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The Coastal Module of the Global Ocean Observing System

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1. Changes in Coastal Ecosystems

The combined effects of climate change and human alterations of the environment are especially pronounced in the coastal zone where inputs of energy and matter from land, sea and air converge. Coastal ecosystems are experiencing unprecedented changes as indicated by the frequency or magnitude of a wide diversity of phenomena (Table 1) that affect the safety and efficiency of marine operations, the susceptibility of coastal populations to natural hazards, public health risks, the health of coastal marine and estuarine ecosystems, and the sustainability of living marine resources. Increases in the occurrence of many of these phenomena indicate profound changes in the capacity of coastal ecosystems to support goods and services. They are making the coastal zone more susceptible to natural hazards, more costly to live in, and of less value to national economies. In the absence of a system for improved detection and prediction of the phenomena of interest and their environmental and socio-economic consequences, conflicts between marine commerce, recreation, development, environmental protection, and the management of living resources will become increasingly contentious and politically charged. The social and economic costs of uninformed decisions will increase accordingly.

Anthropogenic and natural drivers of change and their expressions in terms of the phenomena of interest are not independent of each other. Coastal ecosystems are subject to multiple drivers of change and any given driver may have multiple effects that are exacerbated by other drivers of change and their effects. Major anthropogenic drivers of change include (1) extractions of living marine resources; (2) land-use practices that alter inputs of water, sediments, nutrients, human pathogens, and chemical contaminants from coastal drainage basins; (3) physical alteration of habitats; (4) the globalization of marine commerce; and (5) the release of greenhouse gases. Changes in the state of marine systems occur through natural processes as well. Thus, many of the changes occurring in coastal ecosystems are related to extreme weather and to large scale, natural processes such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO).

2. Managing Human Use in the Context of Natural Variability

Changes in the frequency of or secular trends in the magnitude of the phenomena of interest reflect both the dynamics of coastal ecosystems and the nature of the external forces that impinge on them directly or indirectly via the propagation of variability among scales (global ⇔ regional ⇔ local). However, current efforts to manage human uses and mitigate their impacts typically focus on specific human activities, specific habitats and places or individual species without due consideration of the propagation of variability and change across multiple scales in time, space and ecological complexity. It is becoming increasingly clear that managing human uses and mitigating their effects with the goals of sustaining and restoring healthy ecosystems and the goods and services they support can best be achieved through ecosystem-based strategies that consider ecosystems and their state changes in a regional context where a *region* is defined as the next larger scale that must be observed to understand and predict the local scale of interest.

	FORCINGS OF INTEREST
"Natural"	• Global warming, sea level rise • Natural hazards (extreme weather, seismic events) • Currents, waves, tides & storm surges • River & groundwater discharges, sediment inputs
Anthropogenic	• Alteration of hydrological & nutrient cycles • Inputs of chemical contaminants & human pathogens • Harvesting natural resources (living & nonliving) • Physical alterations of the environment • Introductions of non-native species
	PHENOMENA OF INTEREST
Climate & weather	• Variations in sea surface temperature; surface fluxes of momentum, heat & fresh water; sources & sinks of carbon; sea ice
Marine operations	• Variations in water level, bathymetry, surface winds, currents & waves; sea ice; susceptibility to natural hazards
Natural hazards	• Storm surge & coastal flooding; coastal erosion & loss of buffer habitats; sea level; public safety & property loss
Public health	• Risk of exposure to human pathogens, chemical contaminants, and biotoxins (contact with water, aerosols, seafood consumption)
Healthy Ecosystems	• Habitat modification, loss of biodiversity, cultural eutrophication, harmful algal events, invasive species, diseases in & mass mortalities of marine organisms
Living marine resources	• Fluctuations in spawning stock size, recruitment & natural mortality; changes in spatial extent & condition of essential habitat; food availability & hydrographic conditions

Table 1. Natural and anthropogenic drivers of change (forcings) and their expression in terms of phenomena of interest in coastal marine and estuarine ecosystems that affect the safety and efficiency of marine operations, the susceptibility of human populations to natural hazards and global climate change, public health risks and ecosystem health, and the sustainability of living marine resources. Natural drivers of change occur in the absence of human intervention but may be altered or enhanced by human activities. With the exception of introductions of human pathogens and chemical contamination, anthropogenic drivers fall into the latter category.

The goal of formulating ecosystem-based approaches to managing human activities and mitigating their effects, as well as those of extreme weather and global warming, begs the question of how to define ecosystems and specify boundary conditions in marine environments that are not constrained by geographically fixed boundaries. Large marine ecosystems (LMEs) provide a good first approximation. LMEs encompass large areas of the coastal ocean (> 200,000 km^2) and are characterized by distinct hydrographic regimes, submarine topography, productivity and trophic structures. Although porous, the boundaries of LMEs are based on the concept that critical processes controlling the structure and function of marine ecosystems are best addressed in a regional context. They are natural ecological units for ecosystem assessments and ecosystem-based, adaptive management.

In addition to establishing initial boundary conditions, the development of an ecosystem-based approach involves a shift from highly focused, short-term sectoral approaches as now practiced to a more holistic approach that spans multiple scales in time, space and ecological complexity. Implementing ecosystem-based approaches depends on the ability to engage in adaptive management in which decisions are influenced by knowledge of the current state of marine ecosystems and natural environmental variability. This requires the capacity to routinely and rapidly assess environmental conditions, detect changes, and provide timely predictions of likely future states. *We do not have this capacity today*.

3. Linking Science and Management

Effective environmental management and sustainable use of natural resources depends (1) on efficient coupling between advances in the environmental sciences and their application for the public good and (2) on our understanding of the interdependency of ecological and socio-economic systems. Today, there are unacceptable gaps between these processes on both counts. Although the challenges are many, successful establishment of the Global Ocean Observing System will fill the current void between science and management through the routine and repeated provision of scientifically credible, quantitative assessments of the status of coastal ecosystems on local, regional and global scales.

The observing system for the World Weather Watch is a case in point (Figure 1). The WWW is an operational observing system that consists of three closely linked subsystems: (1) a global monitoring network of sensors and platforms (surface and radiosonde networks and aircraft- and satellite-based sensors to monitor wind velocity, atmospheric pressure, and air temperature and moisture content from the earth's surface to the outer limits of the troposphere) with a global telecommunications subsystem (GTS) for data telemetry; (2) a global network of data centers that collect, process, archive and disseminate data and information in near real-time; and (3) numerical weather prediction centers. In addition to providing and managing the data required for numerical weather predictions, the data served by the observing system benefits the environmental sciences which enable improved forecasting skill through advances in sensor technologies and understanding of the causes of atmospheric variability on global to local scales. This synergistic relationship not only sustains the integrity of meteorological research (hypothesis-driven, research projects that are finite in duration), it strengthens it.

The WWW observing system is a useful model of an operational, "end-to-end" system. However, unlike the WWW which has a singular purpose, the GOOS is a multi-purpose system, the development of which depends on and benefits a broad spectrum of scientific disciplines

(Figure 1). Development of an observing system that effectively links scientific advances in many disciplines to the information needs of multiple user groups will require a sustained effort by many groups that do not have history of collaboration to achieve common ends. Thus, many of the challenges are cultural, not technical.

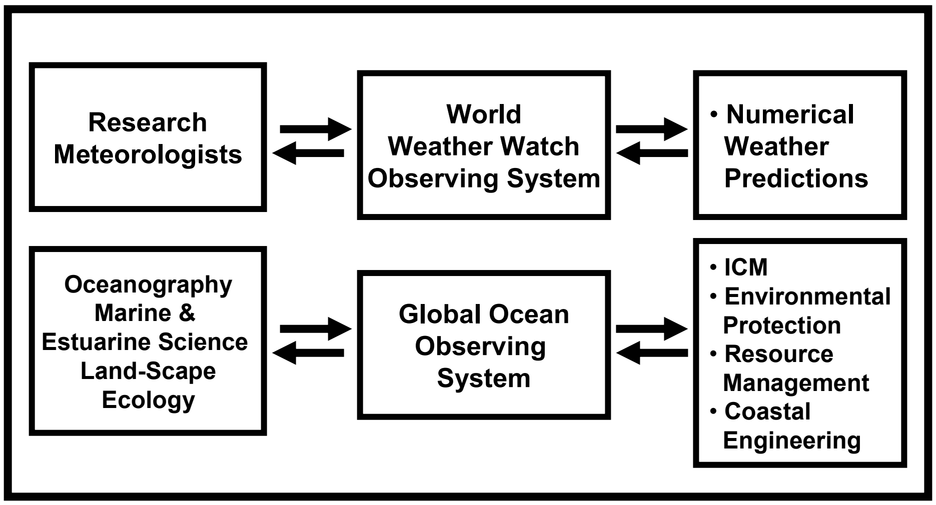

Figure 1. The observing system for the World Weather Watch is operational (routine, continuous provision of meteorological data and data-products of known quality) with guaranteed data streams and products (nowcasts forecasts of the weather and weather patterns on local to global scales). The operations system benefits from meteorological research, but numerical weather prediction are not dependent on the meteorological research community directly. The operational system also contributes to advances in the science of meteorology, but it's primary purpose (and motivation for government funding) is to predict the weather for the public good, e.g., to improve social and economic conditions. A similar but more complex system, the Global Ocean Observing System, is needed for coastal and ocean environments (ICM – Integrated Coastal Management).

4. The Coastal Module of the Global Ocean Observing System

Purpose and Scope

The purpose of the GOOS is to establish a sustained and integrated ocean observing system that makes more effective use of existing resources, new knowledge, and advances in technology to continuously provide data and information in forms and at rates required to more effectively achieve six related societal goals:

1) improve the safety and efficiency of marine operations;
2) control and mitigate the effects of natural hazards;
3) improve the capacity to detect and predict the effects of global climate change on coastal ecosystems;
4) reduce public health risks;
5) protect and restore healthy ecosystems; and
6) restore and sustain living marine resources.

Achieving these goals depends on developing the capacity to assess the status of marine systems and to detect and predict changes in them rapidly and routinely. Although each goal has unique requirements for data and information, they have many data needs in common. Likewise, the requirements for data communications management are similar across all six goals. Thus, an integrated approach to the development of a multi-use, multi-disciplinary observing system is feasible, sensible and cost-effective.

GOOS is a movement to integrate, enhance and supplement existing research and monitoring activities for rapid data acquisition, dissemination, and analysis in response to the needs of governments, industries, science, education, and the public for information on marine and estuarine environments. The System is envisioned as a sustained and integrated global network that routinely and systematically acquires and disseminates data and data products on past, present and future states of the marine environment, ecosystems and the goods and services they provide. The observing system is being organized in two interdependent and convergent modules: (1) the global ocean module being developed by the Ocean Observations Panel for Climate (OOPC) and (2) the coastal module being developed by the Coastal Ocean Observations Panel (COOP). The former is primarily concerned with changes in and the effects of the ocean-climate system on physical processes of the upper ocean and on the global carbon budget. The latter is primarily concerned with the effects of climate and human activities on coastal ecosystems and socio-economic systems of coastal nations including marine operations.

A Global System for the Coastal Ocean

The design of coastal GOOS must take into account the changing mix of ecosystem types that constitute the coastal environment in different regions of the world and the time-space scales that characterize the phenomena of interest within them. In this context, design and implementation must also consider (1) the need to address a broad diversity of phenomena encompassed by the 6 goals; (2) although the six goals of GOOS have unique requirements for data, data management, and analysis, they have many requirements in common; (3) the phenomena of interest tend to be local expressions of larger scale forcings; (4) ecosystem theory posits that the phenomena of interest are related through a hierarchy of interactions; and (5) the kinds of ecosystems and resources that constitute the coastal ocean and priorities for detection and prediction differ among regions.

The coastal module consists of a Global Coastal Network (GCN) and Regional Coastal Ocean Observing Systems (RCOOSs) that link global, regional and local scales of variability through a hierarchy of observations, data management and models (http://ioc.unesco.org/goos/). To the extent that the six goals of coastal GOOS have data requirements in common, a global network of observations provides economies of scale that minimizes redundancy and allow regional observing system to be more cost-effective. In this context, there is a relatively small set of variables that, if measured with sufficient resolution for extended periods over sufficiently large areas, will serve many needs from forecasting changes in sea state and the effects of tropical storms and harmful algal events on short time scales to predicting the environmental consequences of human activities and climate change on longer time scales. These are the "common" variables that are required by most regional systems and are to be measured and processed as part of the global coastal network (Table 2). Depending on national and regional priorities, GOOS Regional Alliances (GRAs) may increase the resolution at which common variables are measured, supplement common variables with additional variables, and provide data and information products that are tailored to the requirements of stakeholders in the respective regions. Thus, GRAs both contribute to and benefit from the global network.

Physical	Sea level, Bathymetry & Shoreline position Temperature & Salinity Currents & Surface Waves Sediment grain size Attenuation of solar radiation
Chemical	Sediment organic content Dissolved inorganic nitrogen, phosphorus, & silicon Dissolved oxygen
Biological	Benthic biomass Phytoplankton biomass Fecal indicators

Table 2. Common variables recommended by the Coastal Ocean Observations Panel to be measured as part of the global coastal system. This initial list of common variables is a first step in the process of determining what variables to measure as part of the global coastal observing system. The list will change as the Global Federation of Regional Observing Systems comes into being. The procedure for selecting the common variables is described in more detail in the "The Integrated, Strategic Design Plan for the Coastal Ocean Observations Module", the software for which may be downloaded from www.phys.ocean.dal.ca/~lukeman/COOP/.

It must be emphasized that the global network will not, by itself, provide all of the data and information required to detect and predict changes in or the occurrence of many of the phenomena of interest. Additional variables must be measured to quantify external forcings of coastal ecosystems. These include large scale ocean processes and inputs from atmospheric and land-based sources to be measured as part of the overall Integrated Global Observing Strategy. In addition, there are categories of variables that are important globally, but the actual variables measured change from region to region. These include species-specific stock assessments for fisheries management; coral reefs, sea grass beds, tidal marshes and mangrove forests; species of harmful algae, marine mammals, turtles and birds; and chemical contaminants. Decisions on what variables to measure, the time and space scales of measurements, and the mix of observing techniques to be used are best made by stakeholders in the regions affected. Thus, the establishment of regional observing systems will be critical to detecting and predicting most of the phenomena of interest in the public health, ecosystem health and living marine resources categories.

In addition to economies of scale and improved cost-effectiveness, the global network will establish, maintain, and improve the observational, data management and modelling infrastructure that benefits national and regional observing systems in several important ways:

- provide a network of reference and sentinel stations and sites to establish long-term time-

series observations, provide advanced warnings of events and trends, and enable adaptive monitoring for improved detection and prediction**;**
- establish internationally accepted standards and protocols for measurements, data dissemination, management, and models;
- optimize data and information exchange;
- link the large scale network of observations for the ocean-climate module to the local scales of interest in coastal ecosystems and provide information on open boundary conditions and atmospheric forcings;
- provide the means for comparative ecosystem analysis required to understand and predict variability on local scales of interest; and
- facilitate capacity building.

Elements of an End-To-End Observing System

Both detection and prediction depend on the development of an integrated and sustained observing system that effectively links measurements to data management and analysis for more timely access to data and delivery of environmental information. The system must be integrated to effectively link the interdependent processes of monitoring and modeling and to provide multi-disciplinary (physical, geological, chemical and biological) data and information to many user groups. Linking user needs to measurements to form an end-to-end, user-driven system requires a managed, two-way flow of data and information among three essential subsystems (Fig. 2):

- The observing subsystem (networks of platforms, sensors, sampling devices, and measurement techniques) to measure the required variables and transmit data on the required time and space scales;
- The data management subsystem (protocols and standards for quality assurance and control, data dissemination and exchange, archival, user access) and communications (data dissemination and access); and
- The data assimilation, analysis and modeling subsystem.

One System, Six Goals

As discussed above, GOOS is intended to provide the data and information required to achieve six broad goals. The capacity to rapidly detect and predict extreme weather and the physical conditions of the upper ocean is far more advanced than the capacity to rapidly detect and predict changes in public health risks, ecosystem health, and the sustainability of living marine resources Thus, the evolution of the coastal module of GOOS depends on advances in both technologies and knowledge.

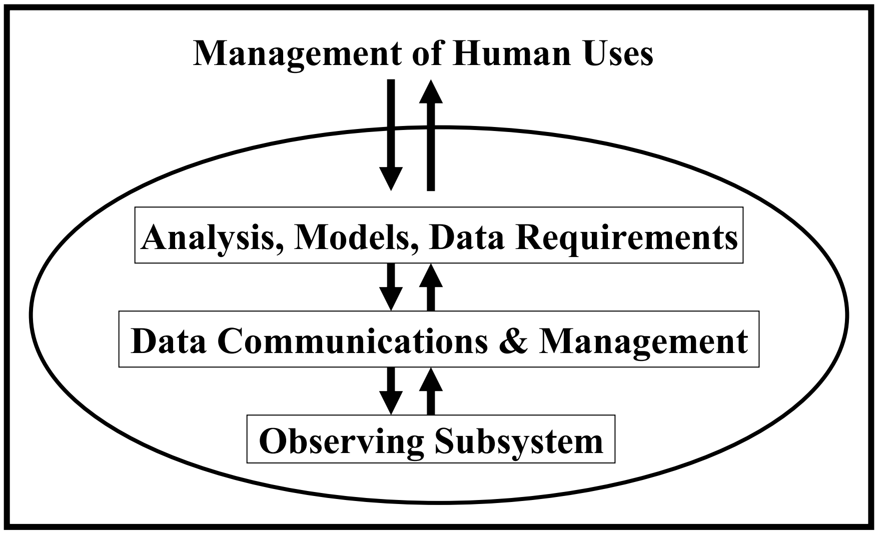

Figure 2 The observing system consists of three subsystems (inside the oval), the development of which is driven by user-requirements, technical capabilities, and the sustainable investments in infrastructure (capitalization) and operations (including the required technical expertise). Depending on capabilities and needs, user groups may access data from any one or all of the subsystems directly.

The evolution of the coastal module will be guided by many considerations including the following:

1) The data requirements for improved coastal marine services are, for the most part, common to all of the goals addressed by the coastal module. Safe and efficient coastal marine operations and the mitigation of natural hazards require accurate nowcasts and timely forecasts of storms and coastal flooding; of coastal current-, wave-, and ice-fields; and of water level, temperature and visibility. The set of variables that must be measured and assimilated in near real time include barometric pressure, surface wind vectors, air and water temperature, sea level, stream flows, surface currents and waves, and ice extent.

2) In addition to these variables, minimizing public health risks and protecting and restoring coastal ecosystems require timely data on environmental variables needed to detect and predict changes habitats and in biological, chemical and geological properties and processes, e.g., distributions of habitat types, concentrations of nutrients, suspended sediments, contaminants, biotoxins and pathogens; attenuation of solar radiation; biomass, abundance and species composition of plants and animals; and habitat type and extent. Mitigating the effects of natural hazards and reducing public health risks also requires a predictive understanding of the effects of habitat loss and modification (coral reefs, barrier islands, tidal wetlands, sea grass beds, etc.) on the susceptibility of coastal ecosystems and human populations to them.

3) In addition to data on the state of marine ecosystems (e.g., hydrography, currents, distribution and condition of critical habitats), the demands of sustaining living marine resources and managing harvests (of wild and farmed stocks) in an ecosystem context require timely information on population (stock) abundance, distribution, age- (size) structure, fecundity, recruitment rates, migratory patterns, and mortality rates (including catch statistics).

Thus, the system is being designed to evolve and incorporate biological and chemical variables as new technologies, knowledge and operational models are developed.

5. Research to Operational Oceanography

Closing the gap between advances in the environmental sciences and applications of new technologies and knowledge to achieve the six societal goals given above depends on the establishment of mechanisms for efficiently incorporate new knowledge and technologies from research to an operational mode. An iterative process is needed by which advances in technology and knowledge are identified, selected, incorporated, and evaluated over time. The selection process by which candidate technologies, data management techniques and models become incorporated into an operational system can be conceptualized as in four stages as follows:

Research Projects: Observational (platforms, sensors, measurement protocols, data telemetry), data management and communications, and analytical (e.g., models and algorithms) techniques are developed by research groups. Research programs such as LOICZ, GLOBEC and GEOHAB are critical to the development of a fully integrated and operational coastal module.

Pilot Projects: Acceptance of techniques by research and operational communities is gained through repeated testing and pilot projects designed to demonstrate their utility and sustainability in a routine, operational mode. Techniques that show promise as potential elements of the operational system or sustained observations for research are tested repeatedly over a range of conditions. This exposes weaknesses, provides opportunities to address those weaknesses, and permits a better understanding of how they may be applied. Research groups, with involvement of operational groups, are primarily responsible for this stage.

Pre-Operational Projects: Research and operational communities collaborate to ensure that incorporation of new techniques from pilot projects into the operational system are likely to lead to a value added product (is more cost-effective, improves or expands existing capabilities) and will not compromise the integrity and continuity of existing data streams and product delivery of the operational system. Operational groups, with the involvement of researchers, are primarily responsible for this stage.

The Operational System: Routine and sustained provision of data and data products in forms and at rates specified by user groups are performed by operational groups with researchers functioning as advisors and users. This stage is improved through the incorporation of elements that are successful in a pre-operational mode. The appropriate government agency, ministry or GOOS Regional Alliance is responsible for the coordinated incorporation of such elements into the operational system, i.e., successful pre-operational projects, or elements thereof, are transferred to an operational agency, office, center or GRA for incorporation into the operational system.

Although presented as a linear sequence, in practice all four stages will be in play simultaneously with feedback among all stages. Research and development projects (stages 1-3) may focus on elements of the system (a particular sensing technology, development of sampling protocols, model development, data management protocols, etc.) or on the development of an integrated system (e.g., end-to-end, regional observing systems). Successful pilot projects, or elements thereof, may be incorporated into long-term time series observations for scientific purposes, may become pre-operational, or both.

From sensing capabilities to models, operational capabilities are most developed for safe and efficient marine operations, forecasting extreme weather and its impacts on coastal populations, and predicting long-term climate change. Thus, the initial GOOS is primarily concerned with improving forecasts of marine weather, natural hazards, and surface currents and waves and with predicting global climate change with greater skill. Developing those aspects of the observing system concerned with ecosystem health and living marine resources will require synergy between research and the evolution of operational oceanography with an emphasis on *in situ* and remote sensing of biological and chemical properties, the formulation of climatologies for chemical and biological properties, and the development of data assimilation techniques and operational models that link physical and ecological processes for routine nowcasts and forecasts of phenomena of interest relevant to reducing public health risks and sustaining and restoring healthy ecosystems and the natural resources they support in an ecosystem context.

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