Ocean Observatories and Information: Building a Global Ocean Observing Network

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Article Outline

Glossary

Ocean observatory A collection of platforms that collect data over a range of spatial and temporal scales.

Definition of the Subject and Its Importance

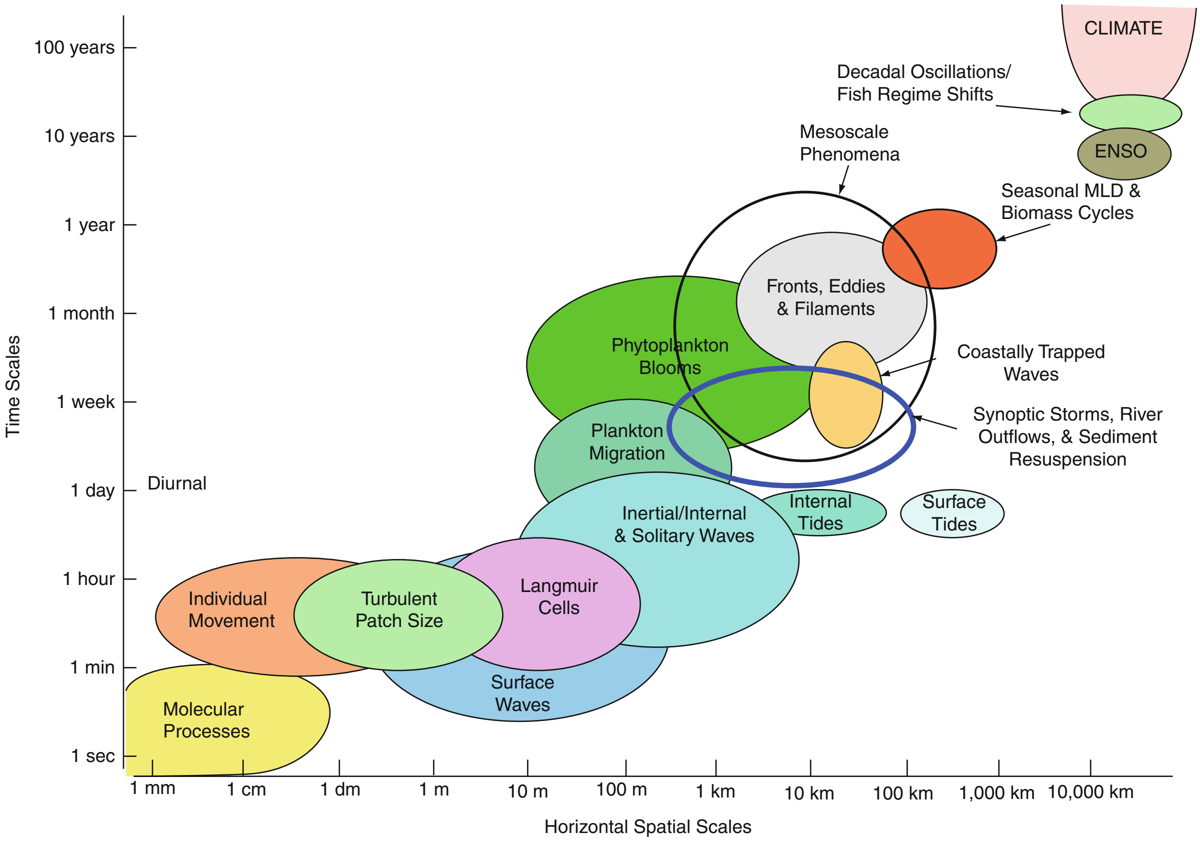
Ocean observatories are collections of networks of sensors that are deployed to sample the ocean physics, chemistry, and biology. The goal of these networks is to overcome chronic undersampling of the oceans by providing sustained measurements in space and time. The data collected by these networks are used to address a range of basic and applied research questions, hindered by a lack of data. The ocean observatories represent collections of platforms capable of collecting data over a range of scales. The platforms include ships, satellites, radars, and a range of Lagrangian systems. Data from the individual platforms are aggregated by sophisticated cyberinfrastructure software systems, which when combined with global communications allow for two-way communication between the shore-side personnel and the networks that can be deployed anywhere in the world. This two-way communication allows the networks to be adaptively configured to improve sampling of specific processes. The maturation of these systems comes at a fortuitous time as the oceans are increasingly showing evidence of changes in the physics, chemistry, and biology over the last few decades. Understanding those changes will require the data collected by the ocean observatories.

Introduction

The Need for a Global Ocean Observing Network

The oceans cover the majority of Earth's surface, and despite centuries of human exploration, the oceans remain relatively unexplored. Oceanographers have historically collected data on the ocean and the seafloor from ships during cruises of limited duration. This expeditionary research approach has resulted in major advances that span understanding global ocean circulation, the energy associated with mesoscale circulation [1–4], plate tectonics (cf. [5]), global ocean productivity [6–8], and climate-ocean coupling [9–11]. These and many other successes have expanded our view of the role of ocean processes on Earth, and have demonstrated a need for sustained sampling spanning temporal and spatial scales that are not effectively carried out using ships. Filling these informational gaps will require the oceanographic community to develop new modes of sampling the oceans. Developing these new approaches is urgent, as data collected over the last few decades show that in many regions of the ocean the physics, chemistry, and biological properties are exhibiting significant change.

The observed changes in the oceans over the last few decades span from local scales (kilometers) to global effects operating over a wide range of spatial and temporal scales (Fig. 1). These changes reflect both natural cycles and increasingly reflect human activity, which now plays a significant role in structuring the world's oceans. Local changes include alterations in circulation, increased introduction of point source concentrations of macro- and micronutrients,



Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 1
A stommel diagram showing the range of spatial and temporal scales over which ocean processes operate. The figure was constructed by Tommy Dickey and is published with his permission

transport of pollutants to the sea, the introduction of invasive species, associated pressures of aquaculture efforts, and altered food web dynamics due to the overexploitation of commercially valuable species. These local features are embedded within regional and global scale changes. These large-scale changes include altered physical (temperature, salinity, sea level height), chemical (oxygen, pH, nutrients), and biological properties (fishing out of top predators).

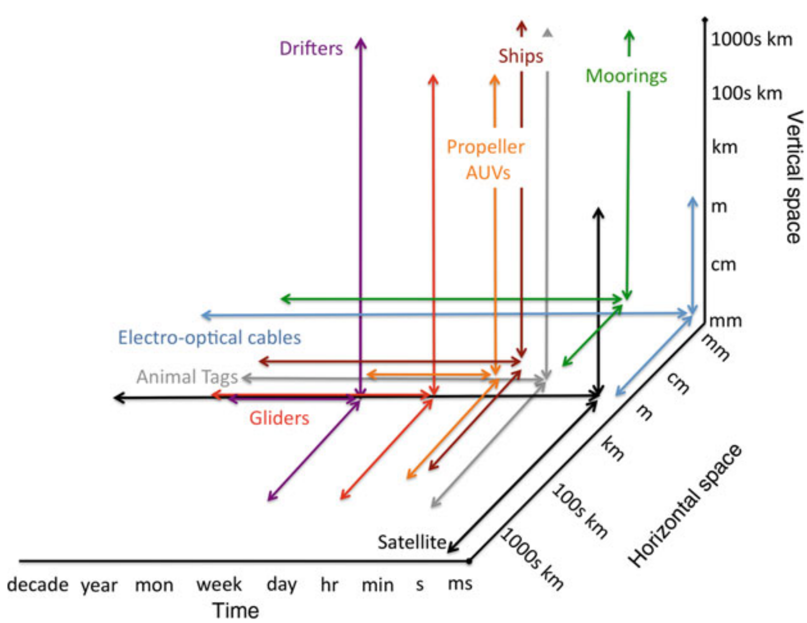
Quantitatively understanding the relative role of natural and anthropogenic forcing of the ocean is a paramount challenge for oceanography. The urgency will only increase as in the next 20 years as anthropogenic environmental impacts associated with humans are expected to increase. This reflects the growth human populations [12] with current projections predicting the human population will reach ten billion by 2040. This will be especially prominent at the coastlines, which are predicted to show the largest population increases [13]. This will require a thorough understanding of ocean processes, which will be used to improve human health and safety, promote economic vitality, and provide the tools for sustainable environmental stewardship. These needs will require an improved fundamental understanding of the oceans.

Given the need for a quantitative understanding of the oceans, the ocean science community is fortunate to be poised to take advantage of many technical advances. These advances include a diverse set of new platforms capable of carrying sensors for sustained periods of time and the maturation of cyberinfrastructure tools that can link distributed individual observing networks to form a "system of systems." These components will provide the foundation for an international global ocean observing network. In this entry, we will outline the developments and, where appropriate, provide specific examples of how the data will be used.

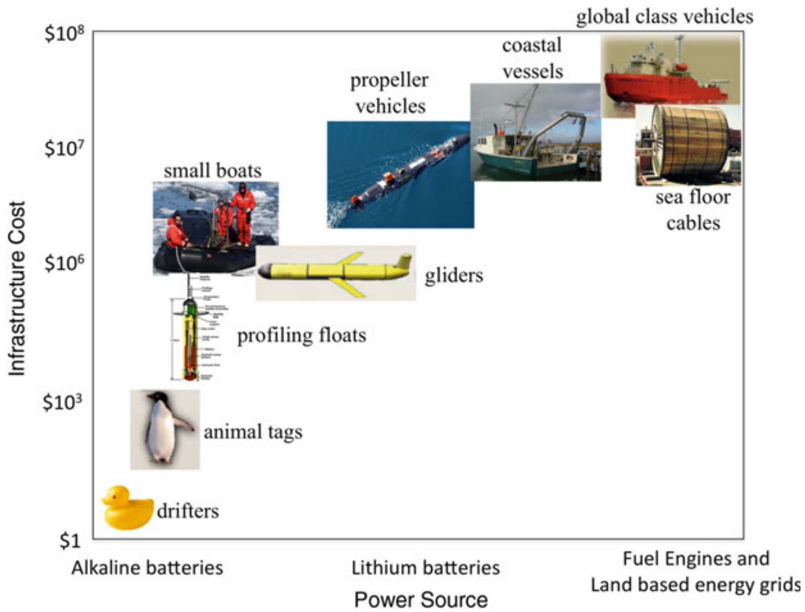
Design Considerations for Building an Ocean Observing Network

Ocean observing networks are designed to address a specific need, which is used to define the required sampling resolution in space and time. Defining the appropriate scales can be a difficult problem as many large-scale (thousands of kilometers), long period (annual-to-interannual) processes are determined by small-scale, short-period variations in atmospheric forcing, and small-scale, relatively short-lived, oceanic processes [14–18]. As highlighted by Munk [19], 95% of the oceanic kinetic energy is associated with mesoscale currents having time and space scales less than about 100 days and 100 km. Other forcing factors can operate over inertial or diurnal time scales [17]; therefore, a comprehensive understanding of the oceans will require nested sampling capable of resolving the feedbacks between processes operating over different scales. This generally requires a multiplatform strategy as each system samples a specific time and space domain (Fig. 2). Once the sampling requirements have been defined, it is possible to choose (1) the appropriate platforms, (2) the required measurements, (3) the data latency needs for a particular observatory, and (4) the funds available for construction. The costs generally increase with the flexibility of the system (Fig. 3). Increased power on a platform allows for greater flexibility in carrying a wider range of sensors.

As ocean infrastructure is expensive, most large infrastructure networks must often be able to address a range of basic research and applied science needs to justify the investment. Historically, basic and applied research efforts are often treated as separate enterprises; however, major issues confronting the ocean science communities reveal numerous commonalities that reflect the chronic undersampling of the oceans. Both applied and basic science require information on the physical hydrography, circulation, biological, and chemical properties; however, it is often the real-time availability of data that defines its utility for applied science where data are used to meet real-time needs such as weather forecasting, search and rescue, and national security. When available, however, real-time information has a great deal of utility as



Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 2
The time and space sampling capabilities of different ocean platforms. The different colors represent different platforms



Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 3
The range of cost and power for a range of ocean sampling platforms

scientists use the information to optimize adaptive sampling techniques.

Platforms Available for Ocean Observing Networks

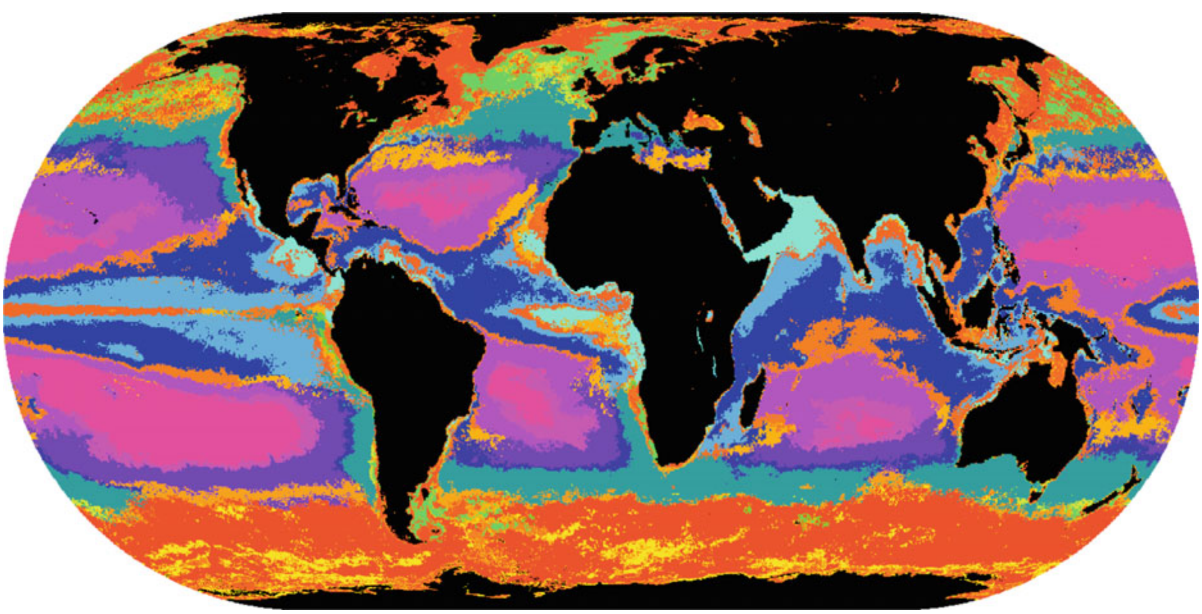
A range of platforms available for building ocean observing networks are described. Note that the list is not exhaustive, but reflects the major pieces of infrastructure widely used by the community today and form the observational backbone of the major ocean observing efforts. For this entry, we focus on physical systems that collect data about the ocean and do not discuss numerical models.

Ships. The primary tool for oceanographers for centuries has been ships and despite significant advances in new technologies (see below), ships will remain a central piece of infrastructure for the foreseeable future [18]. In the last decade, the range of ships available to the oceanographic community has grown with an expanding set of global class vessels being complemented with smaller, capable, coastal vessels. The increasing interdisciplinary needs have resulted in significant upgrades in the capabilities of the ships with improved capabilities in the dynamic positioning and station holding, multi-beam and side-scan sonar systems, and more complex sensors and instrumentation becoming routine tools when at sea.

Satellites. Satellites constitute the most important oceanographic technology innovation in modern times [19]. Satellite observations have resulted in numerous advances in our fundamental understanding of the oceans [20] by resolving both global features associated with the mesoscale circulation of physical and biological properties. It is the fundamental tool for understanding myriad ocean processes and land–air–sea interactions over decadal time scales. Satellite data are fundamental to weather and ocean state prediction. The data have revealed new phenomena over critical space and time scales that were previously inaccessible using only data from in situ observing systems. Physical parameters available from space-based sensors provide information on ocean surface temperature, wind speed and direction, sea surface height and topography, and sea ice distribution and thickness. Biogeochemical parameters are derived from ocean color radiometers (pigment concentration, phytoplankton functional groups, size distribution, particle concentration, colored dissolved organic material). A range of methods that include active scatterometry, microwave array spectrometers, microwave imagers, multi-beam altimetric lidars, altimeters, and advanced gravity missions collect these observations. The coverage provided by a satellite is dependent on its orbit. Currently most environmental satellites are polar-orbiting, covering the whole globe over a period of days. These global maps can be complemented by geostationary satellites that can map the same area of the ocean several times a day, allowing one to resolve the temporal changes such as tidal effects or river plumes. These geostationary satellites are particularly important when monitoring episodic events required for many applied efforts such as monitoring hurricanes and/or oil spills.

The significant time required and high cost of deploying satellites has focused efforts on expanding the utility of existing platforms. These approaches include the development of new algorithms. These new algorithms have focused on objectively defining water masses ([21, 22], Fig. 4), deriving biological rate processes [23, 24], estimating nutrient concentrations [25], and mapping ocean salinity [26–28]. Algorithms are also being developed to allow the satellites to adaptively sample the ocean. This approach has been demonstrated with the scientists re-tasking the satellite to spotlight a region [29]. As flexibility in networks increases, these approaches are likely to become more common.

High Frequency Radar. High frequency radar is a technology for measuring ocean surface current velocities over hundreds of square miles simultaneously (Fig. 5). The systems can provide data on approximately hourly time scales and can collect data out to about 125 miles (200 km) from shore (Fig. 4). The HF radar systems can resolve spatial scales of about 1–10 km, unaffected by clouds, fog, or precipitation. This technology uses low-power transmitters and small stationary antennas that are relatively simple to deploy. Each site measures the radial components of the ocean surface velocity directed toward or away from the site [30–32] and the estimated velocity components allow surface currents (upper meter of water column) to be estimated [33]. These systems are cost-effective and currently much of the coastal zone is now sampled using this technology.



Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 4
A global map of the major ocean biomes as determined using an objective mapping algorithm [22]. The map was created by combining sea surface temperature maps with ocean color imagery, and provides a means to discriminate the major water masses by combining all available satellite remote sensing technologies. Each color represents a distinct water mass

HF radar provides a good example of a dual use technology. For example, HF Radar measures the movement of oceanic events like the winds in the atmosphere provide information about where and when weather systems occur (Fig. 5). The dynamic movements of the ocean and atmosphere are also used to determine where pollutants, man-made or natural, will travel. Modern weather now casts and forecasts generated by NOAA's National Weather Service depend on the thousands of critical wind measurements collected worldwide each hour, mostly from land and satellite-based sensors. In the coming decade, coastal managers will use HF radar data to measure the ocean current speed and direction to track plumes (rivers, pollution, oil), assist in coast guard search and rescue (SAR), assist in marine navigation, define shipping tracks and temporary anchorages offshore ports, and track the transport of harmful algal blooms. One specific example is the US Coast Guard, which currently ingests surface current data from high frequency radar sites into its SAR operations along the Mid-Atlantic coast, which has a mature HF radar network. It is estimated that if HF radar is deployed in all US coastal waters would save an additional 26–45 more lives annually and reduce the $30 M per year currently spent on rescue flights (http://ioos.gov/library/sarops_data_sources_uncert_nov2006.pdf).

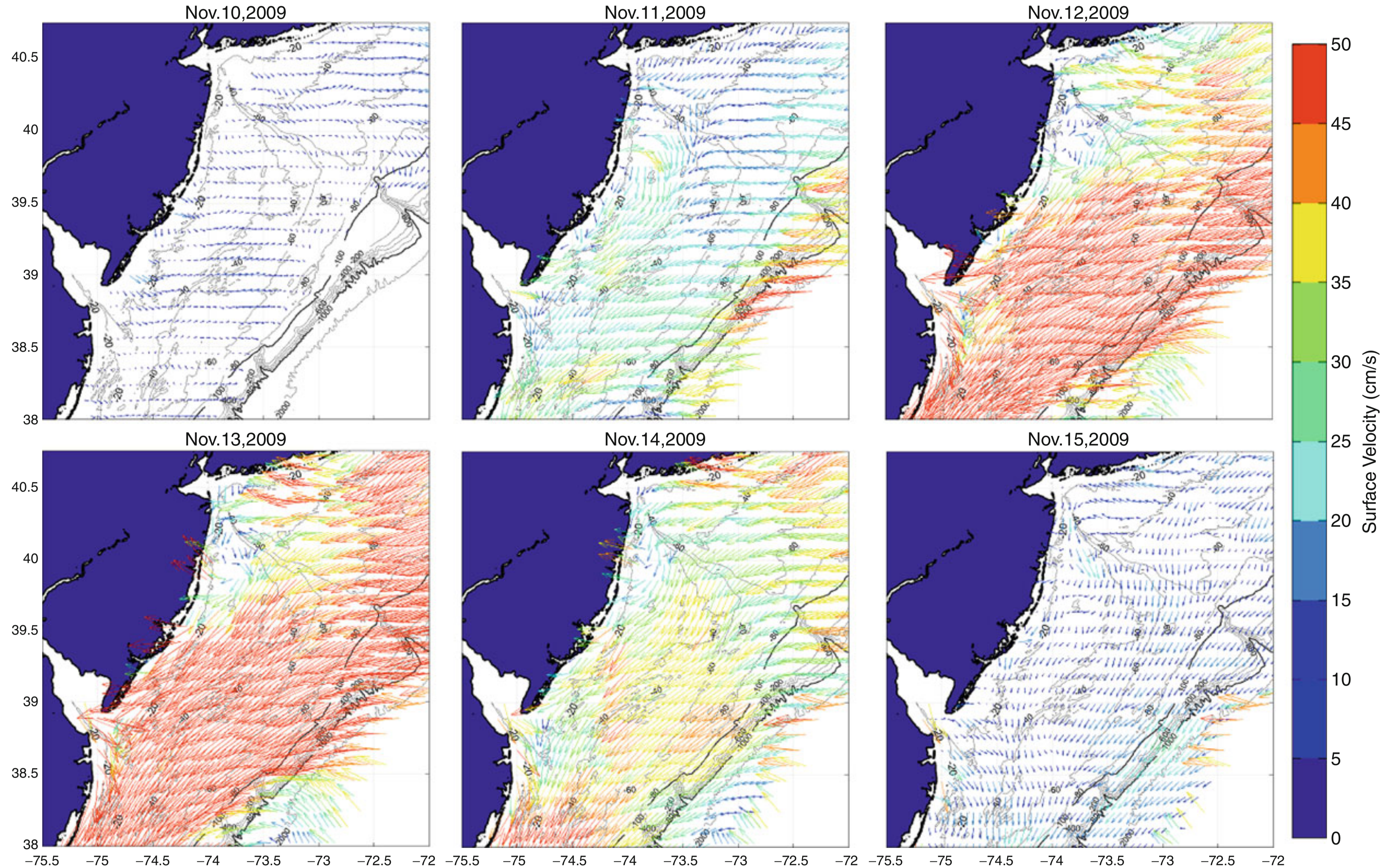
Ocean Moorings. The modern ocean moorings grew out of the weather stations established in the 1940s. Since the 1960s modern buoys have enabled a wide range of studies addressing the ocean's role in climate, weather as well as providing insight into the biogeochemistry of the sea. Moorings provide the backbone to many of the global ocean networks studying ocean–atmosphere interactions and are the foundation for the global tsunami warning system network. They will continue to be a key element of ocean observing infrastructure that provides high frequency fixed location data to supplement the spatial data collected by ships, autonomous underwater vehicles, and satellite remote sensing by providing subsurface data.

Seafloor Cables. Scientists often require high bandwidth and power for sustained periods of time. Seafloor electro-optic cables offer potential means for providing the sustained presence in the ocean. There have been two general strategies when deploying seafloor cables. Cables have been deployed off the east and west coasts of the United States and Canada, Hawaii, Japan, and Europe. These cables have successfully been used to study a wide range of topics which include seafloor seismicity [34, 35], tsunamis [36], seafloor dynamics [37], coastal upwelling (Fig. 6, [38]), ecosystem productivity [39], hydrological optics [40], ocean turbulence [41], sediment resuspension [42, 43], gas hydrates [44], marine boundary layer dynamics [45], bioluminescence [46, 47], and animal swimming behavior [48].

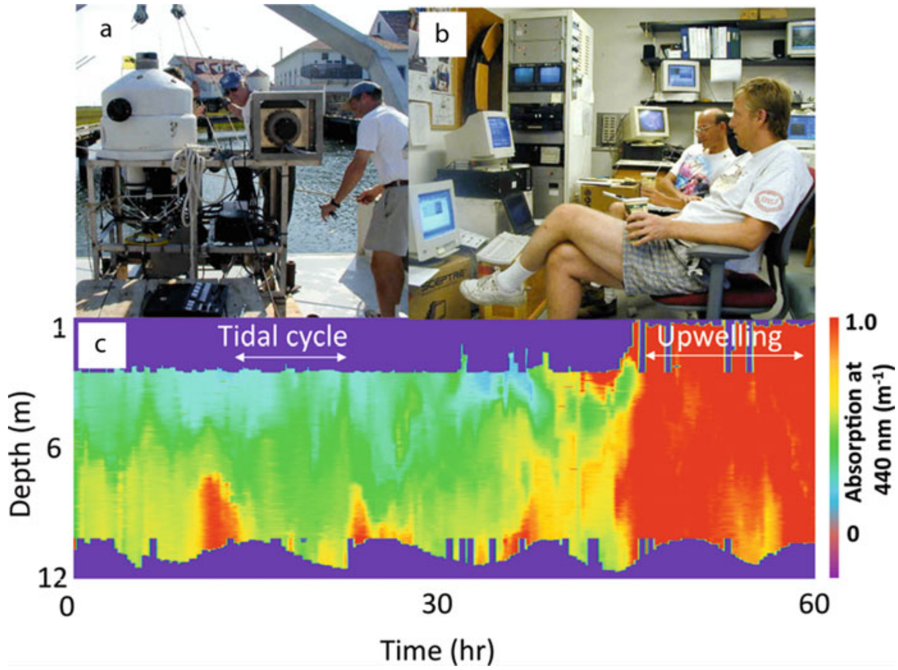
Drifters and Floats. Passive, autonomous, Lagrangian platforms have become an indispensable tool in creating surface and subsurface maps of ocean properties. These platforms are relatively inexpensive and thus allow thousands of these platforms to be deployed. Surface maps of ocean currents and ocean properties (temperature) have been collected using surface drifters. Drifters have historically been a key tool for oceanography as evidenced by the important works of Benjamin Franklin [49] and Irving Langmuir [50]. Improved communications have allowed thousands of drifters to be deployed. The drifters have evolved to carry numerous sensors, which have allowed them to create global maps of surface circulation at a relatively low cost [51].

The first neutrally buoyant floats were designed to observe subsurface currents [52]. The subsurface floats were greatly enhanced in the early 1990s with communication capabilities [53] and now anchor the international ARGO program, which has over 3,000 floats deployed in the ocean (Fig. 7, http://www.argo.ucsd.edu/). The subsurface ARGO network has been a critical tool for oceanography [55] and to date has resulted in over 750 publications since 1998 (http://www.argo.ucsd.edu/Bibliography.html). Publications span from mapping global ocean hydrography, trended changes in ocean properties, and ocean biogeochemistry.

Gliders. Rudnick et al. [56] provided a detailed overview of glider systems for scientific uses. Gliders are a type of autonomous underwater vehicle that use small changes in buoyancy in conjunction with wings to convert vertical motion to horizontal motion, and thereby propel itself forward with very low-power consumption. These are similar in concept to profiling floats (see above) with the exception of the wings. Gliders follow a sawtooth path though the water,



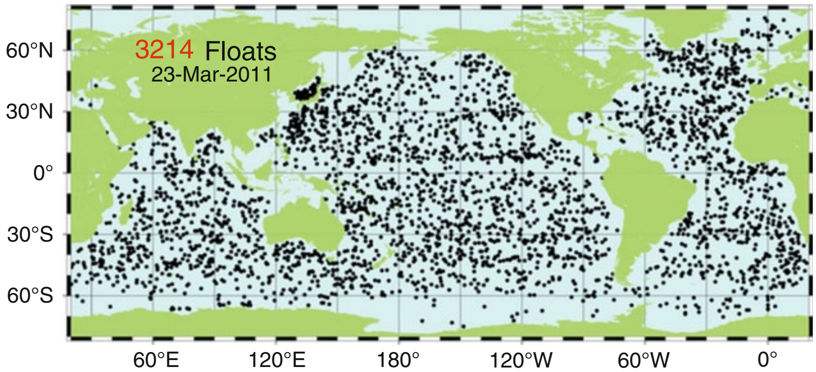
Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 5
The response of surface currents for the coastal waters offshore New Jersey (USA) due to the passage of a large coastal storm. The color of the surface current indicates the current velocity and the *arrows* indicate the direction of the current. The HF CODAR network was able to collect data throughout the storm when clouds interfered with remote sensing approaches and the violent waves would not allow for ship-based operations. Collecting data during such extreme events is of high importance to the ocean science community



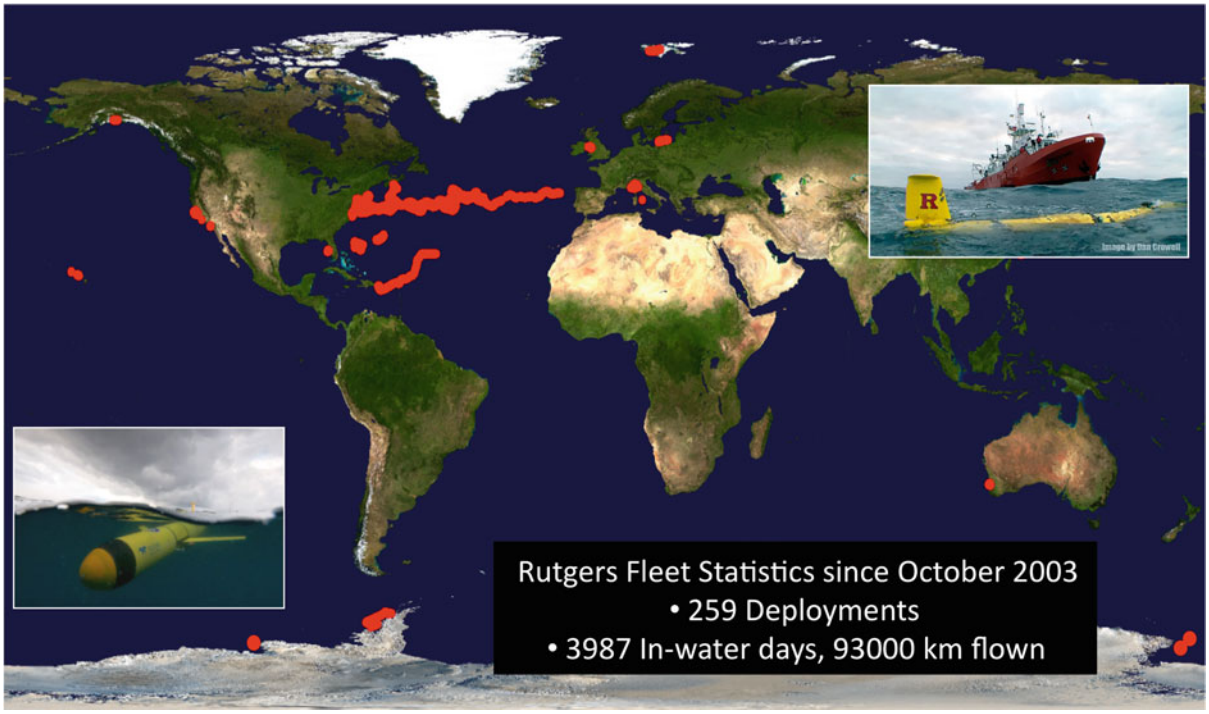
Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 6
Example of data collected by the Long term Ecosystem Observatory (LEO) which is located 5 km offshore the coast of New Jersey and is linked to shoreside laboratories via an electro-optical seafloor cable. (**a**) A profiling instrument node before being mounted to the LEO cable. (**b**) The shore side control center from where the profiler and instruments were controlled. The data was sent to shore in real time to scientists via the LEO cable. (**c**) Data collected during 60 h while continuously profiling the instrument package. The short time series represents over 600 vertical profiles. The data represents the absorption at 440 nm collected with a WetLabs absorption/attenuation meter. The high turbidity water (*red*) was associated with tidal outflows and with coastal upwelling

providing data on large temporal and spatial scales. They navigate with the help of periodic surface GPS fixes, pressure sensors, tilt sensors, and magnetic compasses. Using buoyancy-based propulsion, gliders have a significant range and duration, with missions lasting over half a year and over 3,500 km of range. There are currently three glider types [57–59] being used throughout the world's oceans (Fig. 8). Although the majority of gliders presently run on batteries, thermal-powered gliders, which take advantage of thermal gradients in the ocean, are being developed [59]. Gliders vary in the pressure, they are able to withstand but taken together, and they effectively sample waters depths from 10 to 3,300 m. The duration of the glider mission is variable and depends on (1) the type of battery used, (2) the number of sensors the gliders carry, and (3) the water column depths in which the glider is operating. Because these vehicles are designed for duration, they have limited power for sensors. The standard measurements currently on gliders include temperature, salinity, chlorophyll fluorescence, optical backscatter, bottom depth, and occasionally acoustic Doppler velocity and backscatter. By examining displacement between surface fixes, the vertically averaged absolute velocity can also be determined. The utility of gliders have demonstrated their value in collecting high resolution spatial datasets [60–67].

Propeller-driven AUVs are powered by batteries or fuel cells and can operate in water as deep as 6,000 m. AUVs can navigate by various means; inside a net of acoustic beacons, by position relative to a surface reference ship, or when operating completely autonomously, the AUV will surface and take its own GPS fix. Like gliders, AUVs relay data and mission information to shore via satellite. Between position fixes and for precise maneuvering, inertial navigation systems are



Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 7
The global distribution of ARGO profiling floats on March 23,2011. The floats are outfitted with sensors that measure temperature and salinity. A smaller number are outfitted with biogeochemical sensors [54]



Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 8
Gliders are operated by individual laboratories and allow small groups to occupy a global presence at relatively low cost [29]. The figure shows the glider deployments conducted by Rutgers Coastal Ocean Observation Laboratory from October 2003 until February 2011. The missions represent almost 4,000 days at sea and the Rutgers glider fleet has flown 93,000 km underwater. Currently, there are over a dozen laboratories located throughout the world who maintain a similar sustained global glider presence at sea

often available onboard the AUV to measure the acceleration of the vehicle and, combined with Doppler velocity technology, is used to measure rate of travel. A pressure sensor measures the vertical position. AUVs, unlike gliders, can move against most currents nominally at 3–5 knots, and, therefore, can systematically and synoptically survey a particular line, area, and/or volume. This is particularly important for bottom surveys and operation near the coastline in areas hazardous to ships and small craft. The endurance of AUV systems depends on the size of the vehicle as well as the power consumption, but range from 6 to 40 h of operation under a single charge with ranges of 70–240 km over that period. The sensor payload is also dependent on the size of the vehicle (and battery capacity), with the standard array of sensors measuring, temperature, salinity, chlorophyll fluorescence, optical backscatter, bottom depth, and acoustic Doppler velocity and backscatter. Because of the additional power capacity of AUVs, numerous sensor suites have been integrated into AUVs and remain the primary autonomous platform for sensor development. Hundreds of different AUVs have been designed over the past 20 or so years. Blackwell et al. [68] provides an overview of the historical development of these vehicles.

Information Systems for Ocean Observatories

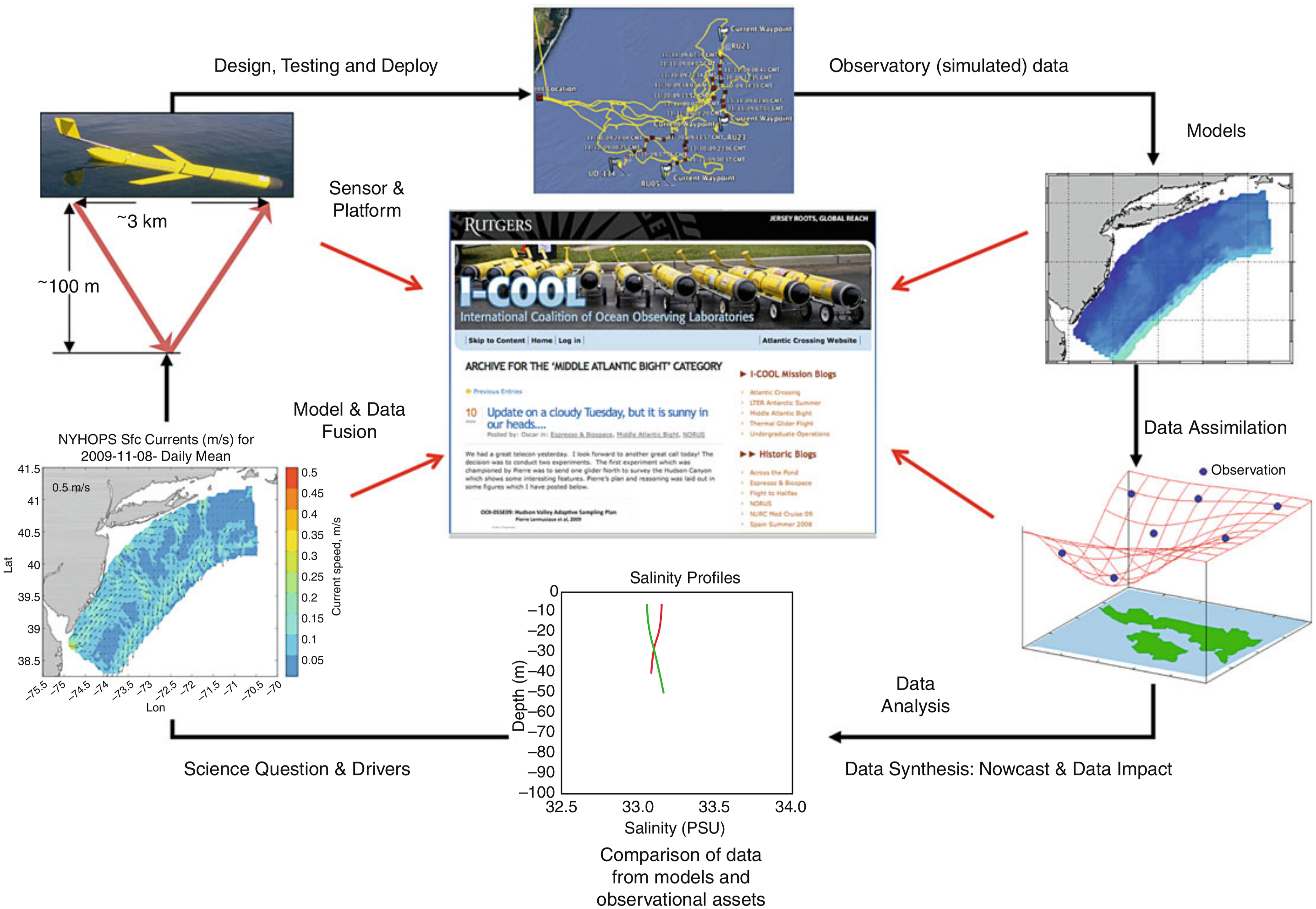
While the range of technologies available to oceanographers has been increasing over the last several decades, it is the availability of global communications and information technology that will allow these technologies to transform ocean sciences. Oceanographers have conducted experiments as either individuals or small groups within a single science focus at any given time; however, the broad scientific and civil demands for multidisciplinary and interdisciplinary research coupled with exponential growth in information technology are transforming oceanography. This history of working in small groups has resulted in the traditional data-centric cyberinfrastructure strategy, where typically a central data management system ingests data and serves them to users on a query basis. This approach is not sufficient to deal with the range of challenges that face ocean sciences.

Given this potential, the community is now dedicated to building the cyberinfrastructure that will be central to any global integrated ocean observing system. A modern cyberinfrastructure backbone will allow globally distributed scientists to operate as a community by aggregating data from individually deployed instruments for any experimental effort. If realized, this would allow anybody with access to the internet to utilize the global array of sensors to study any ocean process of interest.

Given the potential, ocean sciences are increasingly focused on building a system that will provide a comprehensive set of capabilities. Cyberinfrastructure systems must provide a comprehensive set of tools that include (1) end-to-end data preservation and access, (2) end-to-end, human-to-machine, and machine-to-machine control of how data are collected and analyzed, (3) direct, closed loop interaction of models with the data acquisition process, (4) virtual collaborations created on demand to drive data-model coupling and share ocean observatory resources (e.g., instruments, networks, computing, storage and workflows), (5) end-to-end preservation of the ocean observatory process and its outcomes, and (6) automation of the planning and prosecution of observational programs. Additionally the cyberinfrastructure systems must provide the required background messaging, governance, and service frameworks that facilitate interaction in a shared environment, similar to the role of the operating system on a computer. Such a system would provide a suite of tools capable of serving both basic and applied science simultaneously.

The potential of an interactive social network for the ocean sciences is in its infancy and the community is in the process of development and is conducting pilot experiments. One such example is the NSF Ocean Observatory Initiative (OOI), which has focused significant effort on developing a sophisticated cyberinfrastructure, that will link ocean observatories, computation, modeling, storage, and network infrastructure into a coherent system-of-systems. The software is also developing a web-based social network enabled by real-time visualization and access to model outputs to allow for adaptive sampling science.

One such example was a field experiment conducted in 2009, that allowed a distributed community of scientists to assess how well the software could aggregate data from ships, autonomous underwater vehicles (AUVs), shore-based radars, and satellites



Ocean Observatories and Information: Building a Global Ocean Observing Network. Figure 9
The machine-to-machine data flow during the Ocean Observing Initiative's (OOI) Observation Simulation Experiment. A fleet of gliders were informed by model driven forecasts in order to optimize science sampling being conducted by a geographically distributed team of scientists. The observatory data was assimilated by an ensemble of numerical forecast models, which were used to optimize the glider sampling. Optimized glider data was also used to adjust the data collected by the Hyperion EO-1 satellite

and to make it available to ocean forecast models. Scientists used the model forecasts to guide future (next 24 h) glider missions which then were used to optimize data collection for model data assimilation, which demonstrated the feasibility of two-way interactivity between the sensor web and predictive models. The sensor web included the re-tasking of a satellite. The software allowed the distributed community to adaptively modify the in situ observation network throughout the experiment [29]. The net result was a science driven machine-to-machine interactive loop (Fig. 9). These machine networks will increasingly become standard tools for the ocean science community in the future.

As observatories consist of a series individual components that are linked to form a coherent sampling system, an often underemphasized, yet critical need is the ability to register to all components to a common time stamp. The time stamp functionality in the sensor network is necessary to compare the output of one sensor to another. This is not a trivial when sensors are dispersed geographically and the data from sensors need to be integrated with external datasets. The accuracy required is a function of the process being studied and the length of the time series to be collected. For example, seismic studies require time accuracy on the order of milliseconds, acoustic tomography of 1 μs and studies of phytoplankton growth rates require data on the time scale of hours. Additionally, avoiding drift for temporal time series will increasingly become critical as sustained time series become the norm for oceanography. Fortunately, the ability to register time accurately is increasingly improving. A dramatic example is the evolution of small low-power atomic clocks. Atomic clocks offer the frequency stability of one part in ten billion, which is equivalent to gaining or losing 1 s every 300 years. These technical developments are being powered by the evolution of Micro Electro Mechanical Systems (MEMS) chip technologies that can produce clocks with a volume of less than 0.1 cm^3 and consume power on the milli-watt scale. These advances will enable atomic clocks to be operated on batteries and could be integrated throughout the individual components of the ocean observatories.

The potential of cyberinfrastructure tools, such as described above, is dependent on the real-time availability of data; fortunately global communications have improved dramatically over the last few decades. In the early 1990s, the primary mode of communication from ship to shore was via satellite voice calls. This improved over the next decade as ship-based science was provided with limited email communication. Communications have continued to improve and now provide sufficient bandwidth to allow for video-transmission at hundreds of kilobits per second (http://hiseasnet.ucsd.edu/). These improvements are changing the type of science that ships conduct as real-time data allow scientists to adaptively sample the ocean. Additionally, the launch of low Earth orbit satellite communication systems have allowed for global communication and enabled rapidly evolving capabilities for communications to autonomous platforms. The communications have improved from one-way communications with data transmission limited to about 16,000 bits/day to global two-way communications at a rate of 2,400 bits/s.

Future Directions

The ocean science community will over the next decade construct a global ocean observing network by combining a diverse range of platforms. The multiplatform networks will allow scientists to sample over a wide range of time and space scales and the availability of real-time data transmission will allow for adaptive sampling. The development of a robust cyberinfrastructure will encourage distributed teams of scientists to conduct both applied and basic research. The research will allow the community to understand the present and future status of the oceans.

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