Ocean observations: the Global Ocean Observing System

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Introduction

Although humans have been observing and recording aspects of the oceans since the beginning of recorded history, until very recently this has been done in the context primarily of increasing our understanding of the oceans and their contents, rather than for more pragmatic reasons. There were exceptions, of course, such as Benjamin Franklin’s mapping of the Gulf Stream, as an aid to navigation (Figure 7.4); but by and large, oceanographers, unlike their meteorological colleagues, have been concerned more with their science than with the applications of this science, with an associated reluctance to share data with others. However, driven initially by the need to understand and predict global climate and climate change,
coupled with a realization of the critical role of the oceans in the global climate system, recent decades have seen a significant increase in the requirement to systematically monitor ocean behaviour, with the observational data being widely and freely exchanged.

In response to calls from the Second World Climate Conference (Geneva, 1990) and the United Nations Conference on Environment and Development (Rio de Janeiro, 1992), the Intergovernmental Oceanographic Commission (IOC) created the Global Ocean Observing System (GOOS) in March 1991. The creation was also a result of the desire of many nations to gather the information required to improve forecasts of climate change, the management of marine resources, mitigation of the effects of natural disasters, and the use and protection of the coastal zone and coastal seas, the Intergovernmental Oceanographic Commission (IOC) created the Global Ocean Observing System (GOOS) in March 1991.

This paper describes the GOOS, and touches on its relation to the Global Climate System (GCOS), for which the GOOS provides the ocean component; to the Global Terrestrial Observing System (GTOS), which interfaces with the GOOS in the coastal zone; and to the more recent Global Earth Observation System of Systems (GEOSS). It summarizes the GOOS’s plans, priorities and requirements, and assesses the benefits accruing nationally from international involvement in the GOOS.

**What is GOOS?**

GOOS is:

- a sustained, coordinated international system for gathering data about the oceans and seas of the Earth;
- a system for processing such data, with other relevant data from other domains, to enable the generation of beneficial analytical and prognostic environmental information services; and
- the research and development on which such services depend for their improvement.

Implementation of the GOOS is expected to lead to an increase either in wealth (for instance through reducing the costs of certain activities) or in well-being (by ensuring safety of life and security of property). Most countries expect to benefit from the information from the GOOS, given that a significant part of world economic activity and a wide range of services, amenities and social benefits depend upon efficient management of the sea. For many countries, marine resources and services provide 3–5% of Gross National Product. For a few it is much higher. In addition, because the ocean plays a significant role in climate change, information from the GOOS is
expected to contribute to other sectors of the economy including the management of water resources, energy resources, transport, agriculture and forestry.

There are two components of the developing GOOS system, one dealing with climate and the open ocean, and the other with coastal marine observations. They are part of the same system and many of the observations are common, but their goals have been separately defined.

The open ocean component of the GOOS is designed to:

- monitor, describe and understand the physical and biogeochemical processes that determine ocean circulation and its effects on the carbon cycle and climate variability;
- provide the information needed for ocean and climate prediction, including marine forecasting;
- provide observational requirements;
- ensure that the designs and implementation schedules are consistent and mutually supportive and working as planned; and
- ensure that the system benefits from research and technical advances.

Coastal GOOS has six goals for the public good. These are to:

- improve the capacity to detect and predict the effects of global climate change on coastal ecosystems;
- improve the safety and efficiency of marine operations;
- control and mitigate the effects of natural hazards more effectively;
- reduce public health risks;
- protect and restore healthy ecosystems more effectively; and
- restore and sustain living marine resources more effectively.

**Plans, priorities and requirements for the open ocean**

Real or potential applications linked to societal needs should drive the ‘shape’ of the requirements for the open ocean observing system for climate. Ocean data are important in their own right and via their contribution to increased forecast model skill and to the continual improvement and validation of forecast models. Among the applications are: numerical weather prediction, ocean and climate prediction, short-range prediction of ocean waves, sea-ice monitoring and prediction, and future climatologies. Operational applications, on time scales of days to weeks, include coastal and offshore engineering design, tactical ocean forecasting related to national defence and civilian protection, shelf and coastal predictions and predictability, information for off-shore industries, safety and search and rescue. Climate prediction involves understanding links between oceans and atmosphere, for example in
phenomena such as the El Niño Southern Oscillation (ENSO), monsoons and the longer term variability of the Indian Ocean Dipole, North Atlantic Oscillation, Pacific Decadal Oscillation, Atlantic Tropical Dipole and Indian Equatorial Dipole, which involve global scale interactions and deep ocean circulation.

The sampling requirements for these applications developed in the late 1990s included both in situ and satellite observing platforms. The GCOS established a list of the Essential Climate Variables that are both currently feasible for global implementation and have a high impact on the requirements of forecasting climate change. For the oceans these include: sea surface temperature, salinity, sea level, sea ice, ocean colour for biological activity; subsurface temperatures, salinities, currents, nutrient and carbon dioxide concentrations, and phytoplankton distribution.

The systems for open ocean measurement under the aegis of the GOOS were initially designed by the Ocean Observing System Development Panel, refined in the 1998 Action Plan for GOOS/GCOS, and further refined in the GCOS Implementation Plan. Status maps of the distribution of individual components of the network, such as locations of tide gauge stations, drifting buoys, ships’ tracks and so on can be accessed from the JCOMM in situ Observing Platform Support centre (JCOMMOPS): http://wo.jcommops.org/cgi-bin/WebObjects/JCOMMOPS. The marine meteorological observations include measurements of temperature, air pressure, wind speed and direction, precipitation and water vapour.

Much remains to be done to make the GOOS fully operational for climate forecasting. We require global coverage; more high-quality observations; ocean biogeochemical variables; ocean analysis and reanalysis combined with data assimilation to realize the value of the networks; national centres or services dedicated to implementation and maintenance of the observing system; long-term funding commitments; national operational ocean services analogous to national weather services; and commitments to sustained data streams from experimental satellites. At the same time some real progress is being made, as evidenced by the success in implementation of the planned network of Argo profiling floats in a relatively short time period (Figure 11.1).

Systematic sampling of the global ocean subsurface for temperature and salinity to characterize ocean climate variability and ocean behaviour will be addressed through developing the Upper-Ocean Network (currently, 3000 Argo floats; 41 Repeat XBT Lines; 29 Surface Reference Moorings; 120 Tropical Moorings; high-resolution satellite altimetry). The global reference moorings network will provide essential reference-quality, long-time records of subsurface variables to identify climate trends, and the basis for testing models. Deep-ocean time series observations are also essential for determining long-term trends. Much of this work is taking place through the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM), which is the implementation arm of the GOOS.
The routine generation of ocean climate products will provide essential ocean data for global climate and weather models needed by governments. All actions are technologically feasible and can be accomplished with established coordination mechanisms and agreements. The composite approach, with carefully balanced contributing systems and networks and broad coordination and cooperation, is essential for meeting the requirements.

Figure 11.1 (a,b) Progress made in the Argo profiling float network since January 2003. Data from JCOMM.
The major weaknesses of the present observing system are the lack of global coverage of the ocean, the need for autonomous and remote instruments for the entire oceanic variables list, the need for expanded and more effective data and product systems, and the need for long-term continuity of national efforts along with international coordination. Present global effort depends heavily on the efforts and funds of the research community. National and regional agents of implementation with clear tasking and adequate on-going resources are needed. Continued research is required to improve and develop observing capabilities for some variables and to make systems more robust and cost-effective.

The implementation of the GOOS will largely depend upon the commitments made by the participating nations to support the observing subsystems through their national observing agencies, to provide infrastructural elements such as data centres and distribution networks, and to supply the necessary scientific and technical research and development to underpin the system. Much will be accomplished through regional alliances, but a global approach will be needed to address the ocean’s role in the climate system. In addition a number of scientific and technical challenges must be met. We need satellite observations with higher resolution and accuracy and more spectral bands from geostationary satellites; we need improved observing system evaluation and design, including improvements in air–sea flux parameterizations; better ocean platforms are required; better ocean sensors and systems are wanted; and better instruments are needed. These are all technologically feasible, and are happening now, but national commitment to implementation and long-term maintenance remains the key.

Observing system requirements for the coastal ocean

The coastal ocean includes all coastal waters, including lagoons and estuaries, as well as the waters of the continental shelf and Exclusive Economic Zone. As for climate-related observations, real or potential applications linked to societal needs should drive the ‘shape’ of coastal applications.

The establishment and maintenance of such a user-driven, sustained, integrated and end-to-end system is the purpose of the coastal module of the GOOS. Two kinds of plans have been produced for observations from the coastal ocean. The first concerns the actual coastal ocean measurements that should be made. The second concerns the coastal ocean observing systems that should be used to make those measurements.

Integration across the land–sea boundary is essential, because changes in the state of coastal ecosystems commonly depend heavily on changes on the land, for example,
increased population and changing land use can increase pressure on coastal seas. This can be through extraction of living resources, or nutrient or contaminant loading, which may lead to loss of commercial fishing value, decreased public health or costly coastal floods. These in turn require managed, usually government, responses such as fishery management, sewage treatment plants and controlled land use.

Informed decisions by coastal managers, nationally or through local government agencies, demand that information is supplied at rates tuned to the time-scales at which decisions have to be made. To satisfy that requirement the coastal module of GOOS must meet these criteria:

- measurements, data streams and analyses required by user groups are sustained, routine, guaranteed, continuous or repetitive as needed, and of known quality;
- measurements and data analyses (e.g. modelling) are efficiently linked via integrated data management and communications;
- observations capture a broad spectrum of variability in time, space and ecological complexity;
- observations are multi-disciplinary and the resulting data streams and products support a broad diversity of applications; and
- the system provides data and information required to relate changes in environmental systems to changes in socio-economic systems.

Present and potential users for data and information about the coastal ocean are summarized in Table 11.1. These users are interested in knowing about a wide range of phenomena (Table 11.2).

Considering the variety of user communities and their interests, six broad categories of societal issues can be identified:

- improving the capacity to detect and predict the effects of weather and climate change on coastal ecosystems;
- improving the safety and efficiency of marine operations;
- more effectively controlling and mitigating the effects of natural hazards;
- reducing public health risks;
- more effectively protecting and restoring healthy ecosystems; and
- more effectively restoring and sustaining living marine resources.

These six issues have common requirements for data and information. For example, search and rescue, health risks of exposure to pathogens while swimming, and forecasts of the trajectories of oil spills and harmful algal blooms all require nowcasts of surface current fields.
Table 11.1 User Groups for data and information from the coastal ocean

<table>
<thead>
<tr>
<th>Shipping</th>
<th>Marine energy</th>
<th>Marine mineral extraction</th>
<th>Insurance and re-insurance</th>
<th>Coastal engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fishing community</td>
<td>Agriculture</td>
<td>Aquaculture</td>
<td>Hotel and catering</td>
<td>Consulting companies</td>
</tr>
<tr>
<td>Search and rescue</td>
<td>Port authorities and services</td>
<td>Weather services</td>
<td>Government agencies for environmental regulation</td>
<td>Freshwater industry</td>
</tr>
<tr>
<td>Public health authorities</td>
<td>National security</td>
<td>Wastewater management</td>
<td>Coastal management</td>
<td>Emergency response agencies</td>
</tr>
<tr>
<td>Tourism</td>
<td>Conservation groups</td>
<td>Seafood consumers</td>
<td>Recreational swimming and boating</td>
<td>News media</td>
</tr>
<tr>
<td>Educators</td>
<td>Scientific community</td>
<td>Charting and navigational services</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 11.2 Examples of phenomena of interest from the coastal ocean

<table>
<thead>
<tr>
<th>Sea state</th>
<th>Forces on structures</th>
<th>Coastal flooding</th>
<th>Currents</th>
<th>Sea level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoreline change</td>
<td>Seabed topography change</td>
<td>Chemical contamination of seafood</td>
<td>Human pathogens in water and shellfish</td>
<td>Habitat modification and loss</td>
</tr>
<tr>
<td>Eutrophication, oxygen depletion</td>
<td>Change in species diversity</td>
<td>Biological response to pollution</td>
<td>Harmful algal bloom events</td>
<td>Invasive species</td>
</tr>
<tr>
<td>Water clarity</td>
<td>Disease and mass mortality in marine organisms</td>
<td>Chemical contamination of the environment</td>
<td>Harvest of capture fisheries or of aquaculture</td>
<td>Abundance of exploitable living marine resources</td>
</tr>
</tbody>
</table>
The main elements of the Coastal Ocean Observing System are:

- measurements (sensing), sampling and data transmission (monitoring);
- data management and dissemination; and
- data analysis and modelling (including data assimilation).

The measurement subsystem samples the ocean both remotely and *in situ* and consists of the mix of platforms, sensors, sampling devices and measurement techniques needed to measure variables on required time and space scales. The data management subsystem links observations to the data analysis and modelling subsystem and ultimately to products and services.

The coastal measurement subsystem comprises national, regional and global entities. National GOOS Programmes can bring together observations made by a range of national agencies. More broadly, nations sharing a common sea area are encouraged to work together through GOOS Regional Alliances (GRAs) to create a whole that is greater than the sum of its parts, and from which they can all benefit. Aside from GRAs, other regional bodies may have regional interests in GOOS. The International Council for the Exploration of the Sea (ICES) has an IOC/ICES GOOS
Working Group to consider how ICES may contribute to the development of the GOOS in the North Atlantic and the seas around Norway. The Scientific Committee on Antarctic Research (SCAR) and SCOR are developing the design for a Southern Ocean Observing System (SOOS), which could form the basis for a Southern Ocean GRA.

A global approach is needed to recognize that many phenomena of interest occur in coastal waters worldwide and are often local expressions of larger scale forcing. The Global Coastal Network (GCN) is designed to capture variability and change across global to local scales. The observing and data management subsystems of the GCN measure and process the common variables required by most regional systems. The GCN is essential for comparative analyses of changes occurring within regions on global scales, for global assessments of changes in the state of coastal marine systems, and for serving global products on national to regional scales. GCN will include all relevant satellite measurements.

Many of the required elements are already being monitored (often at a higher frequency than is required for the GOOS) by national agencies in industrialized countries. Not all measurements needed for coastal seas are made in the ocean. Stream gauges in rivers make an essential contribution to understanding the coastal ocean. In situ measurement networks are generally sparse, making the coastal ocean undersampled. Increasing coverage by such instrumented networks is a significant challenge, as is a strategy for putting multiple instruments on single measuring platforms to maximize sampling returns. There is also a significant challenge in providing continuity of

Figure 11.3 Marine mammals carrying sensors are excellent collectors of data. Image courtesy of John Gunn, Australian Antarctic Division.
measurement from in situ coastal systems, because local conditions (high waves, fouling, ice) may lead to demands for frequent maintenance and/or replacement of instruments.

Many coastal data are acquired these days, and probably increasingly in future, by remote sensing from satellite. High accuracy is obtained from those systems used for physical mapping of bathymetry, topography and shoreline position. Nevertheless, it is important to ensure access to the highest resolution Digital Elevation Models to

Figure 11.4 Marine observations begin at the shore and extend to the deep ocean: (a) met station and lighthouse © Yegor Korzh/Shutterstock.com, image ID 1021423; (b) Woods Hole Oceanographic Institution (WHOI)-operated submersible Alvin, image courtesy of Woods Hole Oceanographic Institution.
determine elevation with land–sea continuity. Some sensors have problems in the coastal ocean. For example, although satellite-derived sea surface temperature is a mature and robust measurement, it requires improved resolution in space and time to address coastal needs. Although there are numerous multi-spectral satellite sensors (MODIS, MERIS, etc.) that can provide optically derived products such as pigment and dissolved or suspended matter concentrations, they are primarily focused on the global domain, and have limitations in spatial and/or temporal resolution in coastal seas. Improved instrument calibration and validation remain pressing needs. Continuity of satellite measurement is an ever present concern here and in the open ocean.

Significant obstacles exist to hinder the data integration needed for the holistic study of the coastal domain. These include communication difficulties between the disparate elements of the coastal community, data access and management issues, and the unique challenges of the coastal regions. These difficulties can be resolved through community efforts, following a national or regional plan.

Coastal GOOS will evolve in response to user demands for data and data-products and services. Evolution will depend on implementation of known technologies, and on research and pilot projects to develop new observational capabilities, especially for those goals related to public health, ecosystem health and sustainable resources. Transition from sustained observations supported by research funds to those supported by operational funds is a major step and the joint responsibility of both
research and operational communities. Many of these steps are likely to be seen as desirable not merely to meet the demands of the GOOS, but also to meet the growing demands of government departments.

Global, regional and local trends in natural processes and human demands jeopardize the ability of coastal ecosystems to support commerce, living resources, recreation and habitation. Concerns have led to numerous international agreements that require sustained and routine observations of both coastal terrestrial and marine systems. Meeting the terms and conditions of these conventions and action plans requires the establishment of an integrated global system of observations for the atmosphere, oceans and terrestrial systems as part of the Global Earth Observing System of Systems (GEOSS).

The polar oceans

The Arctic and the Southern Ocean are key elements of the Earth system, since it is there that cooled water sinks to ventilate the global ocean, carrying climate signals worldwide. These regions are highly sensitive to global warming. What happens there will have a considerable influence on climates elsewhere, especially at mid latitudes. Despite their importance, polar seas are poorly monitored, not least because of their harsh conditions and geographical remoteness. Many more observations of the polar oceans are needed to understand and predict climate change accurately. A key problem concerns measurement of ocean properties
year-round beneath the sea ice. Modified Argo floats, moorings, gliders and instrumented marine mammals provide various means of escaping from this constraint.

### The Future

Several nations have considered ways in which benefits may accrue from ocean observations. The benefits are shown to be considerable. It appears from these and many other similar studies that an ocean observing and forecasting system will generate positive dividends significantly greater than its costs; that the benefits will be significant, and that because expenditure and incomes for the various parts of the system do not occur in the same places, or agencies, or at the same times, a national and/or regional view is required to maximize the net benefits in terms of public good. The short-term products and benefits should provide an economic return that covers the investment required for the long term.

Most operational oceanography is carried out locally, to solve local problems – for instance to provide information for oil platform operators in a specific area, or to monitor and model water levels in a particular port and its approaches.

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**Figure 11.7** A spray-glider returns from mission. Spray is an underwater glider developed under ONR support by Scripps and Woods Hole scientists to provide a small long-range autonomous platform for long-term ocean measurements. © IOC/UNESCO.
However, local conditions are always subject to regional controls, set in a global ocean-atmosphere-ice system with teleconnections between far-flung areas. The benefits to any particular nation from international involvement in the GOOS arise on two scales – on the broad scale and on the local scale. On the broad scale it is axiomatic that ocean processes know no boundaries. The water masses moving through a nations’ Exclusive Economic Zone may come from many different parts of the particular ocean basin, including the polar regions. Given the global scale of these features, it is simply not feasible for any one nation to monitor these different water masses and the ways in which they change along their course, in such a way as to provide a sound basis for forecasting national environmental or climate changes. The task is global and demands cooperation and coordination.

**Figure 11.8** Observations from space cover vast areas in a short time. Here the progress of a tropical cyclone in the Atlantic Ocean is being monitored. © Vladislav Gurfinkel/Shutterstock.com, image ID 13827235.
Aside from providing the benefits in the form of a wide range of direct products and services, open ocean data from all sources, and integrated by national agencies, also provide the boundary conditions for those agencies running numerical models of the behaviour of their coastal waters. These waters are themselves an integral part of the coastal waters of the whole region. The sharing of data on these waters is essential if the detailed behaviour of coastal seas is to be fully understood and forecast, as the basis for the provision of local products and services. Benefits come from the free exchange of data and information between neighbours, and from implementing local, regional and global ocean observing programmes in a coordinated and cooperative way.

Figure 11.9 So much to measure; so few resources. © Snaprender/Shutterstock.com, image ID 9875449.
To improve those benefits requires improving the observing system in consultation with representatives of the full range of data suppliers and end users, which together form the ‘stakeholders’ in the system. The stakeholders in the GOOS are much broader than organizations with purely ocean and coastal interests, because ocean data are useful not only in the provision of ocean products and services, but also integrated with data from atmospheric and terrestrial observing systems, in the provision of environmental products and services required to address the environmental concerns of many land-based sectors.

There is no doubt that GOOS has come a long way since the initiation of the concept, more than two decades ago. For one, the concept is now part of the international environmental vocabulary, and the GOOS has an established role as the ocean component of the GEOSS. Governments, agencies and individuals generally recognize that they stand to gain many times more from cooperation and sharing through GOOS than their individual contributions. There is also broad acceptance of the need for composite, integrated observations, and that no single approach to ocean observation can ever provide all the answers. At the same time, technological advances in observing sensors and platforms (in situ and remote sensing), as well as in data communications and processing, mean that we are now able to take a snapshot of the physical state of the global ocean, in real-time, on a daily basis. Combining this with enhanced scientific understanding, modelling and data assimilation techniques, and with super-computing power, we have ocean prediction models which show skill comparable to that of numerical weather prediction in the early 1980s. There is no doubt that our scientific and technological capabilities will continue to advance, and will soon extend to coupled physical and biogeochemical processes. The need for and potential of GOOS is perhaps greater now than when we first started.

But there remain problems. Unlike in meteorology, where national requirements for data and services were (and still are) driven largely by aviation and public safety, there is yet no single, ‘big-ticket’ issue to drive the GOOS, apart perhaps from climate. This means that Governments see no compelling reason to invest heavily in observing the open ocean, a global commons, and a large proportion of open ocean GOOS remains funded through and maintained by research programmes. On the other hand, in coastal GOOS, issues of national sovereignty, security and economic interest in many cases continue to override the potential value of international cooperation and data sharing. In summary, as noted in a recent review of GOOS ‘funding commitments are inadequate and mostly short-term, a problem which is particularly challenging for implementation of coastal GOOS since most of the global coastal ocean is in the Exclusive Economic Zones of developing countries’.

Nevertheless, we do have reason to be optimistic. In many countries, drivers for the GOOS related to global change and the increasing degradation of the marine
environment are gaining public as well as scientific attention. Couple this with the ever-improving skills in modelling and predicting the state of global, regional and local ocean conditions, as well as new ways of managing and displaying ocean data, and we have the means to attract and retain the attention of Governments on the need to systematically monitor the oceans on an ongoing basis – for which the GOOS provides the established and successful mechanism.