CHAPTER 3

The Global Ocean Observing System

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In the last 20-30 years, much progress has been made in the deployment of sustained, nationally and internationally coordinated ocean observing programs. These include the Argo array of profiling floats, ocean glider missions, the global drifter array, Ships of Opportunity (SOOP) eXpendable Bathythermograph (XBT) lines, deep water moorings, Global Ocean Ship-based Hydrographic Investigation Program (GO-SHIP), and new pilot studies extending to boundary currents, the deep ocean, and the marginal ice zones. In general, many of the observing systems were originally designed to resolve ocean variability at timescales from sub-seasonal to longer; however, the data are now also essential for ocean forecasting and prediction projects. Improved satellite technologies and telecommunications has enabled much of the ocean observations data to be recovered in real-time. The advent of rapid and timely access to data has led to the increasing use of ocean data in operational oceanography systems for the purpose of providing increasing accurate and reliable global and regional ocean (eddy resolving) forecasts. In this chapter, we provide an overview of the global in situ ocean observing systems for measuring physical Essential Ocean Variables (EOVs), including all the major platforms, and the efforts of the international coordinating programs.

Physical Ocean Observations

Introduction

In situ observations of the ocean remained relatively sparse and regionally-focused until the 1990s (Gould et al., 2013). The success of large multinational projects — Tropical Ocean Global Atmosphere (TOGA), TOGA-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE), World Ocean Circulation Experiment (WOCE), and Joint Global Ocean Flux Study (JGOFS) — provided the impetus for coordinated global-scale in situ observations. This, in part, led to the Intergovernmental Oceanographic Commission (IOC) creating the Global Ocean Observing System (GOOS, www.goosocean.org) in 1991.

The GOOS is a highly collaborative, multidisciplinary system of observation networks built around nationally-managed and nationally-funded observing elements (satellites, buoys, scientists, etc.). GOOS provides a coordination mechanism for national contributions to come together to deliver sustained observations of the global ocean and relies on its expert stakeholders to represent concerns of their home nations. GOOS utilizes the Framework for Ocean Observing (http://www.oceanobs09.net/foo/) to guide its implementation of an integrated and sustained ocean

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observing system. This approach is designed to enable the ocean observing system to build flexible networks that can adapt to evolving technological developments as well as scientific and user requirements.

Essential Ocean Variables

Following the Global Climate Observing System's (GCOS) successful development and advocation for measuring Essential Climate Variables (Bojinski et al., 2014), GOOS has defined the Essential Ocean Variables (EOVs) required to meet the needs of the diverse user community. This user community includes climate and climate variability researchers, operational services and ocean health application areas. The adoption of EOVs is not intended to replace existing ocean observing networks and international coordination groups, but to provide a way to bring them together to develop a holistic ocean observing system and strengthen the ocean observing system's ability to meet all current and future user requirements.

EOVs are identified by the GOOS Physics and Climate, Biogeochemical, and Biology Panels (the GOOS Expert Panels), based on the following criteria:

Relevance: The variable is effective in addressing the overall GOOS Themes – Climate, Operational Ocean Services, and Ocean Health.

Feasibility: Observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods.

Cost effectiveness: Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology and taking advantage, whenever possible, of historical datasets.

The EOVs were determined using these criteria. However, it was recognized that not all EOVs are at the same level of implementation in the global observing system. A readiness level has been developed to offer an indication of our ability to provide a variable to meet the users' requirements. The readiness level considers: (1) **requirement processes**: technological maturity, adequate sampling frequency, measurement precision and quality control, satisfaction of multiple user needs, and ongoing international community support; (2) **coordination of observations elements**: Global and sustained observations, periodic review process, availability of specifications and documentation, and (3) **data management and information products**: Standardized and interoperable data outputs, global availability of useful data, data management and distribution policies. Each EOV is assessed against the three readiness elements and categorized as either concept, pilot, or mature.

The list of EOVs and their readiness level are shown in Figure 3.1. All of the physical and biogeochemical ocean variables are classed as mature, except for ocean surface heat flux, while many of the biological/marine ecosystem EOVs are either pilot or concept.

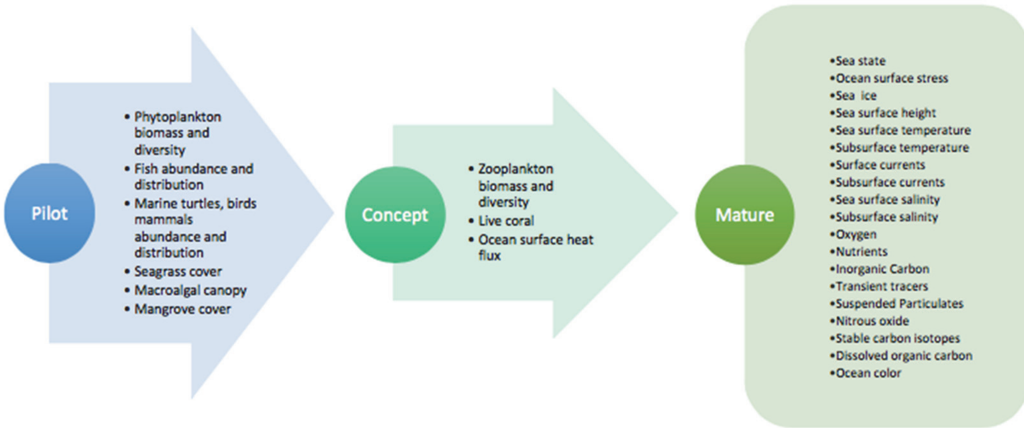

Figure 3.1. List of GOOS Essential Ocean Variables (EOVs) grouped as Pilot, Concept, or Mature.

International Ocean Observing Networks.

The EOVs are collected using a wide array of platforms and, in some cases, instruments and technologies. The technologies comprising the physical ocean in situ observing system include moored surface buoys, surface drifters, sub-surface moorings, satellites, floats, gliders, research and vessels of opportunity, and tidal stations (Figure 3.2).

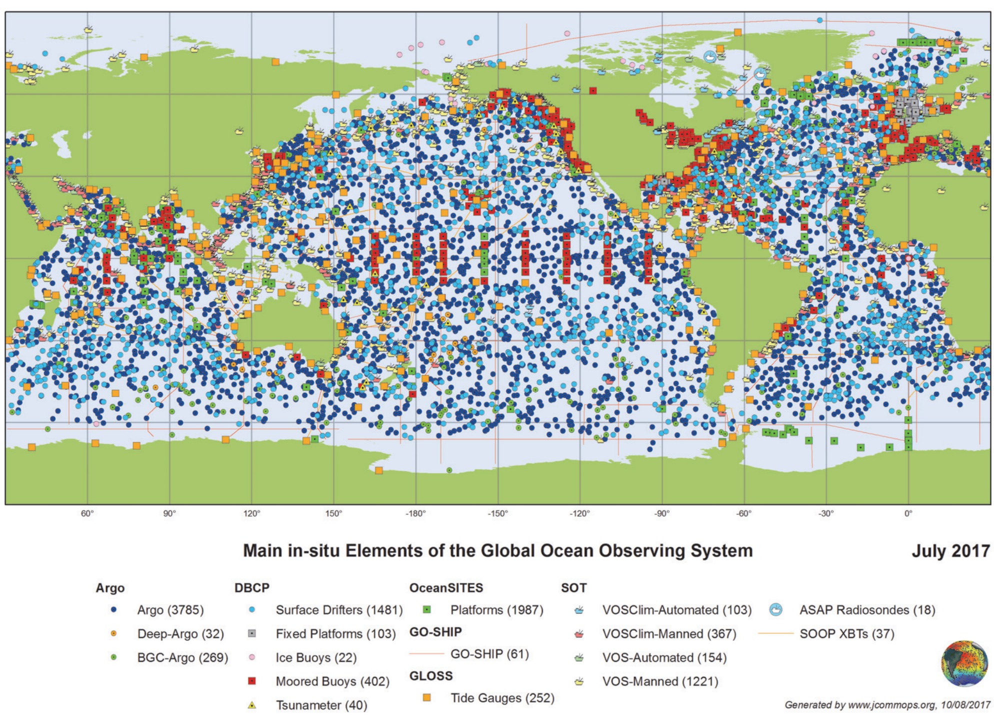

Figure 3.2. Components of the global ocean observing system.

The six major programs that currently comprise the global ocean observing system are Argo, Data Buoy Cooperation Group (DBCP), OceanSITES, the Global Ocean Ship-based Hydrographic Investigation Program (GO-SHIP), the Global Sea Level Observing System (GLOSS), and the Ship Observations Team (SOT), which consists of several programmes including the Volunteer Observing Ship (VOS) scheme and Ship of Opportunity Programme (SOOP). In addition, the international community is now establishing a coordinating group for ocean gliders and animal tagging.

Here we provide a brief overview of these programs. Each program provides detailed information on data collection, data processing, and data availability via comprehensive web pages. The reader is referred to these for detailed information and recent updates.

Argo

The broad-scale global array of temperature/salinity (T/S) profiling floats, known as Argo (http://www.argo.ucsd.edu/), is a major component of the ocean observing system, complementing satellite observations of sea surface height. Argo exemplifies international collaboration and data management, and offers a new paradigm for data collection. Float deployments began in 2000 and continues at the rate of about 800 floats per year. The design of the Argo network is based on experience from the present observing system, knowledge of ocean variability observed by satellite altimeter, and the requirements for climate and high-resolution ocean models. The array of almost 4000 floats provides 140,000 T/S profiles and velocity measurements each year distributed over the global ocean at an average 3-degree spacing, including the seasonal ice zone. Argo park depth is 1000 db where they drift for nine days, descending to 2000 db to begin the full 2000 db ascent profile. Floats will cycle to 2000 m depth every ten days, with four- to five-year lifetimes for individual instruments.

Pilot projects or design experiments are underway for enhanced observations in the equatorial and boundary current regions, as well as a Deep Argo array, and a Biogeochemical Argo array.

GO-SHIP

Building on previous global-scale hydrography efforts (WOCE, JGOFS, CLIVAR), GO-SHIP (the Global Ocean Ship-based Hydrographic Investigation Program; www.go-ship.org) is the systematic and global survey of select hydrographic sections being carried out by an international consortium of 16 countries and laboratories. GO-SHIP sections span all of the major ocean basins and the full-depth water column. Ship-based hydrography, at present and for the foreseeable future, is the only method for obtaining coincident high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. GO-SHIP data are freely available in a timely manner to the scientific and general community from a number of data servers.

GO-SHIP's unique contributions to the observing system are: coast-to-coast, top-to-bottom, near-synoptic section observation resolving boundary currents; highly accurate measurements of a full suite of water properties (salinity, oxygen, nutrients, carbon parameters, chlorofluorocarbons, isotopes, turbulence, and more) to detect subtle changes in the full ocean depth; provision of high-quality reference observations to other components of global ocean observing system that use autonomous observing platforms (e.g., Argo and SOOP), and supports validation and development of regional and global climate models, and a platform for testing new ocean observing technologies.

GO-SHIP provides changes in inventories of heat, freshwater, carbon, oxygen, nutrients, transient tracers, and other ocean properties at approximately decadal resolution. The GO-SHIP data are used for major assessments of the role of the ocean in mitigating climate change, research publications, atlases and other climate products, and outreach materials.

Moored/ship-based time series (OceanSITES)

OceanSITES (http://www.oceansites.org/) oversees a worldwide system of long-term, open-ocean time series stations measuring dozens of variables and monitoring the full depth of the ocean from air-sea interactions down to the seafloor. It is a network of stations or observatories measuring many aspects of the ocean's surface and water column using, where possible, automated systems with advanced sensors and telecommunications systems and yielding high time resolution, often in real-time, while building a long record. Observations cover meteorology, physical oceanography, transport of water, biogeochemistry, and parameters relevant to the carbon cycle, ocean acidification, the ecosystem, and geophysics.

OceanSITES comprises air-sea flux moorings, transport arrays, the Tropical Moored Buoy[2] array, and multidisciplinary time series sites. In some cases, these are individual moorings in a region of high interest. In other cases, multiple moorings are used in an array to measure transport, for example, to observe boundary current transport or to observe basin-scale meridional transports.

While most moorings carry instrumentation that record data internally, technical advances are increasing the real-time availability of OceanSITES data. Surface buoys allow satellite data telemetry, and subsurface data are brought to the surface by inductive, acoustic, or hardwire links. At some sites, ocean gliders are now used to acquire the data from subsurface moored instrumentation via acoustic modems and then transmit the data via iridium when they surface. Other sites use data capsules that are periodically released from the mooring to float to the surface and pass on subsurface data.

DBCP – Meteorological moorings

Marine meteorological moored buoys (http://www.jcommops.org/dbcp/) are deployed, operated, and maintained by various National Meteorological and Hydrological Services (NMHSs) under the World Meteorological Organization (WMO) framework and complement other sources of synoptic surface marine meteorological observations in coastal areas and the high seas. They provide data in support of marine services such as marine weather (and wave) forecasts, provision of maritime safety information to end users, and are assimilated into high-resolution and global numerical weather prediction models. Capabilities vary from country to country, with most (if not all) buoys measuring meteorological variables and some networks also measuring oceanographic variables. Many of these networks have been in place for 20 years or so and deliver data for weather and ocean state prediction.

[2] TAO/TRITON (in the Pacific), RAMA (in the Indian Ocean), PIRATA (in the Atlantic).

DBCP – Global Drifter Program

The objectives of the Global Drifter Program (http://www.aoml.noaa.gov/phod/dac/index.php), formerly known as the Surface Velocity Program (SVP), are to maintain a global 5° x 5° array of satellite-tracked surface drifting buoys (excluding marginal seas, latitudes > 60°N/S and those areas with high drifter 'death' rates) to meet the need for an accurate and globally dense set of in situ observations of mixed layer currents, sea surface temperature (SST), atmospheric pressure, winds and salinity, and provide a data processing system to deliver the data to operational and research users. Data from the Global Drifter Array make a valuable contribution to short-term numerical weather prediction (NWP), longer-term (seasonal to inter-annual) climate predictions, as well as climate research and monitoring. They are also used to validate satellite-derived SST products.

Ocean surface drifters were standardized in 1991, with drogues centered at 15 m below the surface. In 1993, drifters with barometer ports (called SVPB drifters) were tested in the high seas and proven reliable. Recent analysis has refined the array target to improve global coverage, including marginal seas. More accurate thermistors for high-resolution SST have been deployed and are being evaluated for impact on satellite SST calibration and validation. The archive of quality-controlled drifter data is updated quarterly.

SOT- Underway Observations from Ships (Ship Observations Team – VOS and SOOP)

Observations (http://www.aoml.noaa.gov/phod/soop/index.php) are being taken aboard underway vessels for a variety of observation programmes, which requires different levels of engineering and human intervention on the ship. Vessels used include commercial ships, ferries, as well as research and supply vessels. Some of the programmes require repeat transect observations, while others are focused on broader-scale observations. Research vessels and those servicing moorings (DBCP and OceanSITES moorings) provide the added benefit of delivering comprehensive high quality underway observations.

SOT - Voluntary Observing Ships (VOS)

Voluntary Observing Ships (VOS, http://sot.jcommops.org/vos/) are recruited and operated by NMHSs under the framework of the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) Ship Observations Team (SOT) to complement other sources of synoptic surface marine meteorological observations in coastal areas and the high seas. They provide essential support for global numerical weather prediction, climate applications, and marine services activities such as marine forecasting and the provision of maritime safety information to the maritime industry and port authorities. VOS data are also used in climate research and reanalysis. VOS provide most of the air temperature and humidity observations over the ocean.

While observations have increased close to the coast, there has been a decline in the number of observations in the open ocean due to changes in ship operations. VOS objectives are to sustain a network of vessels that provides weather and ocean observations via automated systems and human (manual) observations. There are currently over 3,000 active VOS ships that submit nearly two million observations each year.

SOT - VOS underway thermosalinograph observations

Thermosalinographs collect underway temperature and salinity data from the engine intake on vessels, usually complementary to other data streams such as underway CO_2 observations. These observations are collated and quality-controlled as part of the Global Ocean Surface Underway Data (GOSUD) Project.

SOT - SOOP XBT

An eXpendable BathyThermograph (XBT) is a probe that is dropped from a ship and measures the temperature as it falls through the water to a depth of approximately 800 m. The core XBT mission is to obtain multi-decadal upper ocean temperature profile data along specific transects that typically span ocean basins. The XBT observations constitute a large fraction of the archived ocean thermal data between 1970-1992. Until the full implementation of the Argo array, XBTs constituted 50% of the global ocean thermal observations, providing sampling initially during regional research cruises and later along major shipping lines but with a broad-scale spatial sampling strategy. Currently, XBT observations represent approximately 15% of temperature profile observations and they are the main practical system used for monitoring transports in boundary currents, eddies, and fronts by repeat sampling across fixed transects, some of which now have 30-year time series.

XBT observations are complementary to other ocean observation systems, and transects are maintained in locations that maximize the scientific value of the observations. Fixed transects (30-35) are maintained by the scientific community in either high density or frequently repeated modes. High density transects (occupied at least four times per year, with profiles at approximately 25-50 km intervals along the ship track and finer resolution of approximately 10 km across the equator and in-boundary currents), enable the calculation of heat and mass fluxes of boundary currents and the closing of gyre-scale heat and mass budgets of ocean basins. Frequently repeated transects (12-18 times per year, 100-150 km intervals) are positioned in areas of high temporal variability and enable studies of long-term means, seasonal cycles, and large-scale ocean circulation.

Tide gauge network (GLOSS)

The Global Sea Level Observing System (GLOSS; http://www.psmsl.org/gloss/) maintains high quality global and regional sea level observations. The network is comprised of approximately 300 sea level/tide gauge stations around the world for long-term climate change and oceanographic sea level monitoring that conform to requirements for representativeness of regional conditions, a core set of observations, and data delivery/availability. The core network is designed to provide an approximately evenly-distributed sampling of global coastal sea level variations. The final repository for GLOSS data is delivered to the Permanent Service for Mean Sea Level (PSMSL) repository, which is the preeminent global data bank for long-term sea level change information from tide gauges.

In addition to these well-established programs, GOOS is helping to establish coordinating programs for new technologies, which are increasingly becoming a part of the global ocean observing system (e.g., animal tagging).

EOV	Profiling Floats (Argo)	Repeat Hydrography (GO-SHIP)	Time series Sites - Moored/ Ship	Metocean moorings (DBCP)	Drifters – including buoys on ice (DBCP)	Voluntary Observing Ships (VOS)	Ships of Opportunity (SOOP)	Tide Gauges (GLOSS)	Ocean Gliders	Tagged Animals
Temp. (surface)	X	X	X	X	X	X	X		X	X
Temp. (subsurface)	X	X	X				X		X	X
Salinity (surface)	X	X	X	X	X	X	X		X	X
Salinity (subsurface)	X	X	X						X	X
Currents (surface)		X	X		X					
Currents (subsurface)	X	X	X						X	
Sea level	X		X					X		
Sea state			X	X	X	X				
Sea ice				X	X	X				
Ocean surface stress (OSS)		X	X	X		X				
Ocean surface heat flux (OSHF)		X	X			X				
Atmospheric Surface Variables										
Air temperature			X	X		X				
Wind speed and direction			X	X	X	X				
Water vapour			X	X		X				
Pressure			X	X	X	X				
Precipitation			X	X		X				
Surface radiation budget			X	X						

Table 3.1. Relationship between physical EOVs and Observing Platforms/Networks. Also included are atmospheric observation collected by the observing platforms/networks (GCOS, 2016).

Ocean gliders

Autonomous underwater glider technology has developed significantly over the last decade and gliders are now operated routinely, providing sustained fine-resolution observations of the coastal ocean, from the shelf to the open ocean. Long-term repeat sections can be carried out with gliders, considered steerable profiling floats to maintain oceanic measurements over the water column in regions of interest. A global glider program (http://www.ego-network.org/dokuwiki/doku.php) is being established as part of GOOS that will provide international coordination and scientific oversight to consider the role of gliders in the sustained observing system; the focus will likely be on the ocean boundary circulation area that links the coastal ocean and the open sea.

Animal tagging

Tagged animals (particularly conductivity, temperature, and depth [CTD]-tagged pinnipeds such as seals and sea lions) fill a critical gap in the observing system by providing profile data in the high-latitude ocean, including under the ice. Activity peaked during the International Polar Year (2007–2009). The primary motivation for tagging pinnipeds is for ecosystem monitoring, so coordination is needed to ensure that deployments provide information for biological and physical applications. Coordination is generally regional-/project-based but it would be beneficial to move towards global coordination of observations (including tagging locations, species, and their ranges), and particularly in the coordination of data assurance and quality procedures. Such global coordination would also facilitate systematic expansion and integration of T/S profile collection from other species. As a start toward global coordination, the Marine Mammals Exploring the Oceans Pole to Pole (MEOP) consortium (www.meop.net) brings together several national programmes to produce a comprehensive, quality-controlled database of oceanographic data obtained in polar regions from instrumented marine mammals.

International Coordination and Monitoring of the Observing Network

The complex relationship amongst EOVs and the major ocean observing programs is summarized in Table 3.1. This table clearly shows that the ocean physical EOVs requirements are satisfied in a number of ways using a variety of sensors and platforms. To provide resilience to the observing system, continued coordination through global networks organized around a particular platform or observing approach (e.g., satellites, surface drifters, profiling floats, mooring, time series sites, research vessels, and volunteer ships) is warranted and will benefit from evaluation studies considering combined multi-platform systems. It is the role of the GCOS-GOOS-WCRP Physics and Climate Panel (the Ocean Observations Panel for Climate, OOPC) to evaluate and set requirements, as well as to foster agreement on multiplatform design of the observing system and to evaluate observing system performance against these requirements. The coordination and monitoring of the ocean system is then undertaken by the JCOMM via two connected programs the Ocean Coordination Group (OCG) and JCOMM Operations (JCOMMOPS). The OCG and JCOMMOPS work with the individual observing networks to track the implementation performance of the ocean observing system against targets (e.g., deployments, coverage, data delivery).

The OCG's main task is to work across the observing networks to improve the performance of the observing system while also building on strengths and synergies. The OCG workplan focuses on responding to requirements (in consultation with OOPC and the WMO Integrated Global Observing System), observing system implementation (including roll-out of new technology and performance metrics), standards and best practices, and data and integration. JCOMM OCG is also the interface with data management coordination activities under JCOMM, along with the WMO Information System (WIS) and the Intergovernmental Oceanographic Commission International Ocean Data and Information Exchange (IODE).

The JCOMMOPS (www.jcommops.org) provides the ability to track implementation of the observing networks, systems monitoring, and data flow. From this metadata, we can monitor the key performance indicators of each of the observing networks (Figure 3.3)

	Argo			DBCP				SOT		GLOSS
	Argo Core	Argo Global	Argo BioGeoChemical	Global Drifter Program	Tropical Moored Buoy	Coastal/National MB	Tsunami Buoy	VOS	SOOP XBT	
Implementation										
Activity Global Ocean	85.16% 8/2017 ↗	97.42% 8/2017 ↗	28.73% 8/2017 ↘	115.06% 7/2017 ↗	65.55% 7/2017 ↘	108% 7/2017 ↘	62.5% 7/2017 ↘	92.25% 7/2017 ↗		84% 3/2017
Coverage (Monthly) Global Ocean		50.92% 8/2017 ↗		42.21% 7/2017 ↘				1.24% 7/2017 ↘		
Coverage (Yearly) Global Ocean	58.61% 2016 ↗	66.04% 2016 ↗								
Density (Monthly) Global Ocean	83.5% 8/2017 ↘	86% 8/2017 ↘	39.04% 8/2017 ↘	84% 9/2017 ↘						
Intensity Global Ocean	76.45% 8/2017 ↗	93.87% 8/2017 ↗	44.59% 8/2017 ↗	96.69% 7/2017 ↗						
Data Flow										
Delivery Global Ocean	96.56% 8/2017	95.89% 8/2017 ↗	89.8% 8/2017 ↗					61.74% 7/2017 ↘		
Timeliness (GTS FR) Global Ocean	95.57% 8/2017 ↗	95.62% 8/2017 ↗	93.62% 8/2017 ↗	78.98% 7/2017 ↗						
International										
Diversity (National) Global Ocean	19 2016 ↘	20 2016 →	11 2016 ↗	10 7/2017		13 7/2017 →		27 2016 ↗	9 2016 ↗	

Figure 3.3. Example of assessment of key performance indicators of components of the ocean observing network.

Data Management, Distribution and Integration

Each observing platform has its own data management system that, in association with OCG and JCOMMOPS, is used to closely monitor group collaboration across activities (e.g., observation collection, metadata and data assembly using community accepted standards, and quality assurance and control). Observing networks may provide data as real-time and delayed mode, or only as delayed mode. Real-time data reach operational ocean and climate forecast/analysis centers via the Global Telecommunications System (GTS). The target is for these real-time data to be available within approximately 24 hours of their transmission from the observing platform. Delay-mode data are the climate-standard, quality-controlled data. The production of delayed mode data is, for most networks, the responsibility of individual research in each country following the program/network standards and procedures practices. In general, delayed mode data is available from network data centers within six months of collections of data.

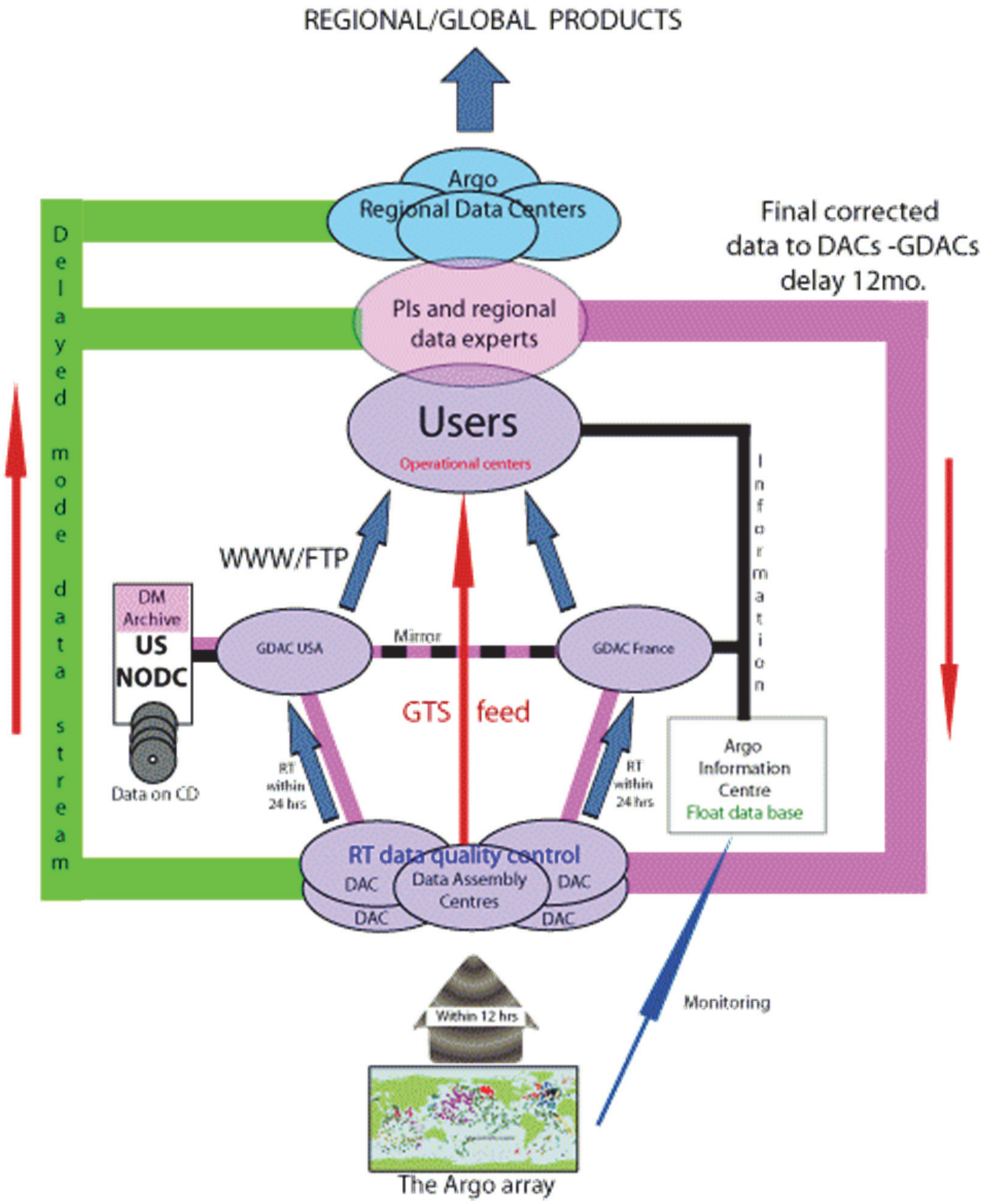

Figure 3.4. Schematic of the real-time and delayed mode data flow from the Argo array (from www.argo.ucsd.edu).

Some ocean observing networks are well developed and are largely successful in all these data management functions, while others are challenged to operate consistently due to varying data policies and submission requirements and sometimes due to a lack of sufficient resources for all the needed experienced staff and cyber-infrastructure for data services and preservation.

Argo provides an example of a well-defined data management system for both real-time and delayed mode data (Figure 3.4). Many observing networks that provide both real-time and delayed mode data follow similar data flows patterns.

The JCOMM OCG observing programs are working to build data systems that enable interoperability between the platforms. Interoperability serves the routine data exchanges within and amongst the networks, as well as user discovery and access. Community standards for metadata, data formats, communication protocols, and data server software infrastructure are the foundation for interoperability. The technical aspects have been demonstrated and successfully deployed in limited regions and specific parts of the global networks.

For example, a software system developing interoperability of the GOOS is the ERDDAP data server (http://coastwatch.pfeg.noaa.gov/erddap). ERDDAP functions as a broker between observational platforms (e.g, Argo, GO-SHIP, OceanSITES, Global Drifter Network) and users of data (Figure 3.5). Because it implements the OPeNDAP protocol and supports modern web services architecture, it is perfectly suited to pair with the various platform networks to provide integrated access to the real-time and delayed mode data streams. From the ingest side, it allows scientists to continue to work with the data formats they are most familiar with, from excel spreadsheets to database tables to netCDF files. From the data user's perspective, the various output formats and protocols supported by ERDDAP allow them to access and use the data through the clients of their choice, without having to reformat desired data.

An example of the application of ERDDAP is shown in Figure 3.6, using temperature data from:

- the Global Data Drifter Program,
- Argo-gridded temperature data,
- GO-SHIP and other ship-based CTD profiles,
- Pacific glider data,
- OceanSITES,
- SOT, and
- DBCP – Meteorological moorings.

The 2015 zonal mean temperature section was constructed for the Pacific Ocean between 30ºN and 30ºS. Here ERDDAP was used as the data framework to unite those platforms as part of an OGC pilot project to show improved integration of data.

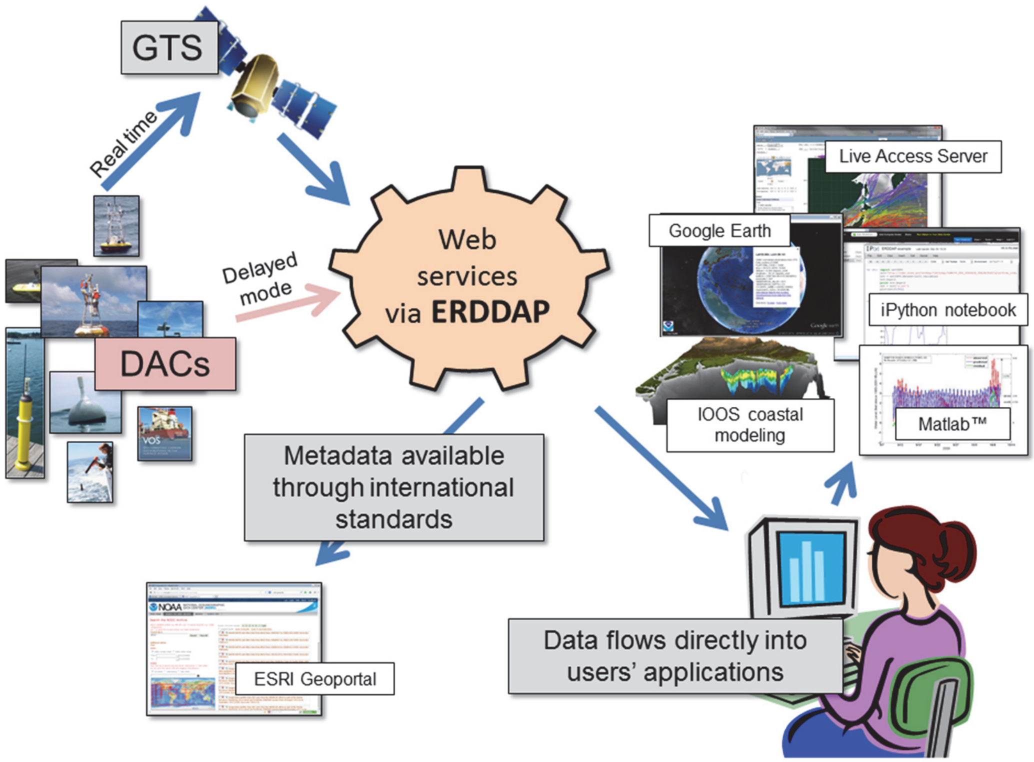

Figure 3.5. A schematic of the functionality of ERDDAP to combine data from various observations platforms to a user based on their requirements and applications.

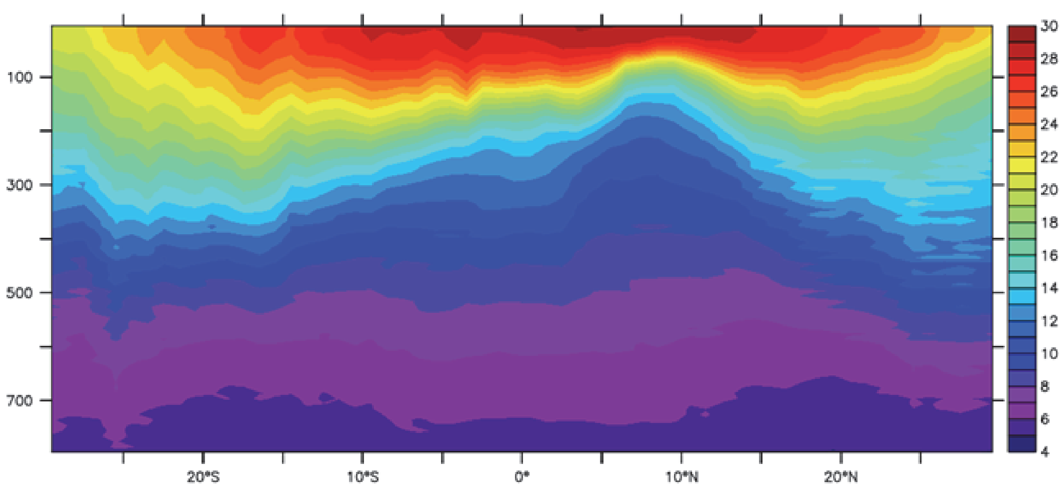

Figure 3.6. ERDDAP compiled 2015 Pacific Ocean zonal mean temperature section between 30ºS and 30ºN from numerous observations systems that collect temperature measurements

Expanding on these successes is important and is being guided by various ocean observing programs (both national and international) as well as by coordinating organizations – JCOMM OCG, JCOMMOPS, and GOOS. Improved interoperability across the observing system networks will enable us to create integrated datasets for the EOVs that include data from all observing networks. Integrated datasets have the potential to change the way operational oceanography utilizes the observational systems.

Future Developments

New or improved ocean observing satellites and in situ sensors and platforms, coupled with advances in telecommunications, are enabling us to close gaps and expand into new areas, measure new variables, lower cost per observation, and improve the impact of the observing system relative to investment (Sloyan et. al., 2017). During the last decade, the use of autonomous in situ platforms has revolutionized the ocean observing system, and the fast technological advance on platforms and sensors (including biogeochemical sensors) will continue to improve our ability to observe the ocean.

These sensor developments and improved telecommunications will make the concurrent observations of ocean physical, biogeochemistry, and biological/ecosystem observations realizable. This will lead to exciting developments towards multidisciplinary observing systems that meet requirements for climate, real-time services and ocean health. Indeed, the ocean community is strongly heading in this direction with the development of the Tropical Pacific Observing System 2020 Project (TPOS, www.tpos2020.org), the Deep Ocean Observing Strategy (www.deepoceanobserving.org), AtlantOS (www.atlantos-h2020.eu), and the related Atlantic Ocean Observing Blueprint (atlanticblueprint.net/). While these projects have a particular science/regional focus, the common thread is building an integrated, multi-disciplinary observing system that will have the ability to provide an efficient and comprehensive set of observations to meet current and future user requirements.

In addition, it is imperative to extend the focus of EOVs into the coastal zones and marginal seas, where societal impacts of the oceans are mostly keenly evident through sea level rise, extreme events, loss of ecosystem services, and impacts on coastal infrastructure. This also requires special attention to the integration of the ocean observing system – physical, biogeochemical, and biological – due to the variability of this region and immediate societal impacts. Coastal/open-ocean exchange processes are also key controllers of coastal ocean water properties, thus strong integration of the coastal and open-ocean observing systems is required.

Conclusion

The ocean observing system is used by an increasingly diverse user group for fundamental underpinning ocean research, as well as for real-time numerical weather forecast and near-term climate prediction services. The sampling strategy of the ocean observing system will evolve as we improve our understanding of the spatial and temporal scales that need to be resolved, technology advances, and experience expands from the user community. An ongoing challenge for the stakeholders of the ocean observing system is designing, implementing, and sustaining the critical multidisciplinary ocean observations required by the user groups.

Improved models are essential for guiding national and international policies that relate to resources (such as fisheries, agriculture, and water supply) that are impacted by climate variability and change, and support efforts aimed at mitigating long-term climate change. As the forecast range increases, processes in the ocean become increasingly important. It is anticipated that improved model skill will result from the addition of sub-surface ocean information, particularly at the seasonal to multi-year timescale (Kirtman et al., 2013). Therefore, the reliability and timeliness of weather forecasts and climate predictions provided to the public, industry, government (including emergency services), and policy makers relies on a comprehensive and timely set of ocean observations.

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