Chapter 14
The Role of Sustained Ocean Observations to the Society and Blue Economy

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Abstract The ocean's contributions to humanity exceeds the products available from it, by absorbing more than 90% of the heat resulting from anthropogenic greenhouse gas emissions. The ocean plays a major role in the global cycles of oxygen, carbon dioxide, nitrous oxide and other gases and rebalances the heat differential between poles and the equator, governing the climate to maintain life on our planet. The need to sustainably observe all areas of the ocean—as well as its unlimited potential for renewable ocean energy—are providing inspiration for new technological innovations. However, it is becoming more evident from recent scientific findings that ocean health is more at risk than previously thought, because different pressures add up and contribute to rapid and unpredictable changes in ocean ecosystems. With

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renewed, revitalized, and changing global scenarios and the United Nations declaring this decade as the UN Decade of Ocean Sciences for Sustainable Development, countries are moving up the ocean in their national policy agendas. Coastal countries, especially small island developing states, are advocating for socially equitable and environmentally sustainable growth. This will require systematic in-situ ocean data collection to understand today's ocean and for forecasts, disaster risk reduction and early warning systems for coastal society and infrastructure and for the assessment and management of ocean resources. This chapter discusses in detail the need for and importance of ocean observations linked to the blue economy, using case studies to understand how under-resourced countries are facing the complex challenges of ocean observing.

14.1 Introduction

The ocean encompasses the majority of Earth's surface and is home to most of its biomass. Ocean dynamics play a major role in every aspect of our planet's climate. The ocean plays a critical function in the prosperity and future of our civilization—in controlling weather and climate (including climate change), and as a source of natural resources and empowering coastal communities and industry (e.g., tourism, fisheries, transport, mining and renewable energy). Observations of the ocean are the backbone for many operational services and industries (e.g., near-real or real-time data, weather forecasts, cyclone warnings, storm surge alerts, monsoon predictions, tsunami warnings and harmful algal bloom detection). Observations are also vital for research and development, including validation of satellite data and parameterizing key processes for models and verifying model simulations. The accumulation of climate-relevant time-series parameters such as surface ocean currents and sea surface temperatures, support the progress of climate sciences. Different phenomena in the ocean require different spatial and time scales of observations, with some changing hourly (e.g., tides, wind breezes) and others over periods of weeks (e.g., mesoscale eddies). A few aspects of the ocean environment, such as the El Niño and La Niña oscillations, require study and monitoring of subtle signatures over decadal periods of time. These phenomena interact ceaselessly and these interactions challenge in-situ instrumentation and ocean science to accurately distinguish between process and event types.

Ocean observations are vital, but not simple to undertake and can be very costly. The ocean is a harsh, difficult-to-observe environment and hence designing and deploying observing instruments requires specialized technology and a range of engineering approaches. Observing systems need to be operated over extended periods of time and increasingly autonomously, considering the vastness of the ocean and remoteness of many locations that are important to observe.

Ocean observing techniques have advanced rapidly in the last few years, although not globally, with many developing countries still not having observing systems. However, an intense need remains globally for information about present trends and allowing prediction of future trends, drawing from past observations. Practical experience gained in data collection, calibration, sampling, instrument use and assimilation in modelling are not available in a single source for reference.

Development of blue economies requires observation systems that are adequate to monitor the status and trends of ocean ecosystems, detect environmental degradation, and value the products and services available from the ocean. The international ocean science community, within the context of assessing societal need and value, as well as feasibility and readiness, has identified Essential Ocean Variables (EOVs; see Box 14.1) that should form the basis for ocean observations. In addition, the main observational needs for capacity development should be focused on improving the observation of EOVs globally, as these are not only useful for science and for prediction capacity, but also are at a level simple enough to inform policy.

This chapter highlights the role of ocean observations as a foundational infrastructure to address many of the issues raised elsewhere within this book, supporting establishment of sustainable blue economies.

14.2 Evolution of Ocean Observing Systems

The beginning of the systematic study of Earth and its planetary environment can be attributed to the framework of international cooperation from July 1957 to December 1958 during the International Geophysical Year (IGY). Over the late Twentieth and early Twenty-first centuries, various global programs—such as the Tropical Ocean Global Atmosphere program (TOGA), the World Ocean Circulation Experiment (WOCE) and the Indian Ocean Air-Sea Interaction Research Initiative–Ocean Mixing Monsoon (ASIRI-OMM) program—were undertaken to understand the status, variability and change in the physical state of the ocean.

The Global Ocean Observing System (GOOS), developed in 1991, is a permanent program coordinating the functioning of a long-term, sustained ocean observing system serving societal needs for climate, operational services and ocean health (see Box 14.2 for more details on GOOS). The GOOS Observations Coordination Group (OCG) coordinates twelve (three of which are emerging) ocean observing networks sustained across the globe (see below). These global networks, comprised of precision in-situ meteorological and oceanographic sensors, provide real-time and delayed-mode coastal and offshore observations and ensure that their data are findable, accessible, interoperable and reusable (following FAIR data principles), through quality control, standards and best practice. OceanOPS—the joint WMO-IOC/UNESCO support center for oceanography and marine meteorology observation programs—provides core network and technical support for metadata and system visualization. OceanOPS (i) monitors and reports on the status of the global observing system and networks; (ii) uses its central role to support efficient observing system operations; (iii) ensures the transmission and timely exchange of high-quality metadata; and (iv) assists free and unrestricted data delivery across operational services, climate and ocean health. One of the methods GOOS OCG uses to inform its stakeholders, ocean observing networks, industry and funders of the status of the ocean observing networks, is through an annual report card (www.ocean-ops.org/reportcard). This outward-facing review, designed to be understood by policy makers and investors in the ocean observing system, is motivated by an increased awareness and importance of the ocean for sustainable development, climate change trends analysis, the integration of atmospheric and ocean observing systems, and the need to guide policy development. The report card also highlights key issues in each edition, such as the COVID-19 pandemic in 2020 and the subsequent impacts on ocean observing systems, and the decline in dissolved oxygen within the ocean and what this means for humans and marine animals alike. The value of ocean observations on our livelihoods cannot be overstated, and continued and enhanced communications in this regard should be encouraged globally.

Categories of EOVs: GOOS began defining essential variables across disciplines; however, as authors of the FOO specifically pointed out, a large part of the current global ocean observing system is driven by climate observing requirements. The reality is that there are more societal and scientific drivers for ocean observations than climate (and weather). Guided by the FOO, discussions about additional scientific questions and societal benefits that require sustained ocean observations were the first step in the EOV definition process. GOOS expert panels identify EOVs based on two criteria; the first being the impact that sustained monitoring of a variable will have on the understanding of ocean health, the climate or operational ocean service. The second criterion is the feasibility of monitoring a variable at a global scale using proven scientific methods, while also considering criteria of cost and ethics, among others. This resulted in essentially three tiers of EOVs: fully ready, pilot and future. A variable of high importance, but without as yet proven observing infrastructure, is either considered pilot (if there are efforts to improve and prove observing capability) or future (if there is as yet insufficient effort on observing capability), with the list evolving as variables move up from future or pilot to fully ready. Societal need and value might soon have a stronger role in the evolving context that motivate adding to the EOV list. In addition, apart from proven scientific methods, other criteria, such as cost (limiting global scale of some high impact observations) or even ethics, are a means of increasing the readiness level of an existing EOV, but also for adding new EOVs.

Box 14.1 Evolution of the Essential Ocean Variables

The development of Essential Ocean Variables (EOVs, including physical, biological and biogeochemical parameters, Miloslavich et al. 2018; Tanhua et al. 2019) and Essential Climate Variables (ECVs, Bojinski et al. 2014), fostered the establishment of globally coordinated networks that are platform- and method-independent (e.g., SOCONET for Inorganic Carbon, GOMON for

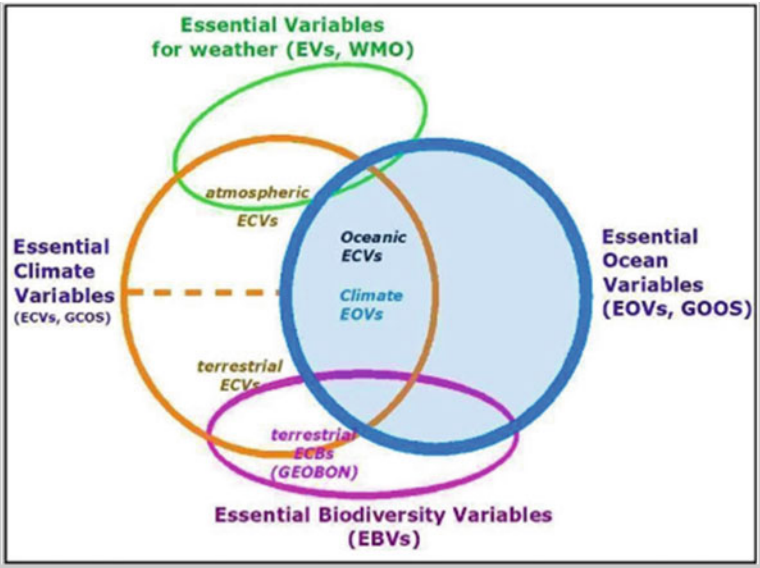
Macroalgal Canopy Cover and Composition) or focused on addressing multidisciplinary phenomena requiring many EOV observations, such as ocean acidification (GOA-ON) and air-sea fluxes (Integrated Surface Ocean Observing System Task Team in development). GCOS provides enhanced coordination across expert panels for ocean, land and atmosphere; in this way, EOVs and their evolution are not isolated disciplinary "stove piped" efforts.

Monitoring the influence of the ocean on the weather patterns and global climate requires sustained and precise measurements of ocean physical parameters, including sea-surface and subsurface temperatures, seawater salinity, dissolved oxygen and near-ocean meteorological parameters such as surface wind speed and direction, barometric pressure, air temperature, air pressure, relative humidity, solar radiation, wave and precipitation, which are used for analyzing heat flux, ocean circulation, monsoon, ocean state, and climate change, and to provide reliable oceanographic services.

The measurement of dissolved carbon, inorganic carbon, nutrients, nitrous oxide, ocean colour, sound, particulate matter, carbon isotopes and transient tracers for characterizing the physical and chemical environment, primary production, ecosystem structure, habitat, spatial distribution and diversity of biomass, energy transfer and the influence of the anthropogenic pressures is essential for studying ocean ecosystems. Enhanced models are required for biogeochemical modelling to understand climate change, nutrient availability and distribution of food webs.

The influence of the cryosphere on ocean biogeochemical cycles, biological productivity and rise in sea levels require analyzing ice-shelf dynamics, paleoclimate, long-term mass balance, energy balance and hydrological balance. These studies require the measurement of salinity, temperature, dissolved oxygen, photosynthetically active radiation (PAR), fluorescence, turbidity, nitrate, water currents and ambient noise.

Conceptual Overlap of Essential Ocean Variables in a Venn diagram. Essential Variables defined by the WMO for weather forecasting inspired the Essential Climate Variables later defined by the Global Climate Observing System (GCOS). The concept has been adopted for Essential Biodiversity Variables on land by the Group on Earth Observations Biodiversity Observing Network (GEOBON). The Framework for Ocean Observing processes defined ocean observing EOVs. Overlap among these groups is shown, which argues for the need to adopt a consistent approach (after Lindstrom et al. 2012).



Concept of EOV

The concept of the ECV was developed by the UNFCC/IPCC during the late 1990s to focus resources on the collection of minimal sets necessary to understand climate variability needed for climate change negotiations. The EOV concept arose from ECVs, following OceanObs'09 and the development of a Framework for Ocean Observations (Lindstrom et al. 2012). The Global Ocean Observing System (GOOS) is engaged in the process of refining, prioritizing and expanding EOVs. Considering ocean biogeochemical processes and their potential role in global warming, GOOS has extended the suite of EOVs to include biogeochemical and biological variables (EBVs) (GOOS Biogeochemistry Panel 2013; Fig. 14.2). The EOVs proposed by the deep ocean observing strategy (DOOS) consider physical parameters such as ocean bottom pressure, seafloor fluxes, ocean turbulence and biogeochemical parameters including seafloor respiration, seafloor organic matter, seafloor fluid, gas effluxes and micro-plastic litter.

The EOV list spans a spectrum of disciplines from physical and biochemical to those representing biological and ecosystem variables, and more recently, also human impact on the ocean (see Table 14.1). The development of EOVs is overseen by one or more of the GOOS Expert Panels that curate EOV Specification Sheets describing societal and scientific requirements, current observing capacity and management of relevant data and information products.[1]

[1] See https://www.goosocean.org/index.php?option=com_content&view=article&layout=edit&id=283&Itemid=441, accessed 11 March 2022.

Table 14.1 Essential Ocean Variable (EOVs)

Physics	Biochemistry	Biology and ecosystems
Sea state	Oxygen	Phytoplankton biomass and diversity
Ocean surface stress	Nutrients	Zooplankton biomass and diversity
Sea ice	Inorganic carbon	Fish abundance and distribution
Sea surface height	Transient tracers	Marine turtles, birds, mammal abundance and distribution
Sea surface temperature	Particulate matter	Hard coral cover and composition
Subsurface temperature	Nitrous oxide	Seagrass cover and composition
Surface currents	Stable carbon isotopes	Macroalgal canopy cover and composition
Subsurface currents	Dissolved organic carbon	Mangrove cover and composition
Sea surface salinity		Microbe biomass and diversity (emerging)
Subsurface salinity		Invertebrate abundance and distribution (emerging)
Ocean surface heat flux		
Cross-disciplinary (including human impact)		
	Ocean colour	Ocean sound
	Marine debris (emerging)	

Source https://www.goosocean.org/index.php?option=com_content&view=article&layout=edit&id=283&Itemid=441

Recognizing changing requirements for ocean observations, as well as innovation and technological progress, which together alter our perception of impact and feasibility of a given measurement to be measured sustainably and comparably on a global scale, GOOS has been reviewing proposals for new, so-called "emerging EOVs". Adding a new EOV requires establishing coordination (and often communication) oversight, services provided by GOOS Expert Panels jointly with relevant coordinated observing networks, and increasingly, in partnership with external groups of experts, projects or programs (e.g., International Ocean Colour Coordinating Group for the Ocean Colour EOV; International Quiet Ocean Experiment for the Ocean Sound EOV; and a plethora of organizations for the Marine [Plastics] Debris EOV). By adopting a new EOV, GOOS commits to building a global network and community of data providers in areas where this was fragmented or non-existent, and gradually increasing the readiness level from concept to pilot to mature.

Ocean observations, such as meteorological data from ships of opportunity or surface drifters and ocean data, such as temperature and salinity profiles from instruments such as eXpendable BathyThermographs (XBTs), Argo floats and CTDs or observations from moored data, are made available to the Global Telecommunication System (GTS), established by the WMO. These data are assimilated into coupled climate models (atmosphere, ocean, land/soil, sea-ice) used for Numerical Weather

Prediction (NWP) such as by the European Centre for Medium-Range Weather Forecast (ECMWF). These observational data are used to determine the near-real time atmospheric state and are compared to short-range (or real-time) forecasts, and the results are used to update medium-range forecasts for dissemination. Although not always highlighted in weather forecasts, ocean data are an essential component of weather and climate predictions. Marine meteorological and sea surface temperature (SST) data are currently shared by in-situ observation platforms (moored, drifting or profiling) through the GTS. In addition, most ocean observing networks have established Data Acquisition Centers (DACs), and in some cases Global Data Acquisition Centers (GDACs), whereby all quality-controlled datasets are archived and made available to users. These datasets are assimilated into global ocean models and coupled-climate models for hindcast and forecast purposes, and they are used by researchers and students for research projects. Additionally, datasets are used by decision-makers to interpret the current state of their countries' ocean domain, and by educators for capacity development purposes.

The aim for data acquired by ocean observing networks overseen by the GOOS OCG is to be freely and openly available to all users without restriction. OceansOPS aims to have all metadata available, although complex issues remain in sharing data within EEZs. These networks are described further:

14.3 Existing In-Situ Observing Networks

14.3.1 Data Buoy Cooperation Panel (DBCP)

The DBCP coordinates two surface buoy systems, namely autonomous drifting buoys and moored surface buoys. The objective of these systems is the continuous acquisition of ocean–atmosphere data in remote regions (by means of free-floating autonomous buoys) and regions of importance (e.g., in terms of moored buoys in coastal regions within countries' EEZs). Data originating from drifting buoys and moored surface buoys are assimilated into coupled-climate models and are used for weather forecasting purposes, in addition to other research and operational purposes. See https://www.ocean-ops.org/DBCP/.

14.3.2 Argo Program

The first Argo floats were launched in 2000 and standard floats are capable of operating to 2,000 m depth and sampling physical properties (temperature, salinity, and pressure). More recently, Deep Argo floats have been launched, with full ocean depth capacity (4,000–6,000 m) and Biogeochemical Argo floats are being deployed with a suite of sensors including dissolved oxygen, nitrate, pH, chlorophyll a, suspended particles and downwelling irradiance. Argo data are used for a variety of applications, including state-of-the-ocean assessments such as steric sea level rise and ocean heat content, ingestion into the GTS, for research and educational training purposes, and assimilation into global circulation models. See https://argo.ucsd.edu/ and https://biogeochemical-argo.org/index.php.

14.3.3 Ship Observations Team (SOT)

SOT is constituted of three smaller groupings: (1) the Voluntary Observing Ship Scheme (VOS), (2) the Automated Shipboard Aerological Program (ASAP) and (3) the Ships of Opportunity Programme (SOOP). A wide range of vessels are recruited for the program to ensure that data are acquired not only from conventional shipping routes, but also from remote regions by means of research vessels and yachts. Data from VOS, ASAP and the XBT component of SOOP are ingested within the GTS for weather forecasting purposes. Data from additional underway observing platforms under the SOOP are acquired from thermosalinographs (TSG) measuring temperature and salinity, partial pressure of carbon dioxide instruments (P_{CO2}) and Continuous Plankton Recorders (CPR) obtaining data on both phyto- and zooplankton species distributions. These data are available in delayed mode in most cases at this stage. See https://www.ocean-ops.org/sot/.

14.3.4 OceanSITES

OceanSITES is concerned with high-resolution, high-quality observations of the full depth of the ocean at moored locations globally (mostly physical data, but with plans to expand to biogeochemical observations). Moorings linked to OceanSITES are found in the open ocean (thus not coastal stations linked to specific regional objectives) and are long term in relation to their deployment duration, so as to provide a series of reference stations for studies relating to global climate change. Data from OceanSITES are essential for understanding climate change in the ocean, but can also lead to improved forecasting of ENSO, as well as tropical cyclones. See http://www.oceansites.org/.

14.3.5 The OceanGliders Program

The OceanGliders program provides a mechanism for observing from the open ocean to the coast to understand processes occurring across this boundary as well as providing long-term observations. Gliders operate autonomously, acquiring data in regions that are difficult to study using vessels of opportunity or research vessels dedicated to inshore or fisheries resource surveys. Due to the innovative designs of ocean gliders, different sensor payloads can be incorporated, depending on the objectives of the survey, thus acquiring data for physical, biogeochemical and ocean sound variables. Data from gliders can thus be used to inform fisheries management and understand ecosystem health, understand boundary currents and for scientific studies of rapid upper ocean evolution as well as high-value profile data for assimilation in both operational and research forecast models. See https://www.oceangliders.org/.

14.3.6 Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP)

Despite the advances in technology, particularly related to observations with autonomous instrumentation, the best way to collect high-resolution, high-quality ocean profile data, especially over a range of disciplines (physical, biogeochemical, biological) is by ship-borne overside instrument deployments to the full depth of the water column. Data from GO-SHIP are aimed at understanding the impacts of interannual and decadal variability in the ocean, as well as long-term climate change, which can be used to better inform the coupled models used by the Intergovernmental Panel on Climate Change (IPCC) to forecast the climate into the future. The recently published SCOR Working Group 154 Report (2020)—recommending how best to sample plankton using discrete samples from Niskin bottles, rosette-mounted sensors and with flow-through systems onboard vessels undertaking GO-SHIP cruises—is important for teams seeking to measure EOVs related to phyto- and zooplankton, as well as microbial abundance and distribution. See https://www.go-ship.org/

14.3.7 Global Sea Level Observing System (GLOSS)

The Global Sea Level Observing System (GLOSS) is a network of global sea level stations collecting high-quality sea level observations used for a wide variety of purposes. These include research into sea level change and ocean circulation, providing information to protect coastal communities in terms of storm surges, tsunami and flood warnings, use in tide tables for port and fishing operations, and for providing sea-level datum data for countries’ EEZs. See https://www.gloss-sealevel.org/gloss-core-network.

14.3.8 HF Radar Network

HF Radars are land-based stations that measure ocean surface roughness from coastal radar transmitters and receivers. From these data, ocean surface waves and currents can be distinguished at a high resolution. Coastal radar data are particularly valuable around ports and regions along the coast where shipping is concentrated, but are also used for ecosystem health studies, pollution monitoring and validation of satellite products as well as assimilation into ocean forecast models. Only a few countries have thus far rolled out coastal radar systems but an aim of the network is to deploy stations in more regions and countries globally. See http://global-hfradar.org/index.html.

14.3.9 Animal Borne Ocean Sensors (ANIBOS)

ANIBOS is an emerging network and makes available to the global community data acquired through sensors attached to marine mammals, turtles, fish and birds, also known as bio-logging. These tagged animals are usually those occurring in data-sparse tropical and polar regions. Biologging data are not only related to physical (e.g., temperature, salinity), biogeochemical (e.g., oxygen) and meteorological (e.g., wind speed and direction) parameters, but also data on animal foraging routes and behavior. See https://anibos.com/about/.

14.4 Satellite Observations

Though not a program or specific network per se, satellite observations provide vital information for understanding ocean state and complement ocean observing in-situ networks, as well as being utilized to calibrate and evaluate ocean models and as a key input for data assimilation into forecast models. The remote sensing community has an approach to planning and coordination under CEOS (Committee on Earth Observation Satellites) that evaluates the future coverage of a given variable and works across nations to ensure coverage by future satellite launches. The spatial and temporal coverage of Essential Climate Variable (ECV) measurements for ocean surface variables have been greatly enhanced by satellite remote sensing. Satellite-based data allow for global mapping of physical variables such as sea surface temperature, salinity, ocean surface topography, winds, currents, sea ice, and waves, as well as biological properties such as chlorophyll concentration, phytoplankton content and net primary production. Satellite observations achieve spatial coverage that is not possible by in-situ observations. However, satellite observations, for instance for ocean color, can be limited and not realistic near the coast or in validation of shallow

Fig. 14.1 Schematic diagram of GOOS components (*Source* IOC 2019)

water surfaces. Satellite observations are also limited to the ocean surface and in-situ observations and models are always needed to observe the water column to the bottom of the ocean. This limitation can challenge the application of satellite data in some places. Thus, a combination of satellite-based data and in-situ observations and numerical models allows for a coherent global mapping of the ocean.

Through enhanced technology, funding and collaborations, driven by the increasing knowledge of the importance of our ocean, ocean observations have progressed significantly in the past few decades; however, many challenges remain. For example, observations of biological and ecological parameters need significant development to reach the same level as the global climate and operational forecast observing capability. In addition, we need to integrate from open ocean to coasts and expand coastal observations, by improving support of nations developing ocean observing capability, particularly those with large EEZs compared to their GDPs. It is also essential to ensure that observations reach service providers that provide accessible information required by the users in society, from reinsurance, to shipping, resource management, coastal planning, and even citizens viewing a weather forecast in their native language. Observational data collected by non-governmental organizations and private companies or industries also need to be incorporated in national/regional observing systems.

Box 14.2 The Global Ocean Observing System (GOOS)

GOOS was established in March 1991 by UNESCO's Intergovernmental Oceanographic Commission (IOC), and is co-sponsored by the IOC, WMO, the United Nations Environment Programme (UNEP) and the International Science Council (ISC). The implementation of GOOS and other observing systems are key to creating and maintaining sustainable blue economy activities; the following is a summary of how GOOS operates. Since its inception, GOOS has created an extensive global system, based on contributions from a large number of organizations and nations, from which countries and people worldwide benefit. In its first decades, GOOS coordinated the development of a system designed to support climate science, and to serve as the observational backbone for operational forecast systems. The Ocean Obs'09 conference, coupled with growing concerns about the health of ocean and demand for information products to help nations manage their ocean economies, sparked the development of the visionary Framework for Ocean Observing (FOO, Lindstrom et al. 2012). GOOS has since led the implementation of this framework by the ocean observing community, with the goal of serving users across climate, operational services and ocean health, increasingly with a focus on coastal areas and regional seas.

The GOOS Strategy 2030 (http://www.goosocean.org/2030Strategy) envisions a fully integrated global observing system ranging across the value chain that extends from observations, through data management systems, scientific analysis and forecast, to end users via information, data and decision-making services. The eleven Strategic Objectives of the 2030 Strategy provide guidance on priorities for the development of a more user-focused and integrated system, and for the core work of GOOS itself.

GOOS Regional Alliances (GRAs) are coalitions of nations and/or institutions that share GOOS principles and goals. GRAs were introduced to integrate national needs into regional systems and to deliver these at a global level. The mission of GOOS within the 2030 Strategy is '*To lead the ocean observing community and create the partnerships to grow an integrated, responsive and sustained observing system*' (Fig. 14.1).

14.5 Emerging Ocean Observation Methods

Aware of the limits of existing methods and instruments for collecting marine data, such as networks requiring observers to be at sea for long periods of time or limitations within technical observing teams in terms of capacity and skills, policymakers and scientists continue to seek more, and more reliable, data regarding ocean conditions and climate change. They also seek new and better data regarding natural disasters, particularly in the wake of the Asian tsunami resulting from the 2004 Sumatra–Andaman earthquake and more recently the east Japan tsunami resulting from the 2011 Tohoku earthquake. In addition, the frequency of extreme events such as marine heat waves and tropical cyclones are increasing, as is the severity of their impacts on marine life, coastal communities and economy (see Chap. 12). These extreme events result in loss of human life, coastal and marine biodiversity and resources, and infrastructures, challenging well-being and economic development. Strategic technologies that will greatly enhance the capability of in-situ observations using multiple platforms should be immune to bio-fouling, capable of self-calibration during extended deployment periods, and be equipped with artificial intelligence-enabled low-power sensors capable of sending real-time or near-real-time measurements to open databases. Recent technological advances—both in observing but also in the communication and decision support tools—have made cyclone forecasting and problems associated with cyclones such as intense rainfall, storm surges, strong winds and coastal inundation or floods more accurate in terms of magnitude, timing and place of occurrence, resulting in reduction in loss of lives, and reducing the costs involved in evacuations of people (Mohanty et al. 2015).

More challenging is to determine the best way for the observing system to adopt new observing methods that are more affordable, easier to deploy, and open the doors to more nations and users, but that do not achieve the accuracy, stability, and reliability of the premium sensors and instruments. For example, adding inexpensive temperature sensors to lobster traps has engaged a segment of the fishing community and helped track poleward shifts in oceanic temperature that are accompanied by poleward shifts in lobster populations. There is a need to evaluate what is needed, not by technology or platform, but by variable and need, to understand the value of the additional observations.

To maintain long-term observing records, it is necessary to establish the comparability of new observing methods with older/existing ones. Observing methodology transition requires great care and documentation (Trenberth et al. 2002). At the same time, we need to be able to evaluate the observation needs and it is up to national and other investors to decide what technology is best. This may depend on many factors (e.g., capacity, etc.), but some checking is required to ensure the new technology can meet quality standards.

14.5.1 Marine Telecommunication Cables

Traditionally, the commercial telecommunications and scientific applications of submarine fiber-optic cables have operated independently. Submarine cables carry an overwhelming, and growing, percentage of the world's voice, data, and Internet traffic (up to 95% of the global traffic). Scientists also operate submarine cables to power, and transmit data from, marine observatories, in some cases using retired submarine cables previously used for commercial telecommunications. Recent technological developments and scientific imperatives have generated significant interest in multipurpose submarine cables that would transport commercial telecommunications traffic while also gathering and transmitting real-time data regarding ocean temperature, salinity, and water pressure by using scientific sensors.

Deep ocean temperature and pressure measurements can improve estimates of ocean circulation and heat content. Cable-based pressure and seismic-acceleration sensors can improve tsunami warning times and earthquake parameters (fault slip length, slip angle etc.).[2] The resulting data would address the long-term need for sustained climate-quality data from the under-sampled ocean, particularly in deep ocean areas far from land. The need for the same is driven by the themes of OceanObs'19 (e.g., the "Blue Economy" and "Ocean Discovery," particularly in the deep ocean) and the United Nations' Sustainable Development Goals (SDG 13—Climate and SDG 14—Oceans).

Deploying oceanographic sensors on new undersea telecommunication cables is a promising solution for obtaining the extensive, longitudinal, real-time data that are critical for understanding and managing urgent environmental issues such as climate change and tsunami hazard mitigation. The Science Monitoring And Reliable Telecommunications (SMART) subsea cables initiative is a solution to integrate sensors into future undersea telecommunications cables (Howe et al. 2019). SMART sensors would "piggyback" on the power and communications infrastructure of a million kilometers of undersea fiber optic cable and 20,000 repeaters, creating the potential for seafloor-based global ocean observing at a modest incremental cost. Initial sensors would measure temperature, pressure, and seismic acceleration. These cables are repaired, replaced, or expanded on 10- to 20-year cycles, meaning that every year tens of thousands of kilometers of new cables are being laid. By developing new connectivity projects through the SMART cables program, the ocean science community need only raise the incremental cost of the added sensor packages, resulting in globe-spanning sensor coverage at a fraction of the cost of alternative systems.

SMART cables as a new technology could provide valuable data for developing countries, assuming that local technicians can be shown how it will be used for big systems that will, in return, provide them useful data. In particular, SMART cables will be more useful for tsunami warnings, as they allow for a faster warning time than tide gauges.

14.5.2 Emerging Autonomous Ocean Observing Systems

Existing autonomous ocean observation systems making observations over a wide range of temporal and spatial scales, measuring salinity, temperature, nitrate, pressure, oxygen, biomass, and many other parameters have shown that there are many complex levels of dynamics in the ocean from global to meso and local scales, each coupled in non-linear ways. In order to cater to the complex strategic requirements, future autonomous ocean observation systems should be designed to be more affordable, modular, capable and easier to operate. Creative new types of platforms that are compact, low power, with calibrated and stable sensors are under development to expand autonomous observations.

[2] https://www.itu.int/dms_pub/itu-t/oth/4B/04/T4B040000160001PDFE.pdf.

Various mobile platforms—including Autonomous Underwater Vehicles (AUVs), gliders, Remotely Operated Vehicles (ROV) and hadal landers enable comprehensive data collection in specific locations. AUVs enable data collection in an increased spatial domain. The developments until now have resulted in AUVs with excellent performance in terms of vehicle endurance, precise navigation, reliable acoustic telemetry, high-resolution bathymetry/imagery, collision avoidance and excellent reliability. Strategic requirements will require higher spatiotemporal capabilities, energy efficiency, agility and improved maneuverability. The demanding requirements can be illustrated by the challenging need to understand the impacts of Gulf of Mexico Deep Water Horizon oil spill on the ocean in 2010, the Polar challenge by the World Ocean Council involving a 2,000 km continuous under-ice mission in the Arctic and Antarctica, and the ongoing Seabed 2030 project aimed to create a full global seafloor map by 2030 with a 100 m resolution.

The key technologies required for next-generation AUVs for ocean observations include the following:

- Intelligent autonomy for the AUV to sense, interpret, and act upon changes in the environment and the vehicle itself, which requires intelligent decision-making capabilities in navigation, energy management and system error handling.
- Swarm capability involving multiple AUVs that takes inspiration from the spatial self-organizing, navigation behavior and collective decision-making behavior of social animals.
- Subsea homing and docking to enable leveraging the submerged endurance capability of AUVs for long-term operations and reducing operational costs and hazards.
- Bio-inspired design to innovate vehicle designs that emulate the performance of animals, particularly in instances where animal performance exceeds existing technology associated with AUV propulsion, sensing, control and navigation.

In addition to emerging technologies, low-cost technology solutions and innovative methods of getting more observations into the global system are gaining traction. For example, making use of sailing yachts, particularly those involved with long-distance races crossing ocean basins not often covered by shipping vessels, are ideal mechanisms for deployment of Argo floats and satellite-tracked drifters, but also to host automatic weather stations and underway oceanographic sensors. Another key vessel type being engaged more frequently is that of fishing vessels, including the smaller types that don't transit far from their countries' coastlines. These vessels could be providing very valuable data from coastal regions from onboard meteorological and oceanographic sensors, but also from CTDs deployed on fishing nets.

The need for low-cost, easy-to-use sensors is particularly relevant for countries with limited funding for observations. For global coastal observing systems to be sustainable and impactful it is essential that the same set of minimum variables are observed with consistent accuracy worldwide. This need has very much come to the forefront in recent years and is beginning to be addressed through GOOS, as well as

Coast Predict (https://www.coastpredict.org/). A dedicated working group—Open-MODS—Open Access Marine Observation Devices,[3] funded through the Partnership for Observation of the Global Ocean (POGO), was tasked "to devise ocean sensors and monitoring devices, globally available to all and not just to a privileged few." A significant advance in coastal observing systems is now possible given recent technological advances in both the instruments and data communications (Marcelli et al. 2021).

14.5.3 Leveraging Private Sector Data Collection Initiatives

Private sector organizations are becoming increasingly involved in ocean observing; either through the collection of data for their own needs, or through the development and operation of ocean observing technologies. Improved data sharing is essential between, for example, oil and gas industry and public and research institutes. South Africa (through Operation Phakisa) has instituted the South African Marine and Exploration Forum (SAMREF, https://samref.saeon.ac.za/) to identify and take advantage of opportunities provided by oil and gas exploration activities and platforms, and to facilitate new collaborative offshore studies. By developing a demonstration project with private partners, there is potential to prove enhanced value through better forecasts, as has been discussed with Project Azul (in Brazil, see case studies). Such efforts are needed to build an environment of mutual trust. Another major private sector contributor is the shipping industry, which is already involved in the observing system through Voluntary Observing Ships (for meteorological observations) and Ships of Opportunity (for near-surface ocean observations) programs (see above). The shipping industry values corporate social interaction. There is a need to work with the industry to encourage the inclusion of observation packages as part of ship build specifications, rather than retrofitting with observing equipment later (see https://scor-int.org/Publications/OceanScope_Final_report.pdf).

In addition, emerging commercial networks may be key to ocean observations in the future. SOFAR Ocean (https://www.sofarocean.com) has developed drifting wave and meteorological parameter buoys which are available commercially but are also deployed through opportunistic means to validate their state-of-the-art global wave forecast model. Their business model allows for data acquired by their buoys to be used for marine research purposes, but products developed from their high-resolution global wave forecast model, such as those required by shipping fleets for safe passage, are what brings them revenue, allowing for continued infrastructure development as needs arise.

Autonomous surface vehicles (ASVs), such as Saildrone (https://www.saildrone.com) acquire observations of the atmosphere and near-surface ocean parameters, but are piloted autonomously. Not only is the size and look of the Saildrone different

[3] https://pogo-ocean.org/innovation-in-ocean-observing/activities/openmods-open-access-marine-observation-devices/.

from other ASVs, but their business model does not allow for external purchase of the platforms. Instead, users hire individual Saildrone platforms and services, fully inclusive of shipping, launching and recovery, operation, maintenance, data processing and dissemination to the preferred data portal for a single fee. This takes away the need of each organization to have its own set of engineers, technicians and data scientists to remotely operate autonomous instruments at sea. Saildrone is open to deployment of different sensors on its ASVs, with joint sponsorship of missions by different organizations.

The principals of private–public partnerships, in particular in developing countries, can support advances in ocean observing independent of financial constraints, that can be achieved through stakeholder engagement and dialogue without depending on government funding. While these types of new technologies and business models don't necessarily comply with the GOOS mandate of freely available and accessible data for all, discussions between GOOS and new technology teams are ongoing. Such technological developments and possibilities for academic research are growing exponentially. However, it is important to understand the validation and accuracy of new technology driven through private sector partnerships, with the sustained observing system welcoming new methods, but also validating new measurements to establish their provenance. This is a roll that the WMO/IOC Regional Marine Instrument Centre (RMICS) could play.

14.6 Case Studies: Role of Sustained Ocean Observations in Society

To have a full understanding of the role of sustained ocean observations in society, this chapter highlights several case studies from developing countries looking at the successes and difficulties encountered.

14.6.1 Government Buy-In of the Importance of Ocean Observations Ensures Their Sustainability—A Case Study from South Africa

14.6.1.1 Development

The development of a national Oceans and Coastal Information Management System (OCIMS, https://www.ocims.gov.za/) was prioritized as part of the South African Government's Operation Phakisa Initiative 6: "Unlocking the economic potential of South Africa's Oceans".[4] Operation Phakisa (meaning 'hurry') is an initiative of the

[4] https://www.environment.gov.za/white_paper_national_environmental_management_ocean_no37692.

South African government that was designed to fast track the implementation of solutions to critical development issues, as highlighted in the National Development Plan 2030, such as poverty, unemployment and inequality. The Government recognized the vast value of the ocean areas surrounding South Africa and the need to utilize ocean resources sustainably.

14.6.1.2 Stakeholder Engagement

In the beginning phases of OCIMS, a lot of work was devoted to establishing the system, getting stakeholder buy-in and developing partnerships. The tools were then rolled out in phases. A particularly successful dynamic tool is the ship-tracking decision support tool, which is very important for surveillance. Using vessel monitoring systems as well as Synthetic Aperture Radar (SAR) data, activity of vessels can be monitored, including ship movements around marine protected areas; highly suspicious activity can be identified and targeted. Approved stakeholders are alerted whenever there is unusual activity. The end users of this tool are the South African Maritime Safety Authority for safety and security, and other state security enforcement agencies. The Harmful Algal Bloom (HAB) tool has helped drastically reduce the loss to the aquaculture industry from HABs (for a discussion of HABs, see Chap. 10). Given the focus on 'ops at sea', a tool is being introduced to automatically identify the optimal search area for sea rescue in support of the National Sea Rescue Institute.

14.6.1.3 Challenges, Successes and the Future

As OCIMS is a government-run program, reports are made to the Deputy Director General and the Minister of the Department of Forestry, Fisheries and Environment, as part of the ocean economy portfolio, given that OCIMS is also intended to boost economic development. By providing knowledge and basic information for people to use by making value-added products available, economic growth is driven.

The success of OCIMS is largely due to active engagement of stakeholders. Each decision support tool has a technical advisory group in charge of managing stakeholder engagement to ensure that stakeholders drive the development of the support tool. Many of the stakeholders and partners are also end users, and this is a strength of OCIMS; it builds on collaboration and partnership, helping to mitigate the high costs of, for example, data.

However, there is a lack of real-time in-situ observations for the program. At the moment, the system relies on satellite imagery, but in-situ observations are key to validate the satellite observations and to derive proxies from satellite observations. For daily operations, HF radar and autonomous platforms would be very useful. In addition, real-time buoys would allow wave, weather and current measurements a little off the coast to be used to validate regional models. For the system to be successful, it is essential that open data policies are enacted.

14.6.2 Enhancing Projects by Ensuring Community Understanding—Case Studies from the South Pacific

14.6.2.1 Development

The South Pacific Community (SPC), an international development organization owned and governed by its 26 country and territory members, has several different successful programs focusing on using marine observations to inform society. Described here is the Climate and Oceans Support Program in the Pacific (COSPPac), an Australian Government-funded program. The Pacific Sea Level and Geodetic Monitoring project operates under COSPPac and is a continuation of the 20-year South Pacific Sea Level and Climate Monitoring Project.

SPC has recognized the need for integrated ocean sciences across its divisions and created the Pacific Community Centre for Ocean Sciences (PCCOS), which aims to help Pacific Island governments and communities easily access the ocean science and expertise they need to make informed decisions and to protect and sustainably manage ocean resources (see also Chap. 13).

Recent actions led by PCCOS are showing the possibilities and benefits of in-country collaborations between met services and fisheries agencies. The latter are often in charge of deploying anchored fish aggregator devices (FADs) nearshore to provide local fishers with access to pelagic resources. These FADs can be coupled with small-size wave buoys by leveraging the nautical capabilities of fisheries agencies and the instrumentation capacity of met services. This approach would allow a sharp increase in the number of coastal wave buoys around Pacific islands.

14.6.2.2 Stakeholder Engagement

In countries with limited capacity, meteorology (met) offices are often the most appropriate organization to raise ocean visibility, either by upskilling met officers or by creating an ocean post in the met office. But, with a growing need for improved ocean policies, it is important that different sectors providing ocean services work together. For example, met services may forecast waves, but the Navy and the hydrographic offices are also key participants and stakeholders. Creating multi-sectorial ocean policies is one way to bring together providers and users of ocean data. This is how COSPPac evolved through upscaling of met services and ensuring that products get to stakeholders; this is a major achievement of COSPPac.

In-country workshops have been facilitated since 2015 between the weather services and their stakeholders to identify how they can interact more effectively. This includes a field trip to tide gauges and introducing the local contact person to answer questions about ocean conditions. It is also important to link the observations to issues people care about on a day-to-day basis. For example, tide gauges are not only important for tsunami warnings, but also in the longer term to show how sea level is rising, which makes coastal villages more susceptible to storms that occur every year.

14.6.2.3 Challenges, Successes, and the Future

Vandalism and lack of buy-in from communities has been a major issue, driven by lack of co-development and clear communication. In the Solomon Islands, a tide gauge was installed and communities were told that it was to warn against tsunamis. When a tsunami hit, the communities had expected the tide gauge itself to emit a siren and when there wasn't one, they were frustrated. The need to explain the tide gauge's contribution to an early warning system had been overlooked. Following this, videos were created showing the benefits of sea level gauges and more emphasis was placed on downscaling the application of data, making it more visible, creating data products and telling stories about the data products. A big piece of the change has been making visible the benefits of ocean data through efforts such as the creation of a real-time tidal display for anyone, not just for the benefit of the local met service, and signage in local languages explaining the importance of the tide gauge.

In 2016, Australia (funded through Green Climate Funding) transitioned technical maintenance that was carried out by experts from Australia to regional people within the Pacific islands, creating cost savings and enhanced sustainability. Having technical maintenance capacity at the regional level has had a two-fold positive effect during the COVID-19 pandemic. Since Australian technicians were unable to travel, the development of local technical expertise has been expedited and tide gauges are now being maintained by in-country people. In addition, regional technical skills have had to develop further as additional responsibilities that were previously performed by Australian technicians needed to be managed by Pacific Islanders. This has been a phased approach, building regional capacity and then building capacity at national levels.

Traditional knowledge on ocean observations can provide valuable information in its own right and contribute to validating and updating tailored marine information, strengthening a community's ability to adapt to climate change. Within COSSPac there has been a focus on validating traditional knowledge with climate indices, with the marine component being integrated through work with the Secretariat for the Pacific Regional Environment Programme (SPREP) to establish traditional databases. The approach is focused on recognizing traditional knowledge and including a page on local knowledge in the tide calendars, either a generic sheet or nation-specific sheets. However, SPC, SPREP and the national met offices are working hard to not only expand communities' knowledge and understanding of marine science, but also growing the traditional knowledge base.

User communities are generally aware of the tides. In Kiribati, tides have a special importance, and the officials there use the tide calendars to look at where the high tide through the year reaches a threshold of over 2 m (identified through local knowledge), a critical level for coastal inundation. From this they make their own page highlighting these times of the year and share it with the communities on the beaches that will get flooded. In Samoa, port authorities rely on the calendar to know when big ships can access ports.

14.6.3 Global Monitoring in Ghana

14.6.3.1 Development

The Global Monitoring for Environment and Security (GMES)[5] and Africa program aims to promote sustainable management of natural resources by improving decision-making processes through effectively integrating Earth Observation (EO) data, technologies and services in support of socio-economic development in Africa. Specifically, the program seeks to improve African policy-makers' and planners' capacities to design, implement, and monitor national, regional and continental policies and to promote sustainable management of natural resources through the use of EO data and derived information. The Regional Marine Centre (RMC) at the University of Ghana implements Marine and Coastal Areas Management in western Africa project under the GMES and Africa program.

The implementation of the GMES and Africa program by the RMC evolved from a series of EO programs beginning with a simple research activity involving tracking of local artisanal fishing boats fitted with locally constructed corner reflectors in collaboration with the U.S. Navy in 2008. Thereafter, the University of Ghana—in partnership with institutions from the UK, South Africa, Tanzania and Egypt—implemented the Europe Africa Marine Network (EAMNET) program. The EAMNET program involved the use of satellite data to monitor the surface temperature and chlorophyll of the ocean by accessing data with a simple antenna and a set of computers without the Internet, in order to eliminate the challenge of limited Internet access. Capacity of students was developed to use these data for the generation of various products, including potential fishing zone maps. This attracted the attention of the ECOWAS (Economic Community of West African States) Commission and, through a competitive process, the University of Ghana (UG) was selected to coordinate the Monitoring for Environment and Security in Africa (MESA) program. Under MESA, UG developed three EO services, namely (1) provision of potential fishing zone charts overlaid with vessel traffic, (2) monitoring and forecasting oceanographic variables, and (3) forecast of ocean conditions disseminated as SMS alerts. As the MESA project metamorphosed into the GMES and Africa program, two new services were incorporated: (4) generation of coastal vulnerability indices and (5) mapping of coastal ecosystems/habitats.

[5] Geoportal: https://geoportal.gmes.ug.edu.gh/. Youtube Channel: UG-GMES_Regional Marine Centre.

14.6.3.2 Stakeholder Engagement

A variety of sectors use the GMES and Africa program data for (1) research and studies, (2) policy and decision making, and (3) individual decision making. The research section consists of universities, individual scientists and students. The second category includes government institutions such as ministries, departments and agencies, for example, fisheries ministries, navies and coast guards, environment ministries, etc. The third category of users mainly comprises artisanal fishers, coastal communities, and private entities. Although a variety of training is offered for data use, it may not be targeted enough and given the attention it deserves in order for data and products to be used widely.

14.6.3.3 Challenges, Success and Way Forward

Ongoing Learning to Integrate Indigenous Knowledge

The main barrier overcome so far, although not completely, is the uptake of information from EO products by the local fishing communities for decision making in addition to their local knowledge. Additionally, some ministries, departments and agencies of government such as the navy, fisheries ministries and meteorological agencies have also adopted the use of marine EO products in their daily activities.

Before the use of ocean condition SMS alerts were introduced to fishermen, it was important to understand how they observed the ocean in order to tell the "weather" at sea. An example was that early in the morning a fisherman will wake up and feel the temperature of the ocean with his/her feet. Combining this temperature information with observations of the physical behavior of the ocean, the fisherman predicts the ocean state before going to sea. In addition, the position of the moon is used to indicate calm conditions and bumper harvest.

14.6.4 Public–Private Partnership Leads to Improved Knowledge of the Ocean in Brazil

14.6.4.1 Development

A successful case study on public–private partnerships is the Project Azul, implemented in Brazil for the development of an ocean observing system for the Santos Basin region (www.projetoazul.eco.br, MacKenzie et al. 2019). This project consists of a partnership between the Laboratory of Computational Methods in Engineering of the Federal University of Rio de Janeiro, and an ocean technology company, Prooceano, in Rio de Janeiro. Both partners had well-defined roles, wherein the university was responsible for numerical modeling and data assimilation while

Prooceano was responsible for the observations and data analysis. In order to understand the oceanography of the Santos Basin region, data were collected from 60 surface drifters, 36 Lagrangian floats, and 5 underwater gliders during the pilot stage of the project (2012–2016). Critically, the data contributed to a dynamic representation of the region and was assimilated into a regional ocean model, additionally being evaluated against drift trajectories and non-assimilated model products. In 2017, and lasting five years, the second phase of the Azul Project began, with an increase in observational capability linked to instrumented anchor lines and an autonomous surface vehicle. Much of the improvements of the second phase are linked to model products: the implementation of a wave-forecast model, increased capabilities related to data assimilation techniques and increased resolution of the regional ocean model. An additional improvement is linked to the optimization of autonomous vehicle tracks to acquire data needed for the benefit of the regional and coastal models (MacKenzie et al. 2019).

14.6.4.2 Stakeholder Engagement

This project demonstrated the collective responsibility in the ocean observation value chain between the Federal University of Rio de Janeiro and Prooceano, with well-defined resource sharing responsibilities and future plans to move forward to further enhance the benefit of the successful collaboration. Public investment in research and development by oil companies in Brazil is encouraged by the National Petroleum Agency, suggesting an investment of 1% of their exploration budgets. This successful model of Project Azul could be adopted by other countries to utilize local resources and to build capacity.

14.6.4.3 Challenges, Successes and the Future

A major issue facing many developing countries after they have acquired specific equipment is that the maintenance (calibration and repairs, etc.) of the equipment has to be conducted overseas. At the beginning of the project, all glider maintenance was conducted outside Brazil. During the project, part of the team had the opportunity to acquire knowledge and technical licenses to proceed with part of the maintenance, breaking down a large barrier to using such equipment locally.

Historically, the main oceanographic observation efforts in Brazil were conducted by the Brazilian Navy to meet their own data requirements. Most of these data are represented by temperature and salinity observations acquired from Nansen and Niskin bottles (very old approaches) and CTD casts (newer ones). All of these datasets are publicly available for the community on the National Oceanographic Data Bank. There are other regional datasets acquired, mostly by oil companies in Brazil, but unfortunately, most of these data are not publicly available. Project Azul has made a visible difference to this approach.

Key skills development outcomes of the project are linked to student development, from undergraduate to doctoral level, peer-reviewed articles and publications, but also the development of both professionals and academics in operational oceanography. Successful relationships were established with international universities and scientific organizations, developing cooperation around operational ocean modeling and data assimilation. While much of the data and the analysis is still being interpreted, the overall understanding of the oceanographic dynamics of the southeastern Brazilian region has increased. An example is the successful linkage of fisheries and oceanography whereby some fisheries communities located along the Brazilian coast use some oceanographic observations and their generated information in order to support their daily activities.

14.6.5 Societal Benefits of the Ocean Observation Systems—A Case Study from the Indian Ocean

14.6.5.1 Development

The Indian Ocean basin, surrounded by 22 countries, is one of the most densely populated regions in the world. The economy of many of these rim countries is agrarian and depends on the seasonal monsoons, with many others depending on fisheries for their livelihood. Several studies have documented the warming of the Indian Ocean and its impacts on monsoon rains (Saji et al. 1999; Webster et al. 1999; Roxy et al. 2016), sea level rise (Han et al. 2014), and changes in fisheries and marine ecosystems. The intensity of extreme weather events is also increasing due to the warming of the Indian Ocean. The Indian Ocean, apart from its direct impact on weather and climate of rim countries, also influences ocean-atmospheric interaction processes such as Madden–Julian Oscillation (MJO), Indian Ocean Dipole (IOD) and El-Niño Southern Oscillation (ENSO) in the Pacific Ocean (Izumo et al. 2010; Luo et al. 2010). These features demonstrate the need for an ocean observing network to provide sustained high-quality oceanographic and marine meteorological measurements.

The Indian Ocean Observing System (IndOOS) consists of five in-situ observing networks: moored buoys, Argo floats, surface drifters, XBT network, and tide gauges. The observations, especially temperature and salinity from Argo floats, moored buoys maintained by National Institute of Ocean Technology, Chennai (NIOT; www.niot.res.in/niot1/oos_intro.php), and Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA; McPhaden et al. 2009; www.pmel.noaa.gov/gtmb), are used for assimilation in the High-Resolution Operational Ocean Forecast and Reanalysis System (Francis et al. 2020). The model output, along with remote sensing products, are also used to forecast Potential Fishing Zone (PFZ) advisories for fishing communities (Francis et al. 2020). The fish catch in the PFZ is observed to be 3–4 times higher compared to the non-PFZ area (Nammalwar et al. 2013). In addition, the time-series observations from this network of data buoys provide valuable information on important meteorological observations, particularly during the cyclone period supported by the Indian Meteorological Department, to predict the track and intensity of cyclones.

The moored buoy network in the Northern Indian Ocean commenced in 1996 under the National Data Buoy program of NIOT. The first-generation data buoys were equipped with sensors to measure surface meteorological and oceanographic (met-ocean) parameters. Technological advancement within a decade led to the development of next-generation buoys, which are capable of measuring the met-ocean, surface and subsurface parameters up to 500 m water depth. These buoys are fitted with sensors to measure parameters such as sea level, air temperature, relative humidity, downwelling short-wave and long-wave radiation, wind direction, wind speed, precipitation and directional wave parameters apart from sea temperature and salinity at discrete levels up to 500 m depth and current profiles up to 150 m water depth. The met-ocean parameters are transmitted in real time to NIOT every three hours and the high-frequency datasets are retrieved while servicing the buoy system. OOS-NIOT is presently maintaining a 19-buoy network, along with specifically deployed CAL-VAL (CALibration & VALidation) buoys for the validation of satellite data. During cyclone passage, the moored buoys trigger rapid mode transmission for real-time data transmission in shorter intervals to closely monitor cyclone tracks.

The Bay of Bengal witnessed two intense pre-monsoon cyclones in 2019 (Fani, Category 4) and 2020 (Amphan, Category 5). Super cyclone Amphan made landfall in West Bengal with sustained wind speeds of 155–165 km per hour, claimed 86 lives, and caused widespread devastation. Even though remote sensing platforms provide the spatial patterns of ocean-atmospheric variables, the temporal resolution is very low compared to observations from the buoys. Remote sensing platforms cannot measure the subsurface temperature, which is very essential for estimating the ocean heat content, which fuels the cyclones. The high-frequency subsurface temperature observations from moored buoys and Argo floats are extremely useful for the accurate estimation of ocean heat content and in understanding the role of the ocean in the intensification of tropical cyclones (https://india.mongabay.com/2020/06/leverage-improved-forecast-to-deal-with-disasters/).

14.6.5.2 Stakeholder Engagement

The CLIVAR/IOC-GOOS Indian Ocean Regional Panel led a 3-year international review of the IndOOS by more than 60 scientific experts, highlighting the need for an enhanced observing network that can better meet societal challenges, and provide more reliable forecasts (Beal et al. 2020). A key action in achieving this is bringing together the IndOOS Resources Forum (IRF), which is made up of key directors from ocean institutes around the world who fund observing programs. There needs to be good interaction between IORP and IOGOOS/IRF in order to inform them of what IORP has learned about IndOOS and how this can be passed on to the relevant countries to help sustain these observations.

14.6.5.3 Challenges, Successes and the Future

Challenges experienced are similar to other regional observing systems, although these can be exacerbated further in developing countries: cost, longevity of the buoy system to remain at sea, battery life, sensor performance, drift and ability to work in a hostile environment. Through sharing experiences during meetings, such as the GOOS regional alliances, publications, newsletters and many web portals, as well as through international bodies (e.g., the OCG observing networks, the Ocean Best Practices System), industry interaction and the active roles of technical societies such as Marine Technology Society/Institute of Electrical and Electronics Engineers, many of these challenges have been resolved.

Early warnings and preparedness made possible by the observing system helped to save many lives during the tropical cyclones in the recent decade.[6] Several studies (Mathew et al. 2018; Chaudhuri et al. 2019; Navaneeth et al. 2019; Venkatesan et al. 2020) have used observations from moored buoys to understand the ocean-atmospheric interaction and upper ocean response to cyclones.

The high population density along the coasts of India necessitates a real-time storm surge warning system. Keeping this in view, the Earth System Science Organization (ESSO)—Indian National Centre for Ocean Information Services (INCOIS) has implemented the Storm Surge Early Warning System for Indian coasts using the ADCIRC (Advanced Circulation) model (see Fig. 14.2). ADCIRC is a finite-element based, depth-integrated shallow water model that can be used to model storm surges and for other coastal applications. This warning system utilizes the automated Decision Support System (DSS) based on Geographic Information System (GIS) and database technology. Wind and pressure fields are generated using the Jelesnianski and Taylor dynamic wind model, which makes use of track forecasts from Indian Meteorological Department. After testing of the system during the very severe cyclonic storm Phailin, it was successfully used for other cyclones.

[6] WMO Factsheet *Early warning system saves millions of lives* https://library.wmo.int/doc_num.php?explnum_id=7560.

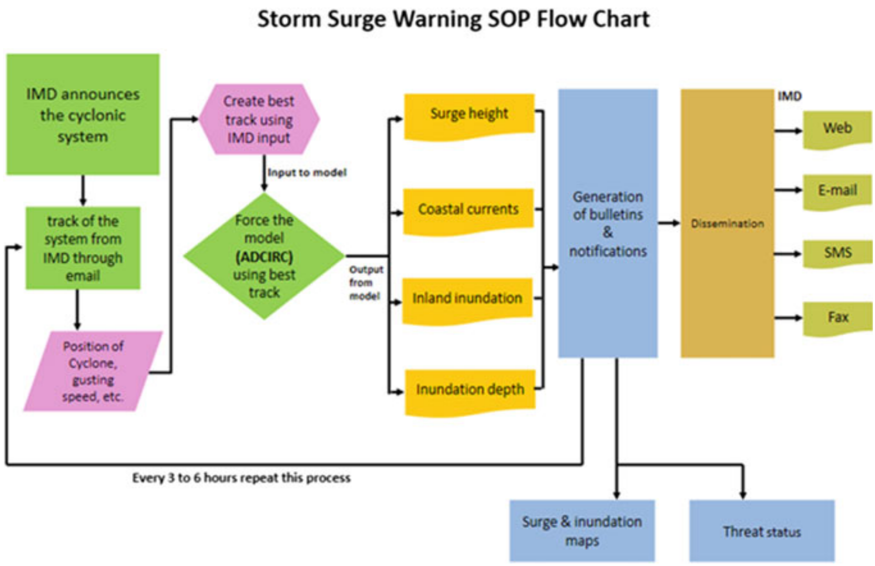


Fig. 14.2 Storm surge warning flow chart developed by the Indian Meteorological Department (IMD)

14.6.6 The Importance of International and National Programs Working Together for Sustainability—Case Studies from the Mozambique Channel

14.6.6.1 Development

The Mozambique Channel, between Mozambique on the Africa mainland and the island of Madagascar, has unique characteristics of ocean circulation in the form of a train of intermittent mesoscale eddies (Sætre and da Silva 1984; de Ruijter et al. 2002; Schouten et al. 2003; Halo et al. 2014); a continuous and permanent western boundary current is absent. While cyclonic eddies can also occur, anticyclonic eddies dominate and are the largest (>300 km) in diameter. These eddies propagate southwards at about 6 km a day (Schouten et al. 2003), with the majority on the western side of the channel over the Mozambican slope, creating an eddy corridor (Halo et al. 2014), resulting in a favorable route for ships transporting goods and people. Eddies, especially dipoles, can generate high (up to 2 ms^{-1}) velocity boundary currents (Roberts et al. 2014; Ternon et al. 2014), with cross-shelf exchange of biotic and abiotic material between coastal and offshore waters (Tew-Kai and Marsac 2009; Malauene et al. 2014, 2018) with implications on coastal ecosystems and fisheries, thus on blue economies in the region. This eddy field can be considered a key natural laboratory to understand the interaction between eddies and ocean productivity (Tew-Kai and Marsac 2009). Eddy-induced high productivity can support marine species at different trophic levels from plankton and fish to top predators and megafauna (Weimerskirch et al. 2004; Jaquemet et al. 2005) promoting fishing for food security and coastal tourism. These eddies extend deep into the ocean, interacting with the seafloor at more than 2,000 m depth, hence cannot be studied with satellite observations alone, which are limited to the ocean surface. However, observational data needed to improve our knowledge of this unique ecosystem are scarce.

14.6.6.2 Stakeholder Engagement

In the Mozambique Channel, the first and the longest in-situ observations were conducted by the Long-term Ocean Climate Observation (LOCO) program from 2003 to 2009 (Ridderinkhof and de Ruijter 2003; Ullgren et al. 2012), after the experimental phase between 2000 and 2001 (de Ruijter et al. 2002). LOCO was an international program developed by NIOZ Royal Netherlands Institute for Sea Research and Utrecht University in the Netherlands. The array consisted of a series of eight moorings deployed across the narrowest section of the channel at about 17oS between the shelves of Mozambique and Madagascar. Measurements included temperature, salinity, and ocean current data vertically through the water column, with emphasis on the bottom layer. This provided one of the first temporal in-situ demonstrations of the Mozambique Channel eddies and water volume transport in the region.

The Mozambican National Fisheries Research Institute (IIP - currently Instituto Oceanogafico de Mocambique) established a long-term observation station off Pemba in northern Mozambique. This was a collaborative project with the Norwegian Institute of Marine Research and funded by the Norwegian Agency for Development Cooperation. The effort included a single observation point at about 1,000 m depth from 2008 to 2011, designed to support the emerging oil and gas sector in the southern Rovuma Basin off Mozambique. The 3-year time-series observation of deep ocean current, temperature and salinity revealed strong currents and eddy influence near the seafloor (Ullgren et al. 2016), which needs to be taken into account for safety during oil and gas activity well drilling and infrastructure installations.

14.6.6.3 Challenges, Successes and the Future

LOCO was a world-class mooring array that has inspired other long-term ocean observation initiatives in the Western Indian Ocean. The unique data time-series generated by LOCO elucidated the driving mechanisms, nature and dynamics of the Mozambique Channel eddies and the water volume transport in the narrowest section of the channel between Mozambique and Madagascar. Yet, understanding changes and trends in the eddy frequency and volume transport, and ultimately relating these to ecosystem function and services, is demanding. This information is vital to understand how climate change and a warming ocean will impact the eddy field, thus ocean productivity and fisheries, which is currently the main component of the ocean economy in Madagascar and Mozambique. Since the LOCO mooring was terminated in the Mozambique Channel, a big gap remained in terms of monitoring this dynamic system. LOCO had no or poor connection with the governments of Madagascar and Mozambique, or with the national research communities. This illustrates the need for international programs and coastal states to work together to sustain of long-term observations, even beyond project lifetimes. It is also important that international projects work together with coastal countries for transfer of knowledge, particularly in developing countries.

While both the LOCO mooring array and IIP's mooring station were located off the shelf deeper than 200 m, no long-term observations exist on the shelf apart from the network of coastal underwater temperature recorders at approximate 18 m depth. Future activities need to observe these regions.

14.7 Relevance and Benefits—The Importance of Observing the Ocean

Ocean and coastal ecosystems are key parts of the global cycles of several important gasses (e.g., oxygen, carbon dioxide, nitrous oxide), absorb 30% of the carbon emissions and sequester more than 90% of the heat added to the atmosphere from human activities. The ocean is the strategic frontier for a global population that will require 30% more water, 40% more energy and 50% more food by 2030. A healthy ocean and coasts help to mitigate climate change and its impacts, offer food security to vast numbers of coastal communities, support coral reefs and mangrove forests that offer coastal protection for humankind, and secure habitat for marine organisms in different phases of their life histories (e.g., spawning ground for adults and nursery ground for larvae and juveniles).

Human vulnerability depends upon a population's exposure to a hazard, and its capacity to adapt to, or otherwise mitigate against, adverse impacts. Coastal vulnerability can thus be expressed as an index which includes exposure to environmental threats, population density and coping capacity. Effective coastal management at the state, regional or national levels requires the ability to identify areas with high population densities, settlement, private and public infrastructure and housing values that would be adversely affected by increases in storm frequencies, sea levels, or coastal erosion rates, inundation, super tidal range, mean significant wave height, tropical cyclones, dynamic coastal geomorphology and other climatological variables.

In-situ ocean observations are vital for improving the understanding of ocean–atmosphere dynamics, which are essential for operational oceanography, weather prediction, and climate modelling. Monitoring ocean stressors is equally essential due to the increase in the rate of loss of biodiversity, changing population distributions and regime shifts, habitat degradation, acidity of the ocean, and accumulation of plastics and other wastes. Natural assets of the ocean (services and products) need to be managed to support human development in the future. Similarly, tropical ocean areas have to be monitored for events such as cyclones and tsunamis to provide advance warning for protecting life and coastal infrastructure, while polar ocean areas need to be monitored from the perspective of climate change and sea level rise (see also Chap. 12).

Coastal and ocean observations can help advance the blue economy related to coastal resources and reduce coastal threats. Other chapters of this book provide greater detail about the contributions of various blue economy resources and how some environmental challenges threaten blue economies. The benefits associated with ocean observations are difficult to quantify in a meaningful way, but evidence to date suggests that benefits from well-targeted investments in integrated ocean observing systems will justify the costs (Kite-Powell et al. 2003). Several examples are highlighted below:

14.7.1 Climate Prediction, Ocean Analysis and Forecasting

As alluded to throughout this chapter, one of the benefits of ocean observations is ocean analysis, validation, assessment of and assimilation into predictive models (Le Traon et al. 2019). Most modern data assimilation systems include bias correction techniques that rely on in-situ observations (Lellouche et al. 2021). For example, the value of the TAO/TRITON array to ENSO prediction is well known, yet it has been hard to sustain. However, this coupled problem is much more complicated than originally envisioned; for example, predictive skill and potential predictability can change from one decade to another. And models are still not quite up to the task of being able to fully utilize the dramatically improved ocean observing systems we now have to provide better forecasts. So when it comes to continued investment in TAO/ENSO (and subseasonal-to-seasonal prediction), we are still challenged by motivating and justifying observations based only on forecast improvement.

Climate prediction is still not on the priority level that it deserves to be, equal to the priority of weather prediction. Climate variability is large scale and slow in time, which means governments should pay for basin/global scale observing systems, to address slowly evolving ocean conditions at the national/local scale. However, needed investments are usually beyond the capacity of any single agency and nation. A consensus is needed that the global public product requires global cooperation and investment and to achieve this product we need to highlight a more explicit connectivity between ocean observing and Earth modelling and societally motivated prediction activities.

14.7.2 Marine Meteorological Services

While the ocean covers more than 70% of Earth's surface, the natural system is fully coupled between the atmosphere and ocean. The delivery of effective and improved metocean (marine and weather) services depends on both atmospheric and oceanic information. The growth of seamless forecasting systems means that meteorological services need an increasing amount of quality information about ocean conditions (both at the surface and subsurface) and the atmosphere above the ocean to be able to deliver the weather, marine and climate services derived from the use of such prediction systems.

14.7.3 Safety, Shipping and Recreation

The safety and well-being of people worldwide, the economic benefits available from the ocean, and the cultural and recreational opportunities can be linked to ocean observations. Coastal tourism and recreation are valued as a high-revenue earner globally (see Chap. 6). This industry requires attractive, safe and functional recreational beaches, clean coastal waters (Blue Flag beach certification) and healthy coastal ecosystems. Safe shipping around the world also contributes to fewer incidents or accidents at sea, reducing the possibilities of harmful bunker fuel and oil spills over coastal and open ocean regions. Moreover, ocean information and forecasts help in planning and selecting ship navigation routes that avoid bad weather and rough seas, thus minimizing fuel consumption, with less emission of greenhouse gasses by burning fossil fuel.

14.7.4 Hazard Warnings

Multi-hazard early warning systems related to weather and climate events have been established by many countries at the national and regional levels. Many lesser developed coastal nations, some of which are likely to be critically impacted by global climate change, have not yet established such early warning systems. Forecast models are imperative to issuing warnings with lead times of 48–72 h for the safety of lives, livelihoods and infrastructure against extreme weather events such as dangerous waves, storm surge, overtopping and tropical storms, along with marine events such as harmful algal blooms and marine heat waves. These forecast models require robust in-situ coastal observations to increase lead time, and accuracy and location of events, and only through sustained ocean observing infrastructure is this possible.

14.7.5 Marine Ecosystem Services[7]

Compared to the assessment of land ecosystems, there is a large knowledge gap and an underdevelopment of tools to assess coastal and marine environments, even though they have been estimated to contribute about 63% of the total worth in services provided by global ecosystems (Carrasco de la Cruz 2021). 60 % of the global ecosystem services are in decline, many of which are provided by marine and coastal ecosystems. It is important to recognize that continual decline in these ecosystem services is a barrier for achieving SDG targets and growing blue economies. The international community has, over the past decade, become increasingly concerned about many issues involving the ocean and coasts. The issues of concern include depleting fish stocks, destruction of natural marine and coastal habitats, uncontrolled pressure of urbanization and tourism on coastal regions and pollution from maritime and land-based activities. Issues such as the impact of climate change on the ocean and coasts, biodiversity, conservation and sustainable use of the high seas and the exploitation of the seabed, have raised the profile of marine issues even further.

There is an urgent need to increase scientific knowledge, develop research capacity and transfer marine technology, considering the Intergovernmental Oceanographic Commission (IOC) Criteria and Guidelines on the Transfer of Marine Technology (CGTMT), to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular SIDS and least developed countries (SDG 14.A). The present IOC/CGTMT guidelines offer to IOC Member States guidance to implement Part IV of the UN Law of the Sea (UNCLOS). The text adopted states as basic principle that the “transfer of marine technology should be done free of charge or at a reduced rate for the benefit of the recipient state” (IOC/ABELOS 2005). Capacity development is particularly relevant with regard to fisheries research, oceanic aquaculture, and the exploration and exploitation of new marine compounds, as well as marketing of these. Chapter 16 discusses the importance of capacity development to blue economies in greater detail.

14.8 Challenges and Lessons Learned

There are numerous challenges to improving and sustaining ocean observations, the biggest being that they generally require collaborative arrangements, funded largely through research grants, with limited sustained government support, particularly in developing countries. In some cases, where developing countries’ governments are involved, they request the observing agencies or institutions to get revenue from the products they develop, thus they are obliged to charge to provide data. This challenges the concept of making the data freely available to the public. An additional important challenge, from an external perspective, is the need to bootstrap some form

[7] A detailed discussion on the definition of ecosystem services within a marine context can be found in Millenium Ecosystem Assessment, 2005: https://www.millenniumassessment.org/en/index.html.

of implementation, proof of concept or value with additional investment, into the growth of the ocean science service enterprises. For example, how do we connect ocean and terrestrial observations to support the coastal zone? Ocean observing needs to be a multi-stakeholder arrangement with enhanced collaboration on data sharing, standards, technology and capacity. Another major challenge is the need for co-development of ocean observing systems, both between countries, but also between physical, natural and social scientists. To address these challenges, it is essential to learn from experience and so this section highlights some reflections from the case studies.

Bureaucracy poses another challenge for the development of ocean observing systems, particularly from regional and international initiatives, with foreign projects avoiding countries with complex licensing procedures. This is worse for countries protective of foreign initiatives, especially as there is often a lack of communication and co-development of the work, with the data often not being given back to the coastal states, perpetuating the protective behavior of these countries.

14.8.1 Governance and Coordination of National Observing Systems

There are many "actors" (funders, implementers, and users) involved in the global ocean observing system. How do we equitably collect and disseminate ocean information to meet the broad range of needs of these actors from a global point of view? One likely avenue for this will be via the UN Decade of Ocean Science for Sustainable Development, as well as the GOOS program looking to co-design (with stakeholder) observing systems, particularly in coastal areas. Within the context of this chapter co-design refers to a multitude of factors—between developed and developing nations; stakeholder engagement; connecting ocean observing to communities that it serves—to modelling and service providers; connecting, through social scientists, to ensure that observing complements local or indigenous knowledge so local management can be empowered. Co-design will ensure that we remain focused on the reasons for collecting the observations.

The increased investment in ocean observing, as well as enhanced capabilities and technologies is impressive and a positive step; however, the global system is not coordinated, with efforts often being duplicated and using less than optimal observing technology. Understanding the key aspects of the ocean economy and the use of ocean observations is essential and needs more data and a deeper knowledge than is currently available. This information should be a key message for enhanced, sustained funding from governments. Under-resourced countries must develop the necessary policies to invest in science and technology so they have the capacity to drive new technology. Oftentimes, experts in the region are forced to adapt to requirements of external funding sources in order to obtain funding. More emphasis should be put in the area of open-source technology development and capacity development. There is a need for more effective system-level management, with planned coordination across the system, and optimal financial and management support levels for many of the efforts (Tanhua et al. 2019).

A major constraint in the global coastal environment is a widespread lack of accurate and timely data at the global level. Although there are regional programs with long-term coastal observations, there is no global coordinating body, aside from the tide gauge network. To establish governance at the national level GOOS, through its 2030 vision, is taking steps to support national focal points and the emergence of national committees.[8] This will strengthen the reach of national needs into global observing, particularly from those countries that are new to GOOS and the roles they play in building capability and access to ocean observing networks. The GOOS 2030 strategic objectives aim to strengthen partnerships, building advocacy and visibility with stakeholders and regularly evaluating the ocean observing system to ensure it is fit-for-purpose for as many users as possible. This requires effective communication and implementation between stakeholders, users and GOOS. We need to ensure there is a cohesive and coordinated agenda for information gathering. A legacy of long-term observing systems is seen as a key outcome of such projects, as well as the research-based observations being widely available for use and reuse following the project, to ensure maximum value for investment.

For governance to be successful it must demonstrate the advantages of improved global engagement at national levels. This would include global coordination and effective governance of open and sustained data mechanisms and systems that focus on expansions for supporting best practices in data discovery, access, and training, sufficient metadata, as well as development of shared/common tools for ocean data access and exploitation. Global networking and coordination should be implemented to minimize regional gaps in all aspects of observing and governance.

In all the case studies described in this chapter, governance and stakeholder relations were a key to their success. In South Africa, the importance of government buy-in for sustainability was highlighted—a top-down approach which was responsive to stakeholder needs. The Pacific Islands focused on a more bottom-up approach driven by stakeholder needs, whereas in Ghana and India a regional approach was successful, and in Brazil a public/private partnership was implemented. However, these are all examples of national efforts with limited links to international programs. In the Mozambique Channel, the lack of connection between the international projects and the governments of Mozambique and Madagascar (on each side of the Channel), resulted in the failure of a long-term mooring array to be maintained when the international project and funding finished. The GOOS 2030 Strategy could effectively stitch together the patchwork of local, national and regional systems, which are beyond the government structure and ensure they are communicating when required. Such engagement would lead to more access and input to the development and implementation of intergovernmental conventions that require ocean observations (Tanhua et al. 2019).

[8] https://www.goosocean.org/index.php?option=com_oe&task=viewGroupRecord&groupID=231.

14.8.2 Blue Economy: Role of Weather, Climate and Coastal Hazards

Economic activities related to the ocean account for 70% of world trade, which provides livelihoods for over 6 billion people and is a source of opportunity, investment and growth. It has been predicted that by 2030 the ocean economy could reach over US$3 trillion per annum (Rayner et al. 2019). The accuracy and timeliness of weather forecasting over the past decades has improved and gains have been made in science, observing (both in-situ and satellite), modelling, computing, and communications to bring relevant Twenty-first Century services to the maritime community. Observations are becoming integrated with value-added products such as forecasts, analyses and dissemination of products. However, millions of dollars in goods and thousands of lives are still lost at sea and on land each year due to extreme weather conditions such as cyclones, hurricanes, tsunamis, strong winds, large waves, fog, thunderstorms, sea ice, coastal erosion, sea-level rise and many other natural coastal hazards. Developing countries are often hardest hit by these conditions. Of the 25 largest island nations and territories, ranked by area, less than 10 have established sustained ocean observation networks (https://www.ocean-ops.org/).

Observations should follow well-defined, science-based and international protocols. But, in addition, there is an urgent need to expand not only our observational coverage, but also to improve how marine data are used and transformed into actionable information, creating systematized value chains for society in all areas of the globe. Downstream services are required to customize value-added products to specific users. Work by the Organization for Economic Co-operation and Development (OECD, Jolly et al. 2021) has highlighted the need to unlock the value of marine data by supporting the entire marine data value chain, while promoting the use and reuse of marine data in policies and communicating the benefits.

In strengthening the value cycle across observations, research and services delivery; we need to identify observational needs, but also improve communication of outcomes and benefits of research and other applications to a broad audience, to demonstrate the value of data sharing for all, articulate needs and advocate for improved observations. Improved products and forecasts need to be translated into useful information and communicated appropriately to ensure uptake by stakeholders and policy makers. An OECD study is underway to estimate the economic value of sustained observations globally, including coastal regions, which could be helpful in demonstrating the value of data sharing (Rayner et al. 2019). More evaluations such as this will aid both in communication and understanding the flow of ocean data in national economies. In the future, regulatory pressures on carbon management, global temperature rise, and sea level rise mitigation may rely heavily on knowing and predicting the ocean state. Ocean observations are critical to improving model-based predictive capability, to elucidating the processes not yet included in models, and getting the ocean storage of heat and carbon correct.

14.8.3 Exclusive Economic Zones

The 1982 UN Convention on the Law of the Sea (UNCLOS) was an extraordinary achievement in international treaty-making. The Exclusive Economic Zone (EEZ) concept was established, extending 200 nautical miles beyond a coastal nation's land territory or internal (or archipelagic) waters. Within its EEZ, a coastal state has the right to explore, exploit, conserve, and manage natural resources; establish artificial islands; installations, and structures; conduct marine scientific research and allow other nations to conduct research; and protect and preserve the marine environment. EEZ claims form the basis for most marine pollution control regulation by coastal states, although many coastal states have framed their EEZ claims narrowly in terms of fishing rights. A coastal state may exercise its rights within the EEZ subject to freedoms of navigation, overflight, and laying of submarine cables and pipelines. Although UNCLOS defines EEZ jurisdiction narrowly in relation to natural resources and the environment, it is often construed broadly as a basis for regulating any economic activity within the zone.

Some countries are apprehensive about deploying, permitting, or making freely available ocean measurements in their EEZs for concerns over national security, resource development, or other reasons. This causes challenges for observations in EEZs, ranging from getting access to ports for research ships through to the implications of autonomous vehicles such as Argo floats, drifting into EEZs (Bork et al. 2008). The problem of measuring in EEZs is a longstanding one that complicates the implementation of ocean observing systems, but observations in these regions are crucial from both a scientific and a societal perspective. The global community is working to facilitate these observations. Argo has a formal communication channel and many countries have given formal concurrence for Argo floats within their EEZs and 6 of the BGC variables are now included in this arrangement (Bittig et al. 2019).

It is becoming increasingly evident that nations need to take ownership and collect data and use the observations from their EEZs themselves. The international marine science community needs to be acutely aware of so-called "parachute science" (Stefanoudis et al. 2021) where developed countries undertake research within lesser developed countries' EEZs, but the involvement of local scientists in these projects is limited. Research project applications need to go beyond just skills transfer "tick boxes" in order to obtain approval for funding, but rather should show how the project was conceptualized and co-designed and will be undertaken with scientists from the local marine science community. This implies a shift towards more co-generation of observing systems and knowledge sharing between developed and developing countries. Effective communication and collaboration between scientists from different parts of the world, enhancing collaborations, as well as sharing knowledge and data, technology and equipment should not be something for the distant future. Meaningful engagement that contributes to the global ocean observing system, while aiding developing countries to manage their resources, is necessary. However, there remains a disconnect between the international legal and policy framework and the reality of global ocean science collaboration, capacity development, data sharing and technology transfer. Building capacity through monitoring will build scientific literacy which, in turn, will enable all countries to engage purposefully in the global dialogue. Global networking and coordination need to be implemented to minimize regional gaps in all aspects of observing and governance. Sustained observations require a coordinated, collaborative and culturally appropriate process, incorporating indigenous and local knowledge, with long-term resourcing that meets identified local, national and regional needs. Given the influence this will have on economic stability for the impacted countries, it is essential that the long-term resourcing be, at the least, derived from a combination of international and local sources.

14.8.4 Communicating the Value of the Observing System

While much of the data collected in the ocean are funded from research grants, increasing amounts of data are available in real time through the GTS or Web services. It is important to demonstrate the benefit of data sharing for the things people care about, and also work towards ensuring that the benefits of data sharing are equitable. The Keeling time-series of atmospheric CO_2 is iconic and the ocean would benefit from a similar record, for example sea level or temperature.

Coastal states are particularly engaging in the process to advocate for benefit-sharing arrangements; for instance, in line with the Nagoya Protocol on access to genetic resources and the fair and equitable sharing of benefits arising from their utilization to the Convention on Biological Diversity. Many states are supportive of ocean observations for scientific and operational applications, but they also see the dual use of these observations for applications over which they are much more protective, for example, bioprospecting for potentially lucrative drugs. Communication of benefits—particularly with an emphasis on engagement and participation—is key to demonstrate the benefits of data already available. Information needs to be communicated on how and where observations will make a positive impact on weather and climate forecast systems and multi-hazard early warning systems.

All of the case studies had a strong focus on ensuring that the value of data from observing systems was clear to government managers and policymakers, stakeholders and users. Responsive decision support tools and easily accessible data were shown to be key success factors. Some case studies discussed the need to exploit citizen science data better to increase not only observations, but also citizen's understanding of the ocean. Today's citizen science can become part of tomorrow's traditional knowledge. Linking the two could create linkages between elders and younger people and enhance the understanding and support of ocean observing systems.

An additional benefit of clear communication around the value of observing systems is the prevention of vandalism. Effective data buoy vandalism refers to the intentional interference with, damage to, or theft of observing platforms by human action. It is essential to promote education and outreach and broaden support by community stakeholders, especially to recreational, artisanal, and commercial fishers about the equipment and the importance of the data produced. Proactive engagement at regional and local scales through the development of new partnerships to share lessons learned and generate new ideas for addressing vandalism issues is needed.

The Pacific case study clearly demonstrated the impact of culturally sensitive communications about supporting ocean observations and many developing countries can learn from the methods they have applied to ensure that the information is relevant, leading to local community support and hence protection of the equipment.

14.8.5 Capacity Development and Retention

Key to ensuring sustained ocean observations globally is the human capacity required. When considering future technical breakthroughs, we also need to look at where we can implement human capacity breakthroughs. Capacity here refers to, but is not limited to, technicians, engineers, marine scientists (including oceanographic, environmental, atmospheric and biological disciplines), social scientists, and data scientists. However, it also includes such disciplines as economics, business and project management, information technology, policy and decision making for governance, and artificial intelligence disciplines (including robotics and similar abstract concepts that, when brought together, answer the full value chain of the skills required to maintain and enhance ocean observing systems). Capacity development and training needs to happen in a way that takes into account the needs of the country, as well as its capabilities to ensure that the most fit-for-purpose technology and skillsets are developed. As highlighted in the OCIMS case study from South Africa, the bureaucracy of working in a government system can be constraining, combined with the lack of positions available to work on the system and qualified people to fill them. To address these issues of human capacity, it is essential to develop capacity and invest in people in the long term, in a transformative manner, using partnerships. However, this takes time and a long-term commitment. In addition, OCIMS highlighted the need for more in-situ data; developing countries tend to rely a lot on satellites. It is not just the cost of acquiring the instruments but also of sending them overseas for maintenance. There needs to be more access to innovative, low-cost sensors that can be maintained within the country.

In addition, skill sets need to be retained as best as possible in the regions where they are developed. This is difficult to do where a gifted marine scientist is trained locally, but may complete their studies or gain in-field work experience in a developed country, and they choose to stay in the developed country to earn a better way of life than what they had experienced at home or, when they return to their home country, they are offered administrative or management positions, rather than technical or scientific positions in the fields in which they have been trained. Opportunities should be created and encouraged to attract individuals back to their local regions, in their field of expertise, where possible to ensure growth within their sector of interest, and to go on to train the next generation. There are numerous programs specifically designed for capacity development within ocean observing systems. These include (but are not limited to) the POGO-SCOR fellowships which have been successful as the proposals are co-created between the developing country trainee and the trainer, so there is knowledge sharing in a more sustainable manner. The POGO-Nippon Foundation Centre or Excellence program allows long-term training (>9 months) in all aspects of observing systems and has created a strong alumni network from developing countries. These programs are successful because they are responsive to feedback from the participants. In addition, the IODE Ocean Teacher program continues to run courses as the need arises and supports IOC member nations in developing capacity. Sharing and training in best practices, through initiatives such as the Ocean Best Practices system (https://www.oceanbestpractices.org/) is essential for countries developing their own observing system both for observing and data processing, quality control and archiving. To ensure regional programs have a global reach, there is also a need to offer access to existing Global Data Assembly Centres and help with data submission, as offered by OceanOps.

There are many other different international efforts and within the Ocean Decade, there is a thrust to coordinate better. The key for any of these programs remains sustainability, measuring impact and being responsive to create a positive and sustainable set of skills with an open feedback loop. For a more detailed treatment of capacity development, see Chap. 15.

14.8.6 Expansion of Networks to Include Less Developed Countries (LDC) and Small Island Developing States (SIDS)

Ocean observing networks are largely built up and funded through research grants. In addition, reporting back to funders requires lead researchers to show value for money within their regions of concern, and not always as a global outlook. This is particularly true for networks that are land-based (e.g., GLOSS and HF Radar). And while some ocean observing platforms are free floating by their nature, acquiring data from the global ocean as they drift (e.g., Argo and DBCP), the deployment opportunities to get these instruments to all regions of the global ocean can be very limited. In addition, understanding the benefits of such global observations in national EEZ contexts is not always clear. For example, individual Argo float data may not be that useful, but the global dataset can be used to provide boundary conditions for models and probably be of more direct use for some SIDS which rise straight up from the seabed thousands of meters below. Furthermore, with BGC Argo, the sensors used are essentially the same as those they may use in coastal waters, so a partnership program where deep-water island and coastal states can assist with deployments in return for some capacity building on sensors and data use and scientific partnership could be a way of developing scientific capacity in ocean observations more generally.

Mechanisms need to be developed through engagement with LDCs and SIDS to assist with funding grants and applications to gain access to ocean observing platforms for in-country deployments, and to brain-storm unique ideas for platform deployments at sea using modified fishing vessels, sailing yachts and other recreational ocean craft large enough to carry an automatic weather station and a satellite transmitter. The expansions required for LDCs and SIDS will likely not be through traditional developed country means, but through innovative and unique approaches. To do this, engagements at the grassroots level of researchers and technicians in the field would be a useful exercise, with engagement through intergovernmental task teams to secure and release funding for ocean observing systems be encouraged.

14.9 Opportunities and the Future

14.9.1 Need for Ocean Observations in Developing Countries

There is a need to understand the ocean and atmosphere environment as a whole, in order to address the coastal hazards and climate change-related challenges to be faced in the future and to enhance the livelihood and safety of people and infrastructure. The natural Earth system comprises a fully coupled atmosphere and ocean. The delivery of effective and improved marine and weather services depends on both atmospheric and oceanic information. As such, a short-term approach with a focus on facilitating surface marine meteorological observations in support of safety of life and property at sea needs to be combined with a longer-term approach, and future collaboration developed with the IOC of UNESCO with regard to ocean observation requirements, including in coastal regions, in particular in support of Earth System prediction and hydro-climate services. It is often difficult for developing countries to know where to start with observing programs and resources and information need to be more widely available to provide a starting point relative to the needs for the country (Box 14.3).

Sharing of data, knowledge, capacity, technology, methodologies and infrastructure is the only way to truly achieve a Global Ocean Observing System. Globally, there is a need to **increase investment in observing networks, ensuring that, where possible, there is co-investment from developing countries to ensure sustainability**. It is necessary to share and draw from the successes and failures of regional and global systems, such as highlighted in the case studies within this chapter, towards building a common and interoperable system. However, requirements for ocean observing vary depending on mission, ocean environment and capabilities; best practices for a system in the Atlantic Ocean may not be applicable to the Indian Ocean. Targeted measurement precision can be different for small climate signals in the deep ocean or for near-real time observations in coastal areas. Human and technological capacities, as well as the needs of society, also vary across institutions and countries. There are also lessons to be applied from the way national space agencies operate. New missions go through a rigorous evaluation of the geophysical process to be observed, the error budget of the proposed sensor, and whether the deployed sensor, orbit, QC/QA and duration will meet the science objective. That approach to new networks in the ocean could be taken so that, for example, a global fleet of gliders in support of the GOOS objectives is not deployed until the end-to-end value chain is shown to be reasonably feasible.

There is a need to standardize, integrate and share operational and data management best practices. Coordinated efforts, such as the GOOS/IODE Ocean Best Practices System (www.oceanbestpractices.org), that ensure easy access to trustworthy best practices around collecting EOVs, will ensure that our observations are interoperable, reproducible and reliable. This is a priority that needs to be addressed for all ocean parameters: physical, chemical and biological. This means serious engagement with biologists in an ocean observing system that is fit-for-purpose and that delivers value to society. This requires recognition that many of the observations made are intended to understand impacts of a changing environment on ocean organism and ecosystems.

As highlighted in the case studies, there is a need **for targeted and continuous stakeholder engagement**. Improved ocean observing governance is required to effectively and efficiently address the growing needs of the many stakeholders. There is a need at the local, regional and international levels for coordination of sustained ocean observing. Although we can look to the remote sensing communities and the WMO, the ocean community task is more complex (ocean, disciplines, coast/deep/open) and the community is more fragmented. We also need to be wary of a top-down approach, which stifles innovation and fosters inertia. The vision for the next 10 years, as highlighted in the Global Ocean Observing System 2030 Strategy, is really about building a comprehensive system, based not just on GOOS, but many players, engaging multiple networks in comprehensive observations including biology. It requires listening to those who need the information in order to design the observing system required. In developing countries, this system needs to be fit for purpose, considering not only what observations are needed to develop blue economies, but also the capacity to collect such measurements. And it requires all ocean observers to deliver the right information into hands that understand how to use it.

Maintaining continuity of data records is critical to establish long base lines for assessing natural variability and anthropogenic climate change. It is important to evolve the observing system in light of new scientific understanding by taking advantage of new technologies that are ready for deployment and nurturing those that are not yet ready. **Complementary systems and emerging technologies need to be included in implementation planning activities**. But, care must be taken when changes are made to the observing system by introducing new technologies to replace older measurement systems. The transition should be managed with awareness, with overlapping measurements to ensure the integrity of the record is not compromised by changing techniques.

Building and maintaining ocean observing systems are expensive propositions and data accessibility and discoverability are essential. The social impact requires that the investments made in ocean observations are validated by the widest possible use of the data for research, forecasting, analyses, assessments, and applications. That is only possible if the **data follow the FAIR principles** (Wilkinson et al. 2016). Ocean data are being increasingly used not only by people in oceanography or associated fields, but also outside the research field by non-experts to deliver services and information for decision making, highlighting the societally relevant system that is being built. Therefore, it is important that data systems are easy to use by people building products and that information in the metadata enables accurate post-processing for products and services. These service needs must be built into metrics; this vital need for partnerships down the value chain is fundamental to the GOOS strategy. For example, the data system requirements are ripe for developing strong partnerships with data scientists that will enable collection and serving of data that are usable to a wider user community.

Communication to the ocean and coastal communities is also essential to avoid vandalism of the existing observing system like moored buoys. Increasing the literacy of these communities about the benefits of these system to their daily life is essential. The importance of the ocean to society is becoming clearer; however, how to address the many real challenges we are facing is still not very well understood. Science needs to provide the foundation for that understanding. **Open knowledge sharing, including transparency and acknowledging uncertainties and gaps** is ever more important. In addition, the way in which we observe the ocean needs to be environmentally sound. The ocean observing community would be doing a disservice to itself and its mandate if it uses large amounts of plastic to monitor the ocean or if deployed equipment is continuously left in the ocean without retrieval plans. The value of making observations using autonomous platforms is also growing, with newer technologies being less reliant on vessels to be deployed. These new technologies look **at not just understanding the environmental health of the ocean, but also promoting it**.

A key achievement of the FOO was to identify the classes and priorities of observations to be made, the societal impact versus the technologies' ability to make the needed observations. The FOO requires partnerships between communities to assess observation elements for every EOV, and to expand the quality, scope and relevance of products. But are the EOVs and particularly the biological EOVs robust enough yet? EOVs have been developed to set priorities for observing, but **metrics for measuring the system performance need to be developed**.

The modeling community is heavily dependent on sustained observations in validating, assessing, assimilating and motivating improvements to predictions. Society needs very much to get views of the future in order to react at present to that future; hence, such forecasts have large economic value. Thus, it is necessary to quantify how forecasts are impacted by gaps in observations to strongly motivate where to make new observations. These should be quantified in terms of impact in forecasts, evaluating the observations' impacts on models and thus on their application products and their utility to users. Society is willing to invest considerable funds into climate modelling, for example, but on shorter time scales, future predictions of drought, changes in regional fisheries dependent on future regional ocean conditions and other model-based efforts could have great benefit. **We need a more explicit connectivity between ocean observing and Earth modelling and societally motivated prediction activities**.

In parallel there is a need for continuous validation and model bias correction. Observing system simulation experiments (OSSEs) performed within models to assess the best place for observing systems are vital to provide universal standards for the observational community and decision-makers, with the information that is needed to assess, manage, and maintain GOOS routinely. By so doing, decision-makers are empowered to advocate for the maintenance of GOOS using up to-date evidence and consensus results from numerous models. Systematic evaluations supported by a common standard from the end-user community will ensure the development of future technologies and observing systems that are sustainably implemented and useful to the user community. This approach can support the **routine monitoring and assessment of the observational designs**. A formal way is needed to bring observers and modelers together with sufficient resource support to work at the intersections of ocean observing and model validation and improvement. GOOS, through its Expert Team on Operational Ocean Forecast Systems, as well as the Ocean Decade Ocean Observing Co-design program, could provide such mechanisms.

Sea level and carbon (carbon storage, blue carbon, green carbon, carbon markets, etc.) are all important and a driver for additional ocean knowledge/observations and improved ocean predictions. Much work is underway and there is increasing recognition that **adaptation requires significant effort to inform and explore adaptation practices**. This is now being taken up by the private sector and by government agencies, driving change.

14.9.2 Finally

Climate adaptation, weather prediction, early warning systems, carbon budgets, commercial and tourism activities, coastal cities and communities, renewable energy and marine resource management all rely on accessible data from global, regional and national ocean observations, which are fundamental to achieve sustainable blue economies. The current disparity between the observing systems of developed and developing countries leads to large gaps in the global observing system. A key next step for the global community is to ensure that under-resourced nations are supported in the development of their national observations as well as contributing to global observations.

This chapter has used case studies and literature to highlight the need for improved governance at global levels to ensure that implementation of observing systems is in line with supported by global coordinating infrastructures such as GOOS. Box 14.3 gives some suggestions, but a key recommendation for any nation starting an observing program is to focus on the well-described essential variables (Box 14.1 and Table 14.1) and to reach out both regionally and internationally to ensure that they have access to the best practices[9] and global systems that are there to support observations, In particular the GOOS 2030 vision and the suite of papers from the

[9] https://www.oceanbestpractices.org/.

OceanObs'19 Frontiers of Marine Research[10] provide a great place to start and will be followed up by the work which will arise from OceanObs29.

Box 14.3 Where to start as a developing nation wanting to make observations

- *What are the most critical data for a coastal nation to monitor in terms of operational purposes, not the most advanced research needs?*

There are a number of key parameters that need to be measured, but the question really depends on the coastal nation needs and the stakeholders involved in relation to their blue economies. Also, what are the threats to the coastal nation? A coastal nation impacted by cyclones may require different data to those influenced by upwelling. There needs to be engagement in regional and global observing systems through GOOS and the GOOS regional alliances, but at the same time with the National Meteorological and Hydrological Services (NMHS) and WMO. Local measurements which can be used to ground truth satellites and validate models, or even feed into data assimilation are essential globally and also to make global products more relevant to the region. It is normally considered that basic measurements are wind speed/direction, atmospheric pressure, air temperature and SST with a data logger to collect, process and store the data from sensors and to manage the communication protocols with remote servers (https://library.wmo.int/doc_num.php?explnum_id=318). In addition, for climate change studies, long-term sea level data using tide gauges installed on the coast along with satellite data sets are required. Aside from the aforementioned EOVs and EBVs, measurements related to ocean acidification could start with involvement in GOA-ON (http://www.goa-on.org/resources/manuals.php). In addition, sea level is paramount to measure for coastal nations as it is a key parameter for inundation severity (for early warning systems), and the understanding of local relative sea level (as opposed to global absolute sea level), is necessary for efficient coastal management and policy making.

- *How much of the critical data can be downloaded from satellite services, what kind of training is needed for downloading and using the data and to produce data products tailored to the local context, and who provides such training?*

Most data from satellites is not well resolved or validated near the coast, so even though it can be downloaded (e.g., via the Copernicus Marine Service portfolio), there needs to be a clear understanding of the potential errors. Countries with limited capacity to analyse raw data could be interested in co-designed science products based on several in-situ or remotely sensed datasets. There are

[10] https://www.frontiersin.org/research-topics/8224/oceanobs19-an-ocean-of-opportunity.

various global-scale programs that can assist with this, such as CoastPredict (https://www.coastpredict.org/). The GOOS Observation Coordination Group (https://www.goosocean.org/) and the observing networks discussed in this chapter also have various capacity development workshops to support observations and data access and analysis. There are various python/github packages to help with data analysis (e.g., https://pyoceans.github.io/sea-py/), which are a great place to start if necessary skills are available within the coastal nation. The IODE Ocean Teacher Global Academy (https://classroom.oceanteacher.org/) offers various courses, and POGO and SCOR offer various training opportunities, including visiting scholars, and summer schools in data analysis are often hosted by universities across the world. As part of the Ocean Decade, a program has been put in place to try and begin coordination of capacity development opportunities.

- *What is the use of the global datasets provided through GOOS, to coastal communities?*

Global data may not be immediately evident as useful to coastal nations; however, much of the data (e.g., Argo, drifters, etc.) is very useful in terms of weather and climate forecasting, especially as it is often near real-time. Local phenomena are nested in global patterns. Access to any data is useful but in the short term it often seems some data are more useful than others. However, it might not be possible for under-resourced nations to participate directly in global programs; what is important is that there are opportunities to support global networks with, for example, access to EEZs, support in deployment or maintenance of instrumentation, as well as local knowledge of regional systems and local data for enhanced validation and calibration.

- *What observations need to be conducted locally on a smaller scale for blue economy purposes?*

As discussed in this chapter, Essential Ocean Variables have been globally decided on as important observations to be collected, even at smaller scales. The OECD-GOOS-MEDIN survey gives some insight into variables that different parts of the marine sector use: (https://www.youtube.com/watch?v=36dRXGO7Nqs). It is essential to consider the resources (coral reefs, seagrasses and mangroves, coastal fisheries, groundwater inputs, tourism, offshore minerals) and environmental threats (ocean acidification, coastal pollution, harmful algae, climate change) covered in other chapters of the book and their relevance at the local scale. Ultimately, any measurements, following accepted best practices and that are of known accuracy will contribute to knowledge generation. Through CoastPredict a handbook for coastal observations is being developed.

The focus moving forward needs to be co-development of observing programs from the beginning, whether it is global programs wanting to make coastal observations in under-developed regions through to incorporating local ecological knowledge. In addition, the emphasis is no longer on translating science to policy but rather involving policy makers in the design of the science and observations from the beginning. This will help in the communication between policy makers and scientists.

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