Recent Trends in Ocean Observations

R. Venkatesan, Amit Tandon, Debasis Sengupta, and K.N. Navaneeth

Abstract This chapter focuses on recent progress and emerging directions in ocean observations. The importance of sustained observations and status of the global ocean observing network are covered. Emerging trends include many exciting developments, such as Bio-ARGO floats, autonomous or remotely-operated instruments and platforms, and new measurement capabilities focused on fundamental ocean processes. Numerical models that integrate and assimilate multi-scale observations of the atmosphere, land, ice and ocean will lead to new science as well as improved forecasts of great societal value.

1 Introduction

Throughout history, the oceans have been a vital source of sustenance, transport, commerce, growth, and inspiration. However, our knowledge of the ocean is still quite limited. Thus, Ocean Observations have a central role to play in delivering ocean-related services to the society. Ocean Observational Systems (OOS) typically consist of (a) in-situ measurements using sensors mounted on ships, buoys, moorings and coastal stations to capture changes in properties with time and depth at specific points or tracks and (b) remote sensing systems such as satellites, aircraft and radar to capture the spatial and temporal variations of the ocean properties synoptically. However, the copious amounts of raw data produced by such systems need to result in quality-controlled processed data, which need to be further translated into user-friendly ocean information services.

Ocean observations serve many useful purposes and provide economical and societal benefits to the public. These benefits include safe and efficient marine oper-

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R. Venkatesan et al. (eds.), *Observing the Oceans in Real Time*, Springer Oceanography, DOI 10.1007/978-3-319-66493-4_1

ation, improved marine commerce, coastal hazard mitigation, sustained marine resources and ecosystem management, reducing public health risk, and improve national security. A well-designed observation system should be meet users' needs, providing end-to-end products, and adaptive to changes in user requirements and technology advances. An observation system and any one of its components need to go through several development phases including the initial research and development (R&D), pilot demonstrations, and pre-operational tests and validation prior to becoming operational.

The environmental variables measured by OOS can be classified into physical (such as water level, surface waves, currents, bathymetry, water temperature, salinity), meteorological (such as wind, temperature, pressure, visibility, humidity), biological (such as ocean color, fish species and abundance, zooplankton species and abundance, phytoplankton species), chemical (such as contaminants, dissolved oxygen, nutrients), terrestrial (such as river discharge), and human health (such as seafood contamination, concentration of human pathogens).

Accurate and reliable environmental information can be derived by combining field observations with predictive operational models. Many technologies come together to accomplish these tasks. Data can be measured either directly using in-situ sensors or remotely via remote-sensing techniques such as satellite, airborne, or land-based or ship-based instruments. Predictive models expand the observation coverage and provide forecast capability, provided they have been validated and meet accepted standards prior to becoming an operational tool.

The expanding needs of users and new instrumentation technology have both led to several notable trends in the evolution of observational systems. These include real-time or near real-time data reporting, faster data telemetry via satellite during significant events (such as storm surge or a tsunami), water-level measurements with absolute reference, coastal wave, and water quality monitoring (such as nutrients from watershed, dissolved oxygen), integration of satellite sensing data and increasing spatial resolution of remotely sensed data for coastal applications, developing HF radar for surface current mapping, wireless data telemetry (such as Iridium and Argos satellites data transmission, cellular phone, underwater acoustic modem, spread spectrum modem), and system integration.

2 Recent Trends in Ocean Observations

Recent trends in ocean observations rely on measuring essential ocean variables, using global observing networks, transmitting the data, and applying quality control on the resulting data. We discuss each of these facets next.

(a) Essential Ocean Variables (EOVs)

Ocean Observations are expensive due to the vast, harsh, and remote oceanic environment. The international Global Ocean Observing System (GOOS) has set up the framework and requirements for an effective and efficient ocean observing system. The expert panel of GOOS has identified essential ocean

Table 1 Major physical and biogeochemical EOVs and their measuring platforms (http://www.goosocean.org)

SI No.	Essential oceanic variables (EOV) (physical and biogeochemical variables)	Observing platforms
1	Sea state	Satellite altimeters, moored buoys, drifting buoys, and coastal radars
2	Surface stress	Buoys, ships, and satellites
3	Sea surface height (SSH)	Satellite measurements, in-situ global sea level observing system (GLOSS) water level gauges
4	Sea ice	Passive microwave satellite sensors, e.g. SMOS
5	Sea surface temperature (SST)	Satellite (infrared and microwave radiometers), in-situ observations from ships, moorings, drifting buoys, floats
6	Subsurface temperature	Moorings, gliders, ARGO floats, ship-based Conductivity Temperature and Depth (CTDs)
7	Surface currents	Moorings, HF radars, satellite altimetry, Lagrangian drifting buoys
8	Subsurface currents	ADCP, ARGO floats, gliders
9	Sea surface salinity (SSS)	Satellite, floats and drifting buoys
10	Subsurface salinity	Moorings, gliders, ARGO floats, CTDs
11	Oxygen	Moorings, profiling floats, gliders, ships
12	Nutrients	Ship-based observations
13	Inorganic carbon	Surface moorings, drifting buoys, ships
14	Transient tracers (CFC, sulfur hexaflouride, tritium)	Ship-based hydrography
15	Suspended particulates	Moorings, satellite, floats, ship-based samplings
16	Nitrous oxide	Ship-based hydrography
17	Stable carbon isotopes	Ships, ship-based time series, repeated hydrography
18	Dissolved organic carbon	Ship-based time series, repeated hydrography
19	Ocean color	Satellite

variables in physics (10), biogeochemistry (9), and biology and ecosystem (7), based on their relevance, feasibility of measurement, and cost effectiveness. The major physical and biogeochemical EOVs and their measuring platforms are summarized in Table 1. (1-10 are physical parameters and 11-19 are biogeochemical parameters).

(b) Global Observing Networks: The persistent, core elements of the current global ocean observing system are the Argo float network, the moored buoy network, the drifting buoy network, voluntary observations from ships (VOS) and the global sea-level observing system (GLOSS). These are supplemented by data available from national observation assets, research activities and special projects.

- Ship Observations Team-VOS: About 4000 operational ships with approximately 240 automatic weather stations (AWS) from 25 active countries are part of the Voluntary Observing Ship (VOS) scheme. These observations are concentrated along major shipping routes, primarily in the North Atlantic

Fig. 1 Oceanographic data collection using various platforms such as ships, moored buoys, gliders, Argo floats, remote sensing, and drifting buoys

and the North Pacific. Four hundred new AWS are being installed as part of VOS by a European joint project.

- Argo: The Argo network consists of robotic profilers in the ocean, deployed around the world. This network consists of more than 3800 floats at a spatial resolution of 3 × 3 grids, with about 800 deployed every year, and each float lasting about 3–4 years. Presently, 3829 operational floats are active, contributed by 30 countries. The current network covers about ~70% of the global ocean, allowing observations of oceanic heat gain with unprecedented accuracy. These floats have provided more than 100,000 temperature and salinity profiles of the upper 2000 m of the ocean. The Argo data have been extensively used by the researchers to study the regional and global changes in the ocean temperature and ocean heat content, large-scale circulation [5, 9, 13], salinity and freshwater content [4, 6], upper ocean temperature and salinity structure during cyclones [2, 3, 10], initialization of ENSO forecasts, and sea-level studies [1, 7, 18].
- Moored buoy network: There are currently 318 moored buoys (Fig. 2) which provide 83% of the coastal/national moored wave measurements data to the countries subscribing to the GTS. Moored buoy metadata is collected in a common format and is available to the community to improve forecasts. In the near future, 35% of moored buoys (tropical and coastal/national moored buoys) will report data on the GTS in binary universal form for the representation of meteorological data (BUFR) format. This will allow integration of the moored buoy metadata system into the Joint Technical Commission for

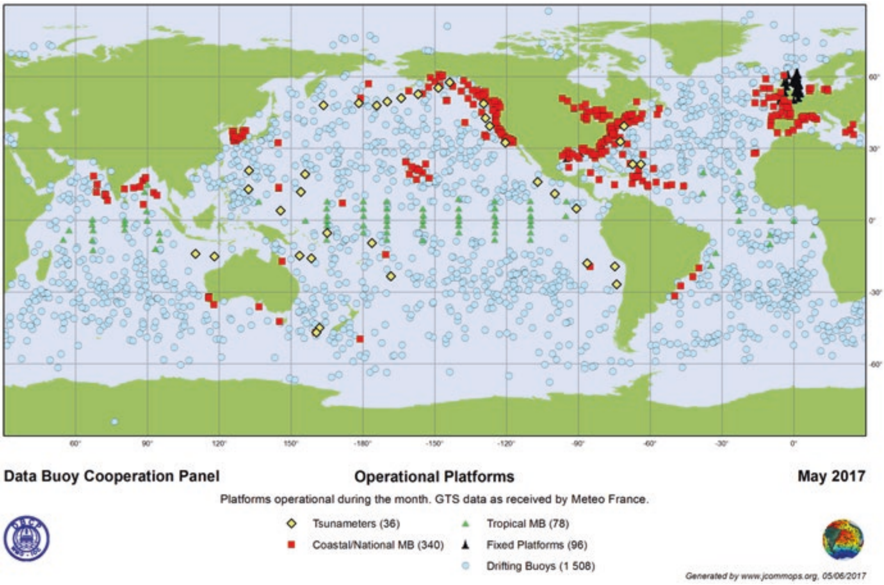

Fig. 2 Status of buoy network in the global ocean (source: http://www.jcommops.org)

Oceanography and Marine Meteorology in-situ Observing Programmes Support Centre (JCOMMOPS). The Global Tropical Moored Buoy Array (GTMBA) includes Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) in the Pacific, the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA), and the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) in the Indian Ocean [11]. Besides the GTMBA, several national networks are maintained by agencies such as National Institute of Ocean Technology (NIOT, India) [14] and National Data Buoy Center (United States). In the Indian Ocean, the moored buoys maintained by RAMA and NIOT provide invaluable data sets for understanding of the Madden-Julian Oscillation (MJO), Indian Ocean Dipole (IOD), intraseasonal variability of currents at the equator [8], and cyclones [10, 15].

- Drifting buoys: There are 1508 drifting buoys which provide data to the GTS from 11 countries. The data from 44% of the drifting buoys is reported to the GTS in less than 1 h. All of the drifting buoys report data to the GTS in BUFR format, with 57% of the drifting buoys reporting barometric pressure data to the GTS. The future plan for the drifter network calls for increasing the number of drifting buoys with air pressure measurements, improving the drifting buoys density distribution coverage, and improving the data reporting timeliness to GTS.
- Global Sea-Level Observing System (GLOSS): This network consists of about 290 sea-level stations around the world. There are roughly 161 stations reporting data, 52 stations with some data, and 77 stations not reporting . The new technologies will use microwave sensors at tide gauges. The University of Hawaii Sea Level Center produces quality-controlled data sets.

(c) Data Transmission and Telemetry

Significant advances have been made in data transmission and telemetry technology in recent years. Several observation systems are experimenting with wireless data telemetry technologies (such as Iridium satellites, IP modem, cellular phone, and underwater acoustic modems). These methods will provide wider coverage, faster data transmission, reduced field work and cost. The Iridium systems consists of a constellation of 66 low-earth orbit satellites (780km vs 35,000 km for geostationary orbits). Its merits include complete global coverage, less transmission delay, small and low power consumption receivers. This system therefore offers a good tool for emergency response applications. One of the major constraints in long-term ocean observation is power demand. The power demand profile for observational tools consists of the required battery capacity for the defined mission period, the load profile, battery chemistry, ambient temperature, self-discharge, terminal voltage, and the efficiency of the battery under the envisaged load profile. The peak power demand that occurs during the data transmission to the INMARSAT satellite transmission is 32 W, which is considerably higher than the 5 W required for an Iridium satellite communication.

(d) Quality Control and Corrections

Real-time observations of oceanographic and meteorological parameters are vital to study various short-term and long-term climatic events like cyclones, monsoons, as well as for weather forecasts. Satellites, ship-based observations, moored buoys, drifting buoys, and profiling floats are the various platforms used in modern times to get the real-time ocean and meteorological observations. These platforms sometimes transmit erroneous/bad data. Hence, to ensure the credibility of data, quality control procedures have to be adopted. Various agencies such as NDBC [7] and Quality Assurance of Real Time Ocean Data (QARTOD) have published manuals for the quality control of data sets. Simple automatic QC procedures at the data-processing centers include gross-range check, spike check, stuck value check, and climatological limits. Gross-range check looks for the values outside the range of a sensor and can measure and flag the data. The spike test looks for the difference between the present value and the average of the previous day, and if the difference is greater than the threshold value, it is marked as spike. Some parameters have a large range of variability within a day, and it is really very hard to find the real spikes in data. The wind speed during cyclonic storms increases very rapidly and crosses the threshold set for a spike. In such cases, other tests such as a correlation test with related parameters such as sea-level pressure (SLP) are used to flag the data. Stuck values or unchanging values arise due to failure of sensors or the communication system. A climatological check looks for the data points which are falling outside the seasonal expectations. Higher level delayed QC involves comparison of data with nearby or colocated observations from different sources. For example, the temperature and salinity data from buoys or floats can be validated against a CTD cast to understand drift in the sensors. Also, multiple sensors utilizing different technologies for measuring a parameter can be colocated, and the data obtained can be compared. This close neighbor approach would provide the ultimate QC check, but cost prohibits such a deployment in most cases. Density inversion tests are performed in the case of subsurface temperature and salinity measurements. Densities are compared at consecutive levels from top to bottom profile. If the density calculated at the greater pressure is less than that calculated at the lesser pressure, both the temperature and salinity values should be flagged as bad data. In delayed mode QC, the data obtained from in-situ platforms can also be compared with model simulations.

3 Emerging Trends

Oceans have been continuously explored by humans for many years. Ships, satellites, and Argo floats have been the backbone of ocean observation systems for the past many years. These are now networked and being used simultaneously for greater understanding, along with the development of new technologies. Figure 3 shows an example of a recent Indo-US collaboration OMM-ASIRI process cruise which used multiple air–sea flux moorings and a series of autonomous observational tools such as wire walkers, gliders, a robotic oceanographic surface sampler, and a large number of drifting buoys. Examples of rapidly innovative technologies include cabled observatories, animal-borne instruments, wire walkers, semi-autonomous robotic surface vehicles, and gliders, which will help to improve our measurements. An array of various sensors connected to the Internet through underwater cable will allow us to detect various energetic phenomena such as big earthquakes and volcanic eruptions remotely, thereby bringing the ocean to the desktop. Cabled observatories are yet another novel technology which has solved the power demand for long-term continuous measurements of the oceans.

While the Argo floats have increased the data density in the top 1500 m, there is a need for increasing observations to deeper depths. Long-term time series of deep observations are necessary to examine the heat budget of the oceans and monitor the long-term changes in the heat capacity of the ocean. To be able to forecast the basin-scale heat budget changes, deep ocean measurements are required. Thus, new designs such as the spherical glass deep Argo floats are emerging to enable these measurements.

Ecosystem monitoring and forecasts require in-situ observations of biogeochemical variables. Therefore, Argo floats incorporating chlorophyll, oxygen, nitrogen, backscatter, color-dissolved organic matter (CDOM), and irradiance measurements have been developed, which are called Bio-Argo (biogeochemical Argo) floats.

Numerical models have improved as faster computers have allowed better resolution, and they are important and widely used tools for oceanographers and meteorologists. Numerical modeling uses mathematical tools (differential equations), which are solved in time and space to simulate the oceanic and atmospheric conditions.

Fig. 3 Ocean data collection during the joint Air Sea Interaction Research Initiative (ASIRI) and Ocean Mixing and Monsoons (OMM) cruise in the Bay of Bengal, showing the US research vessel Roger Revelle and the Indian research vessel Sagar Nidhi

Accurate information about the marine environment is essential for shipping and navigation, defense purposes, fishing, and renewable energy. However, while solving these complex partial differential equations, a number of approximations are made. This leads to generation of errors, which will eventually grow with the model's integration time. To eliminate these errors, the models need to be checked against data, and, during the evolution, corrections need to be applied to the models. Data assimilation, the combining of model output and observations, is necessary to reduce the errors or uncertainties in forecasts. With the availability of the observations from global networks and local data sets discussed in Sect. 2, the process of data assimilation is getting increasingly more detailed. One of the recent challenges is to assimilate high-resolution data sets into numerical models. The current generation of nowcast and forecast models is capable of resolving mesoscale eddies in the oceans. Several forecast systems developed by different countries provide global ocean coverage and provide global analyses and medium and extended range forecasts of 7–18 days depending on the system, and long-range forecasts of 7 months [17]. These are increasingly done using cloud server technologies and parallel computation. Another direction of advancement is numerical investigations of biogeochemical processes to understand the oceanic ecosystem. Models like MEDUSA

(Model of Ecosystem dynamics, nutrient Utilization, Sequestration and Assimilation) and Nucleus for European Modeling of the Ocean (NEMO) are used to study the physical processes that control the distribution and activity of marine ecosystems and also to forecast the oceanic acidification and its effect on marine organisms. New mathematical models to resolve tides and waves, as well as various coupled models (ocean–wave–atmosphere–ice), are being developed [17].

Fine resolution models conducting large eddy simulations and process studies are emerging to focus on the processes which occur at scales too fine to be resolved in global, basin scale, and regional models. These process studies are then used to develop parameterizations for large-scale models. As the supercomputing capability increases in future due to faster electronics and new chip designs, future developments should also consider user efficiency, higher temporal and spatial resolution, as well as improved parameterizations of unresolved processes.

A combination of ocean observations and model simulations allows characterization of individual processes that contribute to recent changes in the ocean. The topic of in-situ ocean measurements is an evolving field, and there is continued interest in adapting new technologies to this topic. Oceanic observations are the backbone for any kind of operational services (operational forecasts, cyclones, storm surges, monsoon variability, tsunami), research and development including validation of satellite sensors, and parameterizing key processes for models and verifying model simulations. First, ocean events are dynamic and require rapid response to measure the phenomena such as eddies and other ocean currents that need to be observed in hours or days. Second, the ocean environment requires study of subtle signatures that challenge in situ instrumentation to accurately distinguish between event types. Third, since the ocean presents a hostile environment, designing and deploying autonomous underwater vehicles, gliders, and drifting buoys presents a range of engineering and technological challenges. Finally, observing systems are required to be operated in extended periods autonomously considering the remoteness of such ocean observations.

The accumulation of climate-relevant time-series parameters, for example, surface ocean currents and deep ocean temperature, will support progress of climate sciences in the years to come. Contributions from citizen-based science (CS) are a novel opportunity to fill observational gaps and increase environmental stewardship among the public (Fig. 4). CS is being used from data collection through to hypothesis generation [11].

4 Concluding Remarks

These are exciting times for future of ocean observations and their integration into predictive and ocean process models. While the ocean observatories are challenging to set up, the research community recognizes that technical ambition and scientific

Fig. 4 Futuristic forecasts will include integrating multiple networked platforms along with the "Citizen in Science" participation

excellence must be balanced with a promise of societal value. New technologies enable multiple networked tools to monitor our oceans economically and often provide greater coverage than traditional shipboard surveys. Modeling to integrate observations as well as diagnose and understand key processes is also a very important component of modern oceanographic research.

Currently using data (i.e., direct and remote measurements, model results) allows ocean scientists to accurately describe the processes occurring in the marine environment and make predictions. The future heralds several new directions, including the role of Citizen Scientist, a systemic approach to address industry needs, and research into biodiversity and climate change. Other developing areas include coastal tourism, biodiversity forecasts, and applications to marine infrastructure developmental projects. Another emerging trend would be the ability to run task-specific ocean models on mobiles and tablets.

Acknowledgments The authors thank the financial support extended by Ministry of Earth Sciences, Government of India, and the Office of Naval Research, USA, for their support during the Indo US Collaborative program (OMM-ASIRI) to conduct field experiments in the Bay of Bengal which led to the idea of writing this chapter.

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