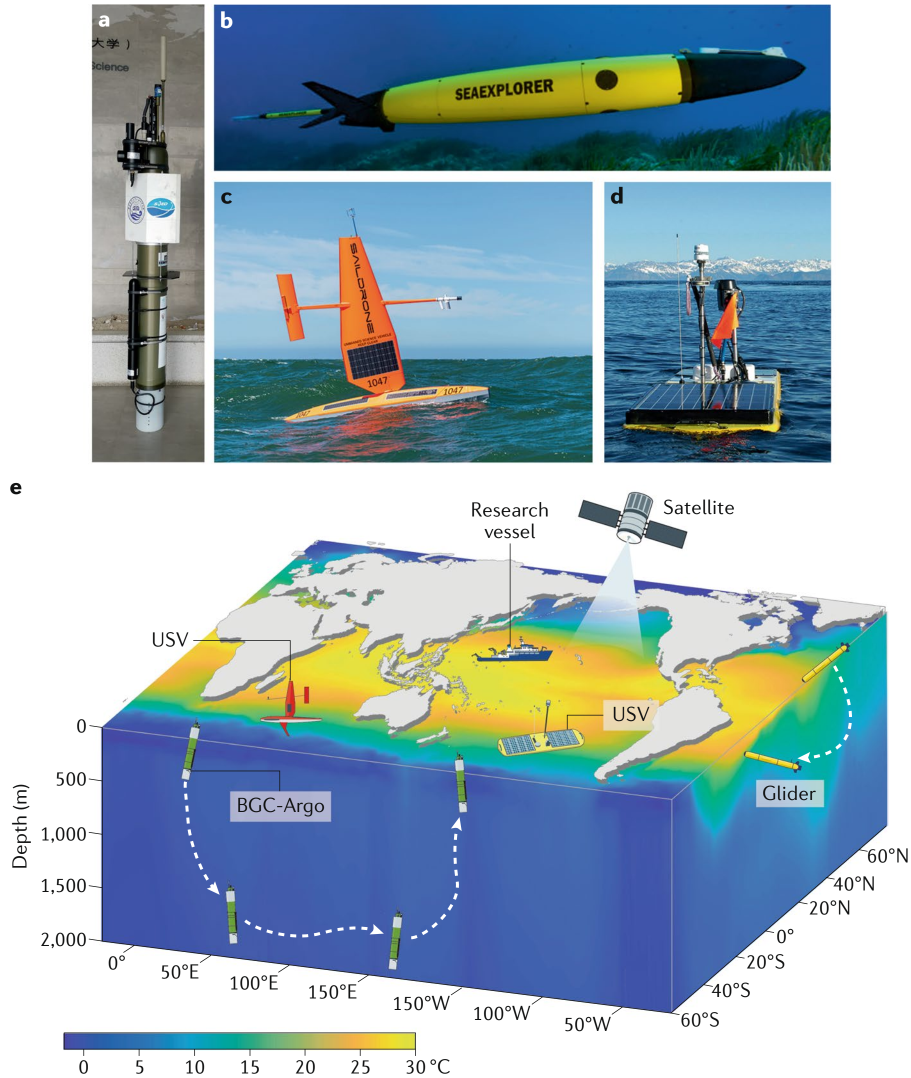

Fig. 3 | **Four available ocean-observation platforms and example areas of operation. a** | A typical Biogeochemical-Argo (BGC-Argo) float. **b** | A glider. **c** | A saildrone (a type of unmanned surface vehicle (USV)). **d** | A Wave Glider (a type of USV). **e** | A schematic diagram of ocean-observation-platform operations, along with research vessels and satellites. Traditional shipborne platforms provide fundamental reference data for many biogeochemical variables across all platforms, and satellite sensing provides the continuous spatiotemporal coverage of sea-surface variables. The Argo and BGC-Argo arrays measure ocean variables through the water column, with all floats reaching up to 2,000 m. Gliders are more suitable for observation at various depths in coastal and shallow oceans, whereas USVs provide air–sea flux data. Panel **b** reprinted with permission from ALSEAMAR. Panel **c** reprinted courtesy of Saildrone. Panel **d** reprinted with permission from NOAA PMEL/Evans (Hakai Institute).

Biogeochemical sensors on autonomous platforms. A novel ensemble of biogeochemical sensors capable of operating on floats, gliders and USVs is now available (FIG. 3e) and has been used on hundreds of profiling floats[93,94] and regional and global networks of gliders[85,95]. Some other sensors have also been equipped on gliders[96,97] and USVs in specific cases[98]. Available sensors are listed in TABLE 1.

New sensors are currently in development; alkalinity sensors[99], for example, could complement already operational pH sensors to robotically estimate CO_2 flux with lower uncertainty than present statistical methods[100,101]. Imaging techniques, as well as active acoustic systems, are presently being developed and tested to better quantify organisms in higher trophic levels, such as zooplankton and mesopelagic fishes. Their applications in the near future could help investigate critically undersampled components of ecosystems and biogeochemical cycles, potentially representing neglected biomass and food resources[102,103]. Finally, passive acoustic sensors have the potential to measure meteorological properties[104,105], as well as anthropogenic noise and mammal presence[89,106–108]. A global integrated observational system, equipped with a large variety of sensors, is now capable of fulfilling the need for multifunctional and multidisciplinary sampling from marginal seas to open oceans and from the surface to the deep ocean.

Current mobile platform networks

The establishment and development of global and regional observation arrays of multiple autonomous platforms will aid

Table 1 | **Major observed biogeochemical properties on mobile platforms**

Observed property	Sensor	Platforms applied	Ref.
Dissolved oxygen	Luminescence lifetime optode sensor	All autonomous platforms	138
pCO_2	NDIR spectrometer	USVs	98
	Equilibration-based infrared gas analyser	USVs	66
Nitrate	Ultraviolet spectrophotometer	Argo floats, gliders	175
pH	Ion-sensitive field-effect transistor	All autonomous platforms	176
Particulate backscattering coefficient	Optical backscatter	All autonomous platforms	82
Particulate beam attenuation coefficient	Optical transmissometer	Argo floats	64
Chlorophyll *a* concentration	Fluorometer	All autonomous platforms	144
Single-channel CDOM fluorescence	Fluorometer	All autonomous platforms	177
Multichannel CDOM fluorescence	Fluorometer	Gliders	97
Downwelling irradiance and PAR	Radiometer	Argo floats, gliders	54
Presence of zooplankton, fish and mammals	Echo sounder	Gliders and USVs	96
Zooplankton size and species	UVP	Argo floats	178

CDOM, coloured dissolved organic matter; NDIR, non-dispersive infrared; PAR, photosynthetically available radiation; pCO_2, carbon dioxide partial pressure; USV, unmanned surface vehicle; UVP, Underwater Vision Profiler.

the development of 4D data sets to inform and constrain oceanographic models.

Global BGC-Argo array. The BGC-Argo programme is in charge of planning and managing global deployment of BGC-Argo floats, with the goal of conducting global measurements of biogeochemistry and ecosystems. The science and implementation plan identified from the Biogeochemical-Argo Planning Group[93] proposed that an initial step was to carry optical and chemical sensors to support the assessment of biogeochemistry and ecosystems in a changing ocean. At OceanObs'19, a multidisciplinary global ocean-observation-system conference, the specifics of BGC-Argo implementation were refined. The revised plan aims for better interaction and synergy with the global Argo programme, allowing the development of a long-term vision for Argo, defined as 'global, full-depth, and multidisciplinary'[11,50].

The initial target size for the BGC-Argo array is 1,000 floats[93], a goal based on modelling[109] and in situ data analysis[110,111]. The BGC-Argo array currently consists of over 350 floats reporting data regularly, fostering interdisciplinary studies that range from the tropics to high latitudes (FIG. 4). It is becoming an essential component of the global observing network proposed for the next decade and will transform our ability to systematically observe, document and understand changes of ocean environment and marine ecosystems. However, there are some drawbacks associated with the BGC-Argo array. As Argo floats move passively with currents, it is possible floats could drift into an exclusive economic zone (EEZ), which can cause legal issues that could delay data transfer. Moreover, operation of Argo floats is expensive; the average lifetime of a float is ~4 years, and the yearly global cost of a sustained BGC-Argo array is estimated to be ~US $30 million[93]. Improving Argo technology to extend its average working lifetime is an important target for the future and could proportionally reduce running costs[50].

Regional arrays of other autonomous platforms. Similar to BGC-Argo, gliders are being used by an international community through the Boundary Ocean Observing Network (BOON)[95], which is also in the initial phases of incorporating USVs into the network[112] (FIG. 4). In the northeast Pacific, two regular glider lines have operated since spring 2006 (REFS[113,114]), supported by the Ocean Observatories Initiative (OOI). These gliders measure major biogeochemical variables, such as oxygen, chlorophyll *a*, coloured dissolved organic matter (CDOM) fluorescence and particulate backscattering[115]. Sustained glider deployments also monitor upper-ocean conditions in areas frequently impacted by tropical cyclones[116–118], which have been an important part of the NOAA Hurricane Field Program[119]. The OOI also sustains a long-term glider line in the USA east coast, focusing on frontal processes[120,121]. Gliders have been deployed in high-latitude oceans and all over the Southern Ocean, including in the Antarctic Circumpolar Current (ACC)[122–124], continental shelves[125–129], near ice shelves[117,130,131] and in the Arctic Ocean[23]. Also, in the Mediterranean Sea, more than five glider endurance lines are currently in operation[132].

USVs are also filling a growing need for surface-based observations in the Southern Ocean (FIG. 4e), assessing physical air–sea fluxes[133,134] and gas air–sea fluxes, notably, CO_2 (REF.[92]). While existing USV missions are primarily regional, saildrones and other USVs are designed and have been used for basin-scale observations[46,66]. Given the ability to actively navigate USVs, they present an opportunity for sampling in regions where ships do frequent less. For example, USV-based seawater pCO_2 observations covering observing gaps of open-ocean missions from the tropical Pacific to the South Pacific Gyre are being incorporated into the 2020 version of the SOCAT.

Multiplatform synergy

Generally, ship-based measurements are of very high quality and include key variables that cannot presently be measured by floats or gliders, for example, levels of silicon, phosphorus, iron, ammonia, bacteria, total dissolved organic carbon (DOC) concentration and phytoplankton species[135]. Moreover, remote sensing offers a large-scale snapshot of the ocean surface, which cannot be covered by individual autonomous platforms. Therefore, autonomous platforms could complement these observation methods by extending observations into full seasonal cycles, or from open-ocean to coastal regions, and by providing the three-dimensional real-time data needed for operational models.

Synergy between autonomous and ship platforms. Although ship-based observations are infrequent and biased to summer months, well-calibrated shipborne data provide, by far, the most important reference for in situ validation of autonomous platforms[77]. For the delayed-mode quality control of autonomous platforms in particular, climatological data captured by ships can validate previously acquired oceanographic measurements. NO_3^- and pH measurements by autonomous platforms may be biased by sensor offsets and drifts[77]. The high-quality GLODAP data set, generated from ship-based measurements, includes deep (>1,000 m) NO_3^- and pH measurements that can be used as reference values to correct the sensor offsets and drifts. Methods for using GLODAPv2 to produce reference measurements at float geolocations are based on multiple linear-regression analyses[136] and neural networks[137,138]. These regressions and neural networks are driven with data from CTD and O_2 sensors on the floats. Similarly, observation of other platforms (ships, buoys and USVs) in the Surface Ocean CO_2 Network (SOCONET)[24] can provide the reference measurements for calculated pCO_2 based on BGC-Argo observations[139].

Synergy between autonomous and satellite platforms. Variables measured by autonomous platforms, for example, chlorophyll *a*, backscattering and photosynthetically available radiation (PAR), can be used to validate satellite platforms[140–142] and evaluate calibration of in situ sensors[143,144]. Several recent studies also present prototype floats that can be used as calibration platforms for ocean-colour satellites through acquiring high-quality radiometric measurements[145,146]. The combination of in situ BGC-Argo observations with ocean-colour remote sensing can be assisted by machine-learning techniques; this approach has been used to develop a 4D global map of the backscattering coefficient, a proxy for measuring particulate organic carbon[11,79].

The calibrated sensor data from floats and gliders can be used to evaluate satellite observation platforms. Recent studies using this approach showed that NASA's chlorophyll *a* and POC algorithms perform without significant mean bias in the Southern Ocean[77,141], despite several publications suggesting the opposite[147–149].

Multiplatform experiments. Comprehensive data sets can be collected by combining data from autonomous platforms, ship, buoy and satellite observations. Increasingly, oceanographic experiments and observation networks are being conducted across multiple platforms. The OOI not only supports two regular glider lines as mentioned above but also hosts several surface and profiler moorings[121]. Early-stage, multiplatform experiments included the in situ iron-enrichment experiment IronEx-I in 1993 (REF.[150]), the CLIVAR Mode Water Dynamics Experiment (CLIMODE) in 2006–2007, the North Atlantic Bloom experiment (NAB08) in 2008 (REF.[58]) and the coastal experiment in the eastern Alboran Sea, AlborEx, in 2014 (REF.[151]). These studies have greatly improved our understanding of phytoplankton physiology and impacts of mesoscale and sub-mesoscale dynamics on regulating primary production, among other biogeochemical phenomena[43,47].

In 2016 and 2017, the Salinity Processes in the Upper-Ocean Regional Study (SPURS-2)[152] and the Northern Arabian Sea Circulation-Autonomous Research (NASCar)[153] coordinated almost all autonomous platforms (including Argo floats, gliders and USVs) and moorings focused on targeted mesoscale eddy. These studies demonstrated the use of multiple platforms to resolve physical

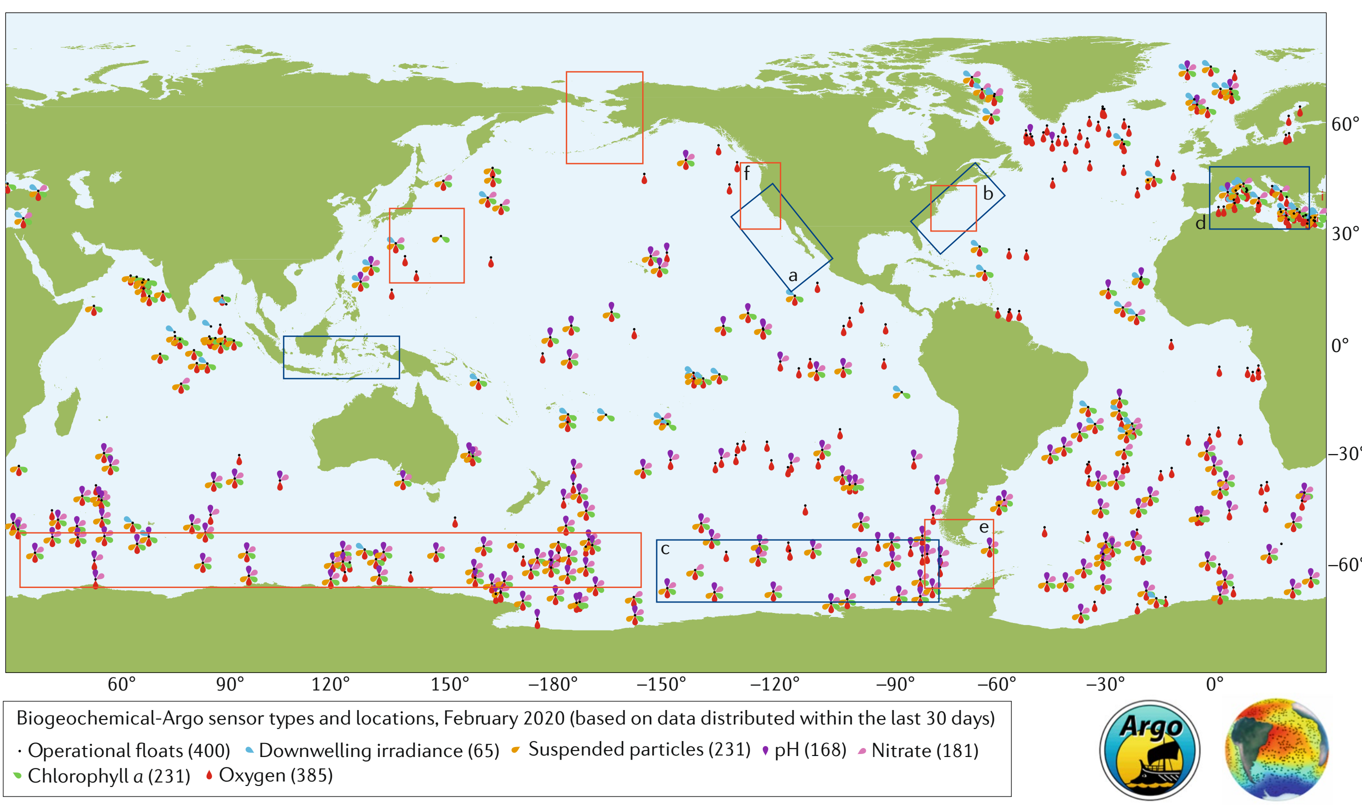

Fig. 4 | **Locations of recent autonomous ocean observations.** A map of the global array of Biogeochemical-Argo floats with various sensors in February 2020, with locations based on data distributions over 30 days. Boxes indicate areas that have been observed frequently by gliders (blue) or unmanned surface vehicles (red). Data in a obtained from REF.[115]; data in b from REF.[119]; data in c from REFS[124,130]; data in d from REF.[132]; data in e from REF.[133]; and data in f from REF.[112]. Adapted with permission from jcommops.org.

oceanography, and their approaches could be used for measuring biogeochemistry in the future. The EXport Processes in the Ocean from Remote Sensing (EXPORTS) project is currently developing a predictive understanding of the export and fate of global ocean net primary production and its implications for present and future climates, based on BGC-Argo floats, gliders and satellites[154]. These experiments and projects suggest a multiplatform future for marine biogeochemical research, in which synergic observations are capable of providing comprehensive 4D oceanographic information at a high spatiotemporal resolution.

The future of modelling and forecasting

Data from integrated observational platforms can be applied to evaluate and improve existing numerical models, ensuring model reliability for predicting marine biogeochemical processes (FIG. 5).

Reliable modelling for ocean biogeochemistry and ecosystem. Biogeochemical models can guide assessments of the current state of the ocean, elucidate ongoing trends and shifts, anticipate impacts of climate change and management policies, and maintain ocean ecosystem health (see a recent overview by Fennel et al.[155]). Such modelling capabilities can only be achieved in combination with comprehensive ocean biogeochemical observations, such as those provided by autonomous platforms.

Presently, biogeochemical modelling applications lag behind physical ocean modelling and prediction, mainly because traditional biogeochemical observation streams are too sparse for comprehensive validation, initialization and optimization of biogeochemical models[155]. Improved biogeochemical models can be used to estimate system properties that are not directly observable, such as lateral NO_3^- supply and air–sea exchange of CO_2 in the Southern Ocean[156]. They further offer spatial and temporal coverage not attainable by direct observations. The technological readiness for assimilating observations from BGC-Argo data into biogeochemical models has been demonstrated for state estimation[53,156,157], as well as parameter optimization[158].

Assimilation of physical observations in biogeochemical models can significantly reduce model biases[157]. BGC-Argo observations provide much better constraints than traditional observation streams on the dynamics and vertical structures of biogeochemical properties, as shown by a forecasting system for the Mediterranean Sea[53] and a biogeochemical-parameter-optimization study for the Gulf of Mexico[158]. New observations might also elucidate previously unrecognized shortcomings in biogeochemical models and satellite-based data products, and prompt modifications and refinements of model structures, parameterizations and algorithms for data products.

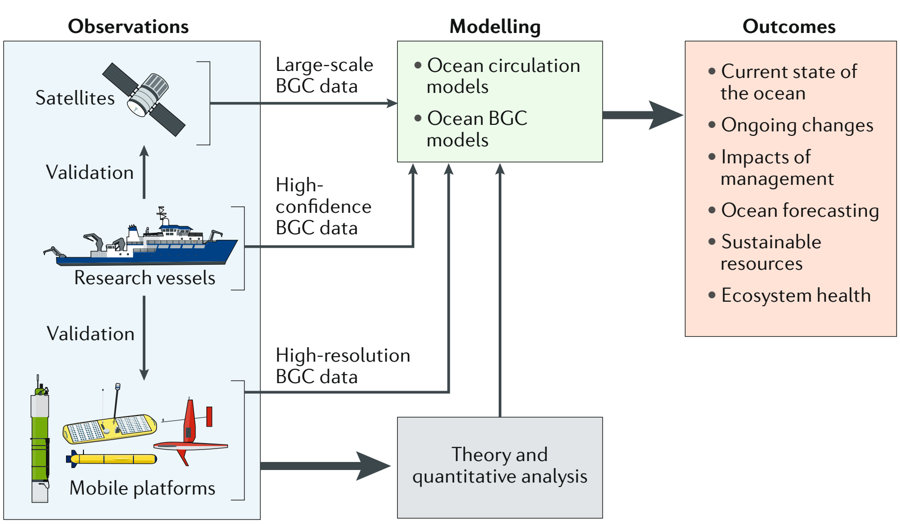

Fig. 5 | **Relationships between new observation technologies, biogeochemical models and ecosystem health management.** Mobile platforms, as an important component of global ocean-observing systems, provide high-resolution biogeochemical data. The data sets acquired by multiple platforms, including also ships and satellite sensors, are crucial to improving ocean biogeochemical models, and, in turn, to better evaluating the current state of ocean ecosystems and forecast its changes. BGC, biogeochemical.

Forecasting systems to support decision-making. A major focus in delivering the UN's sustainable development goals and aims set out in the Paris Agreement[2] is the construction of a reliable and comprehensive forecasting system. Forecasting systems are fundamental for facilitating the decision-making process, and there is great potential for BGC-Argo and other autonomous platforms to be at the forefront of these systems.

4D data sets can optimize forecasting system parameters[71,104]. Autonomous platforms have been used in marginal seas during spring blooms to measure nutrient content in high temporal frequency and vertical resolution, in order to resolve anomalous NO_3^- drawdown[159]. The implementation of high-spatiotemporal-resolution observational data into ocean models can fill observational gaps and help make reliable predictions for biogeochemical cycles, ocean primary production and fishery resource[160,161]. The behaviours of fishes, such as tuna in the tropical Pacific, can be better understood and simulated using accurate observational data to fit the likelihood of spawning, model migration patterns and improve stock assessment[162]. An ecosystem-based modelling procedure could also refine fishing policies adaptively, mitigating stressors induced by anthropogenic activities and guarding ecosystem health by informing sustainable resource use[163,164].

One of the major expectations from the UN Decade of Ocean Science for Sustainable Development is a well-predicted ocean, which relies on a sustainable ocean-observing system[165]. The major bottleneck for the development of biogeochemical models is the lack of observations; the use of in situ biochemical data from floats, gliders and USVs is, therefore, expected to be important for increasing the capability and credibility of ocean models[166]. Well-established models are anticipated to steer sustainable development of human society and can optimize approaches for assessing the responses of marine ecosystems to stress conditions, for example, algal blooms and storms, and help stakeholders make reasonable decisions[167].

Machine learning and artificial intelligence could be used to handle the autonomous-platform data sets[168]. These new approaches can extract spatial and temporal patterns from geospatial data to construct a hybrid model, systematically describing the multidisciplinary marine system[169]. A technique integrating a near real-time data-transmission system and data processing can enable the forecasting system to predict the ocean state in a comprehensive manner[170]. Improved forecasting models based on observational data streaming and cutting-edge data sciences are predicted to help explore the carbon cycle and underlying Earth systems[171]. An accurate forecasting system could, therefore, reduce the threats on climate and marine ecosystems through refining the decision-making process.

Conclusions

Many notable observations of ocean biogeochemistry and ecosystems have been made over the past century using traditional observation methods. However, these methods are now proving inadequate for capturing the varied temporal and spatial scales of biogeochemistry[11]. Autonomous platforms will play an important role in filling the observational gaps in monitoring and forecasting marine ecosystems. Argo floats and other autonomous platforms have also been considered as the most effective way to globally acquire vertical profiles of key environmental, biogeochemical and ecosystem variables[13,82]. They represent a new era of modern oceanographic observations, with great potential to provide new Essential Climate Variables and Essential Ocean Variables (ECVs and EOVs, respectively) related to ecosystem health and resource management[1]. There are ongoing developments in merging satellite and in situ robotic measurements for constructing a global three-dimensional view of biogeochemically relevant variables[79], and, in the near future, these three-dimensional fields will likely become essential parts of the data set for the initialization and/or validation of global biogeochemical models.

Currently, the implementation of integrated observation systems has primarily been addressed by the physical community[172,173]. It is now obvious that the scope of observational networks has to expand to include ocean biogeochemical and ecosystem components, and to integrate efforts across these scientific disciplines. The methodology for developing physical observational systems should serve as a guideline for the development of their biogeochemical and ecosystem counterparts[24]. The integration of biogeochemical and ecosystem components into an already existing physical observational system, however, is not just a matter of adding new sensors[77]. The implementation strategy of these new components will have to be discussed and organized by the physical, biogeochemical and ecosystem components[66].

BGC-Argo and other emerging autonomous platforms equipped with biogeochemical sensors are essential components for global observations of ocean conditions on multiple temporal and spatial scales. These global and regional networks of autonomous platforms, along with remotely sensed data, will provide the 4D information required to improve model simulations and forecasts of ocean conditions and ecosystem health. The success of any future ocean-observation system will strongly depend on the capability of the observing community to improve interactions between physical, chemical and biological oceanographic disciplines and integrate in situ, satellite and modelling components[174].

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F.C., X.X. and Y.W. researched data for the article. F.C., K.S.J., H.C., X.X., K.F., O.S. and A.S. all contributed to the writing of the article. F.C., X.X., Y.W., E.B. and S.R. contributed to reviewing and editing the manuscript prior to submission. All authors made a substantial contribution to the discussion of content.

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