Requirements for Global Implementation of the Strategic Plan for Coastal GOOS

Panel for Integrated Coastal Observation (PICO-I)

GOOS 193

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Intergovernmental Oceanographic Commission

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ABSTRACT

The goal of this report on Coastal GOOS is to develop a plan for sustained provision of data and information to inform Ecosystem Based Approaches (EBAs) for managing human uses of coastal ecosystem goods and services and adapting to climate change. Meeting the terms and conditions of international conventions and agreements on the oceans, living marine resources and biodiversity require adaptive, EBAs to support management decisions. EBAs require sustained provision of multidisciplinary data and information on ecosystems states, especially in the coastal zone where goods and services are most concentrated. A coastal observation system should provide the data and information needed to fully describe drivers of change on estuarine and marine ecosystems (human expansion, climate change and natural hazards). The strategy recognizes that EBAs must consider external pressures on ecosystems, as well as changes in ecosystem states and the impacts of such changes that occur on local to global scales from coastal catchment basins (watersheds) to the ocean basins.

The Coastal GOOS plan will identify priority indicators of ecosystem states (health) to guide the requirements for coastal observing system capabilities: Surface phytoplankton biomass and subsurface oxygen fields; Waterborne pathogens and toxic phytoplankton; Living benthic habitats and ecological buffers to coastal flooding; Calcareous organisms; and, Exploitable fish stocks. In terms of operational readiness, observing system capabilities for the essential biological and chemical ecosystem state variables are limited and fall into two broad categories: Required technologies are mature but implementation on regional to global scales is limited; and, Technologies are still under research and development. Implementation priorities, taking account of these deficiencies, are as follows: Support national and international programs that target priority infrastructure for observations and predictions; Establish data management and communications systems for interoperability and data integration among monitoring systems; Support capacity building and research and development to fill priority spatial and temporal gaps in the global coastal network; and, Facilitate regional implementation of a pilot project in a priority "super site" domain to demonstrate the value added of an end-to-end system of systems.

Addressing the Coastal GOOS plan priorities will require investments by developed nations in a coordinated global network of national and regional observing systems that are locally relevant and based on interoperable data and information exchange. The observing systems must (1) engage marine stakeholder groups in the design, operation and evolution of a coastal GOOS that meets their data and information needs; (2) leverage existing programs with common objectives; (3) promote the development of regional observing systems by and for developing countries; (4) promote the development of a Global Coastal Network (GCN) through coordinated regional development worldwide; and (5) integrate systems and needs with the Global Earth Observing System of Systems (GEOSS), GOOS, GCOS, the Global Terrestrial Observing System (GTOS), and other organizations as appropriate.

The Joint Commission for Oceanography and Marine Meteorology (JCOMM) is the coordinating body for implementing the ocean-climate observing systems of GOOS and GCOS. No such body is in place for coordinating the global implementation of coastal networks of observations, data management, and modeling that includes the full spectrum of required geophysical, biophysical, chemical and biological variables. The creation of a coordinating body for coastal GOOS will address a major gap in the current GOOS governance structure. This coordinating body will be to Coastal GOOS what the Joint Commission for Oceanography and Marine Meteorology (JCOMM) is to OOPC. This body should address the immediate need to estimate the costs of capitalization, implementation and sustained operations of coastal GOOS. This important task could be executed in association with the GEO-CZCP, in coordination with the GOOS Steering Committee. Successful implementation of a Coastal GOOS plan depends on effective cooperation with the OOPC and effective engagement with stakeholders (data providers and users) across the land-sea interface. An expert panel should be tasked and resourced to provide scientific and technical guidance and ensure the coordinated evolution of ocean and terrestrial observing systems across the land-sea interface. The panel should establish a direct link between IOC-GOOS and GEO-GEOSS (and the GEO Ocean Monitoring Task advocated by POGO and Oceans United). Finally, the successful implementation of the priorities for a Coastal GOOS plan depends on developing international partnerships and collaborations, in active coordination with coastal observing systems represented by the GOOS Regional Alliances.

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PREFACE

A brief history of the evolution of the coastal GOOS module is given here to frame the recommendations in this report. As a starting point, we note that prior to 2000 there were four technical panels for GOOS: Health of the Oceans (HOTO) Panel, Ocean Observations Panel for Climate (OOPC), Living Marine Resources (LMR) Panel, and a Coastal GOOS (CGOOS) Panel. The Panels were established in 1992, 1995, 1997 and 1997, respectively. CGOOS was the only spatially-based panel. Consequently, the terms of reference of the HOTO, OOPC and LMR Panels overlapped substantially in the coastal ocean where living marine resources and land-based sources of pollution are most concentrated and the effects of climate change will have the greatest impact on the well-being of human populations. Here we (1) provide the historical context for the merger of the HOTO, LMR and Coastal GOOS panels, (2) underscore the need for a Joint (GOOS-GTOS) Panel for Integrated Coastal Observations (J-PICO) focused on the effects of climate change and human expansion on ecosystems across the land-sea interface, and (3) address the issue of geographic boundaries for "Coastal" GOOS. A chronology of events leading to the PICO report follows.

1998: At the 1st meeting of the GOOS Steering Committee (GSC), the geographic boundaries of "coastal" are defined as **the landward limit of marine influences and the seaward limit of land influences**. The GSC begins to consider merging the designs of the C-GOOS, LMR, and HOTO when the initial designs for these modules are complete (GOOS Report No. 57). The merger is described in *The GOOS Prospectus 1998* (GOOS Report No. 42).

1999: During GSC-II, representatives of the Coastal, HOTO and LMR Panels met to agree on steps towards merging HOTO, LMR and C-GOOS, and a timetable for the merger was agreed to (GOOS Report No. 73).

2000: The GSC reaches consensus that GOOS implementation will be through two modules: coastal and open ocean (GOOS Report No. 87). The goals of coastal GOOS are to monitor, assess, and predict effects of human expansion, climate change and natural hazards on coastal marine ecosystems and the goods and services they support. In this context, it is made clear that "coastal" should not be limited by fixed geographic boundaries. Although the emphasis is on coastal ecosystems from semi-enclosed systems (e.g., estuaries, bays and fjords) to the Exclusive Economic Zone, boundaries should be determined by the problems being addressed and the products that are to be produced. Thus, **the broad domain of concern extends from semi-enclosed systems in the coastal zone to the continental shelf and the high seas** as required to provide products relevant to the issues given above. This reflects the need for "Coastal" GOOS to observe and model a broad range of scales from the ocean basins to estuarine systems in order to achieve its mandate, i.e., changes in local ecosystems cannot be anticipated without observing and modeling larger scale changes and the propagation of change across scales.
The name "Coastal Ocean Observations Panel" (COOP) is proposed as an analog to the Ocean Observations Panel for Climate. The LMR, HOTO and C-GOOS Panels are asked to finalize their strategic designs before the first COOP meeting in fall 2000. The *Strategic Design Plan for*

the Coastal Component of GOOS (GOOS Report No. 90), the *Strategic Design Plan for the Living Marine Resources Panel of GOOS* (GOOS Report No. 94), and *The Final Design Plan for the HOTO Module of GOOS* (GOOS Report No. 99) are published.

2003: *The Integrated Strategic Design Plan for the Coastal Ocean Observations Module of the Global Ocean Observing System* is published (GOOS Report No. 125).

2005: *An Implementation Strategy for the Coastal Module of the Global Ocean Observing System* is approved by the IOC and published (GOOS Report No. 148). This completes the terms of reference for COOP and the Panel is dissolved.

2006: The GSSC recommends (GOOS Report No. 151) the formation of a joint GOOS-GTOS coastal panel (Joint Panel for Integrated Coastal Observations, J-PICO). The Executive Board of the IOC-WMO-UNEP Intergovernmental Committee for the Global Ocean Observing System (I-GOOS Board-I) endorses the proposal.

2007: Regarding the proposed Joint Panel, the GSSC noted that the decision to form J-PICO can only be made by the sponsors of GOOS and GTOS. Meanwhile, **to accelerate the implementation of Coastal GOOS globally, the Committee created a technical sub-panel of the GSSC for Integrated Coastal Observation (PICO) as a first step toward establishing J-PICO in due course**. J-PICO has yet to be formed.

PICO was tasked with providing (1) the GOOS Scientific Steering Committee (GSSC) with technical advice needed for scientifically sound implementation of the Implementation Strategy for the Coastal Module of GOOS (GOOS Report No. 148) and (2) expertise and advice to the GSSC on the development of operational elements of the Coastal module of GOOS including interoperability and the management and dissemination of non-physical, physical and socio-economic variables regarding observations and data telemetry, data management and communications, and modeling and analysis. This report addresses these challenges and completes the Panel's tasks. The next step is to form J-PICO to ensure scientifically sound implementation of observations and modeling across the land-sea interface in collaboration with the OOPC and the GEO Coastal Zone Community of Practice.

EXECUTIVE SUMMARY

Meeting the terms and conditions of international conventions and agreements on the oceans, living marine resources and biodiversity (e.g., United Nations Convention on the Law of the Sea, Convention on Biological Diversity, Global Program of Action for the Protection of the Marine Environment from Land Based Sources) require adaptive, ecosystem-based approaches (EBAs) to sustainable development, including marine spatial planning and management. Sustainable development depends on the continued provision of ecosystem goods and services valued by society. EBAs require the sustained provision of multidisciplinary data (biogeochemical and ecological as well as geophysical) and information on ecosystems states, especially in the coastal zone where goods and services are most concentrated.

While considerable progress has been made by developed countries in implementing those elements of GOOS and the Global Climate Observing System (GCOS) that require geophysical observations and models of the ocean-climate system (emphasizing improved predictions of natural hazards and climate change), implementation of those elements requiring observations and models of biological and biogeochemical states has been slow and uneven geographically, especially in the coastal waters of developing nations and emerging economies. Developing the capacity for sustained provision of these data and information as an integral part of GOOS is the focus of this report. The goal is to expand GOOS to inform EBAs for managing human uses of ecosystem goods and services and adapting to climate change on local to global scales. Thus, our emphasis is on the provision of data and information needed for rapid detection and timely anticipation of the effects of the major drivers of change on estuarine and marine ecosystems (human expansion, climate change and natural hazards).

Building on analyses and recommendations of the Coastal Ocean Observing Panel (COOP), the Coastal Theme of the Integrated Global Observing Strategy (IGOS), OceanObs'09, *A Framework for Ocean Observing*, and *An Assessment of Assessments* of the United Nations, a plan for expanding the Global Ocean Observing System (GOOS) to include biogeochemical and ecological elements is offered herein. Our recommendations are intended to complement and leverage those aspects of the ocean-climate system addressed by the Ocean Observations Panel for Climate (OOPC) and existing operational programs for predicting extreme weather events and tsunami, changes in physical states of the upper ocean, and coastal flooding.

The following are critical to effective implementation of EBAs: (1) frequent, routine and integrated ecosystem assessment (IEAs) and (2) continuous provision of data and information on meteorological, geophysical, biogeochemical and biological states (indicators) needed for timely IEAs that inform decision makers. To these ends, a rationale and framework for EBAs to managing, mitigating and adapting to changes in ecosystems states and their impacts are given in Chapters 1 and 2. A description of a set of end-to-end observing systems for high priority phenomena of interest is provided in Chapter 3; Chapter 4 presents a framework for integrating these systems into a global system of systems; and Chapter 5 updates the list of essential variables for coastal GOOS, specifies a set of key indicators, recommends the ingredients for a global coastal network and procedures for implementing regional observing systems, and describe international collaborations and partnerships needed to implement regional ocean observing systems globally. Our report concludes by recommending four complementary approaches to accelerating the delivery of coastal GOOS (Chapter 6).

The following priority indicators of ecosystem states (health) are identified to guide the specification of end-to-end observing systems (Chapter 3) that are the building blocks of a system of systems for coastal observations and predictions:

- Surface phytoplankton biomass and subsurface oxygen fields,
- Distribution and abundance of waterborne pathogens and toxic phytoplankton,
- Spatial extent of living benthic habitats (coral reefs, seagrass beds, mangrove forests and tidal marshes) and ecological buffers to coastal flooding,
- Distribution and condition of calcareous organisms (cold and warm water corals, coccolithophores and pteropods), and
- Distribution and abundance of exploitable fish stocks.

Although the emphasis of the COOP strategy is on coastal marine and estuarine ecosystems within territorial waters and Exclusive Economic Zones (EEZs), the strategy also recognizes that EBAs must consider external pressures on ecosystems, as well as changes in ecosystem states and the impacts of such changes, that occur on local to global scales from coastal catchment basins (watersheds) to the ocean basins. In this context, the essential variables to be monitored include at least the following:

- External Pressures
  - Atmospheric (ocean surface vector winds, heat flux, precipitation, incident solar radiation);
  - Land-based inputs (freshwater, sediments, nutrients, pathogens, chemical contaminants);
  - Extraction of living marine resources (e.g. fishing);
  - Sea level rise, ocean warming and acidification;
  - Coastal flooding;
  - Natural ocean-atmospheric climate modes; and
  - Basin scale migrations of large pelagic predators.

- Ecosystem states (surface and subsurface)
  - Geophysical (fields of temperature, salinity, suspended matter, sea surface roughness, waves, and currents, sea level, shoreline position);

- Chemical (fields of dissolved nutrients, dissolved oxygen, pH, fCO_2, total alkalinity, aragonite saturation state, and colored dissolved organic matter);
- Biological (fields of phytoplankton biomass, toxic phytoplankton, waterborne pathogens, calcareous plankton, copepod indicator species, fish eggs and larvae; extent of living benthic habitats, coral skeletal density, species diversity, abundance and diet of exploitable fish stocks, bycatch, abundance and size of apex predators); and
- Biophysical (water leaving radiances and downwelling irradiance).

Impacts of changes in these ecosystem states include declines in fish and shellfish catch (food security), increases in human illness and death rates, loss of income due to beach and shellfish bed closures, increases in the extent of and vulnerability to coastal inundation (due to both storm surges and sea level rise), mass mortalities of iconic marine animals, loss of coastal real estate and infrastructure, and losses of aesthetic value and tourism.

In terms of real-time, operational readiness, current and potential observing system capabilities for the essential biological and chemical ecosystem state variables generally fall into two broad categories:

- The required technologies are mature but implementation on regional to global scales is limited by lack of (1) funding for widespread and rapid repeat assessments, (2) common standards and protocols, (3) and/or calibrated and validated algorithms for translating data into useful products, e.g., nutrients, phytoplankton, dissolved oxygen, fCO_2, and pH fields; spectral diffuse attenuation of downwelling irradiance, spatial extent of biologically structured benthic habitats and ecological buffers to flooding).

- Technologies for rapid detection are under research and development (not operational but in a concept or pilot level of readiness), e.g., waterborne infectious microbes and many toxic phytoplankton species and their toxins; biodiversity; aragonite saturation state, macro- and meso-zooplankton, abundance, abundance of size classes of exploited fish stocks and apex predators, species diversity, and iconic species.

With these deficiencies in mind, implementation priorities (Chapter 6) are as follows:

- Support national and international programs that target priority infrastructure described in chapters 3 and 5 for observations and predictions.

Successful expansion of GOOS to incorporate biological and chemical observations required for EBAs depends on sustained national support of regional “pioneer” ocean observing and predictions systems in, for example, Australia (Integrated Marine Observing System), Europe (EuroGOOS and Global Monitoring for Environment and Security) , and the United States (Integrated Ocean Observing System). Priority infrastructure includes data management and communications systems, remote and *in situ* observations, and modeling and analysis as described in Chapter 5. As indicated by their operational readiness, priority essential variables are chlorophyll-a, dissolved inorganic nutrient, dissolved oxygen, fCO_2, and pH fields; spectral diffuse attenuation of downwelling irradiance, and spatial extent of biologically structured benthic habitats and ecological buffers to flooding

- Establish data management and communications systems for interoperability among monitoring systems and data integration within and among regions.

Designing and implementing the data management and communications link in end-to-end observing systems is a critical step toward integration and should be the highest immediate priority. Such a system must provide rapid access to multidisciplinary data from all sources.

- Support capacity building and research and development to fill priority spatial and temporal gaps in the global coastal network.

Capacity building projects that fill gaps in the GCN are needed. This will involve a review of existing and planned programs, identification of critical spatial gaps, and allocation of resources to fill those gaps. The Coastal Zone Community of Practice (CZCP) of the Group on Earth Observations (GEO) could oversee such a gap analysis.

- Facilitate regional implementation of a pilot project in a priority "super site" domain to demonstrate the value added of an end-to-end system of systems (e.g., multiple applications of data and information needed to guide EBAs derived from a common set of observations and models).

Implementation of a regional demonstration project at a "super site" through a sustained and iterative life cycle for designing, implementing, evaluating, and improving a Regional Coastal Ocean Observing System (RCOOS) over time has the potential to address all four priorities. In terms of the value-added of an integrated system of systems, highest priority for regional implementation should be given to "super sites" with the largest number of sentinel and reference sites. A global analysis identified three regions that are subjected to the greatest number of pressures and have multiple sites with high risks of flooding and exposure to waterborne pathogens. One of these, the **Indonesian Archipelago-South China Sea domain**, is unique in terms of its high species diversity and the presence of sentinel sites for human pressures and state changes for all of the phenomena of interest. This region also has two Large Marine Ecosystem (LME) programs funded by the Global Environmental Facility (GEF), a large number of marine reserves (~ 65), and several institutional networks that could facilitate implementation. Such a demonstration project could begin with the establishment of the required facilities (e.g., the Australian approach to implementing IMOS) in support of an international coastal ocean data assimilation experiment (modeled, for example, after a hybrid of the Integrated Marine Biogeochemistry and Ecosystem Research [IMBER] program and the Global

Ocean Data Assimilation Experiment [GODAE]) with the goal of providing data and data-products required to inform adaptive, EBAs to marine spatial planning and coastal zone management for the region as a whole.

Through an international coalition of data providers (scientists and technicians) and users (managers, conservation groups, shipping and tourist industries, and fishers) from developed countries (e.g., Taiwan, Australia and New Zealand), emerging economies (e.g., China) and developing countries (e.g., Philippines, Vietnam, Cambodia, Thailand, Malaysia, Indonesia, East Timor), this could become the prototype for both regional capacity building and developing an integrated system of systems globally, i.e., phased implementation of the system achieves the goal through capacity building.

Addressing the priorities above will require investments by developed nations to ensure the coordinated establishment of a global network of national and regional observing systems that are locally relevant and interoperable in terms of data and information exchange. Such mechanisms must (1) engage groups that use, depend on, manage and study marine systems in the design, operation and evolution of a coastal GOOS that meets their data and information needs on local to global scales; (2) build on and leverage existing programs with common goals and objectives; (3) promote the development of regional observing systems and services in regions populated by developing countries; (4) promote the development of a Global Coastal Network (GCN) through coordinated regional development worldwide; and (5) effectively interface with the existing planning, oversight and implementation bodies of the Global Earth Observing System of Systems (GEOSS), GOOS, GCOS, the Global Terrestrial Observing System (GTOS), and other organizations as appropriate.

The Joint Commission for Oceanography and Marine Meteorology (JCOMM) is the coordinating body for implementing the ocean-climate observing systems of GOOS and GCOS. No such body is in place for coordinating the global implementation and evolution of coastal networks of observations, data management, and modeling that includes the full spectrum of required geophysical, biophysical, chemical and biological variables. This is a major gap in the current GOOS governance structure that must be addressed for coastal GOOS to become a reality.

There is an immediate need to estimate the costs of capitalization, implementation and sustained operations of coastal GOOS. PICO was not adequately resourced in terms of funding, time or the diversity of experts needed to formulate realistic estimates of implementation costs in terms of observations and data telemetry, data management and communications, and modelling and analysis. This important task could likewise be executed under the auspices of the GEO-CZCP, in coordination with the GOOS Steering Committee.

Successful implementation also depends on more effective collaboration with the OOPC as well as on effectively engaging stakeholders (data providers and users) across the land-sea interface in the process. The CZCP was established by GEO to do the latter. Thus, we recommend that the CZCP be charged, and jointly resourced by the IOC, GEO member countries, and GEO Participating Organizations, to oversee both the gap and cost analyses described above.

We also endorse the recommendation of the Joint JCOMM-IOC-GRA *ad hoc* Task Team that an expert panel such as the Joint Panel for Integrated Coastal Observations (J-PICO), or alternatively the CZCP, be tasked and resourced to provide scientific and technical guidance and ensure the coordinated evolution of ocean and terrestrial observing systems *across* the land-sea interface. Should the CZCP be given this important responsibility, this would have the added benefit of establishing an important and direct link between IOC-GOOS and GEO-GEOSS (and the GEO Ocean Monitoring Task advocated by POGO and Oceans United). Finally, successful implementation of the priorities set forth herein as an integral part of GOOS and GEOSS depends on developing international partnerships and collaborations, in active coordination with sustained coastal observing system efforts within and across the GRAs.

UNITED NATIONS CONVENTION ON THE LAW OF THE SEA

Article 145

Protection of the marine environment

Necessary measures shall be taken in accordance with this Convention with respect to activities in the Area to ensure effective protection for the marine environment from harmful effects which may arise from such activities. To this end the Authority shall adopt appropriate rules, regulations and procedures for inter alia:

(a) the prevention, reduction and control of pollution and other hazards to the marine environment, including the coastline, and of interference with the ecological balance of the marine environment, particular attention being paid to the need for protection from harmful effects of such activities as drilling, dredging, excavation, disposal of waste, construction and operation or maintenance of installations, pipelines and other devices related to such activities;

(b) the protection and conservation of the natural resources of the Area and the prevention of damage to the flora and fauna of the marine environment.

1 BACKGROUND AND VISION

The “coastal” ocean observing system must be an integrated (e.g., rapid access to and analyses of multidisciplinary data from many sources), multidisciplinary (geophysical, biogeochemical and ecological observations and models) and multiscale (ocean basins to coastal estuaries and catchment basins) system of systems.[1] Building on analyses and recommendations of the Coastal Ocean Observing Panel (COOP),[2] the IGOS Coastal Theme,[3] OceanObs’09,[4] *A Framework for Ocean Observing*,[5] and *An Assessment of Assessments* of the United Nations,[6] a plan for expanding the Global Ocean Observing System (GOOS) to include biogeochemical and ecological elements is offered herein. Our recommendations are intended to complement and leverage those aspects of the ocean-climate system addressed by the Ocean Observations Panel for Climate (OOPC) and existing operational programs for predicting extreme weather events and tsunami, changes in physical states of the upper ocean, coastal flooding as well as for maritime operations.

1.1 Coastal Ecosystems in a Globally Changing World

Coastal marine and estuarine ecosystems have experienced rapid rates of degradation over the last 150 to 300 years, largely as a consequence of market-driven exploitation of natural resources and the destruction of natural habitats.[7] Today, human expansion, global warming, and natural hazards are driving changes in coastal ecosystems that jeopardize the safety, health, security and economic well being of over 40% of the human population living in the coastal zones of over 230 countries.[8] Since the 1960s, concerns over the impacts of these changes have led to a large and growing body of ocean policies, laws and international agreements aimed at restoring, protecting and sustaining healthy marine ecosystems (Annex I). A common theme of these agreements is the importance of implementing adaptive, ecosystem-based approaches (EBAs)[9] to sustainable development[10] that will maintain the capacity of ecosystems to support goods and services valued by society (Table 1).[11]

Ecosystem Goods & Services	Key Indicators of Ecosystem States Upon Which the Provision of Goods & Services Depends
Resilience to Coastal Flooding & Erosion	Biologically structured benthic habitats, Species diversity
Food Security	Biologically structured benthic habitats, Species diversity, Primary production, Nutrient cycling, Fish stocks, Iconic species, Temperature, Salinity, Dissolved oxygen, Aragonite saturation state
Uptake & Storage of Greenhouse Gases	Biologically structured benthic habitats, Biological pump, Temperature, Thermohaline circulation
Maintenance of Water Quality	Biologically structured benthic habitats, Nutrient cycling, Microbial degradation of pollutants
Storage of Raw Materials	Biologically structured habitats, Species diversity (medicines), Fossil fuels, Minerals
Tourism & Recreation	Biologically structure habitats, Species diversity, Fish stocks, Iconic species
Aesthetic Value	Biologically structure habitats, Species diversity, Iconic species

Table 1. *Examples of ecosystem goods and services and indicators of marine and estuarine ecosystem states upon which the provision of goods and services depends. The mean annual value of goods and services from the world's coastal ecosystems is estimated to be greater than $25,000 billion per year.*[1] *Note that biologically structured benthic habitats (coral reefs, seagrass beds, mangrove forests and salt marshes) are the only indicator upon which all goods and services depend.*

However, design and implementation of ecosystem-based approaches remains an elusive goal, in part because of the lack of operational[12] models of ecosystem dynamics and continuous, synoptic observations of geophysical, biological, chemical, and biophysical variables on local to global scales. Needed are observations and models that detect and predict (1) trends in the "vital signs" of marine ecosystem health;[13] (2) the external pressures that cause changes in ecosystem health; and (3) the impacts of such changes on ecosystem goods and services and the well-being of human populations. **The vision for coastal GOOS is to facilitate development and sustained improvement in the capacity of the international community of nations to provide these observations and models on regional to global scales**.

Changes in states reflect both internal ecosystem dynamics and external pressures associated with the primary drivers (human expansion, natural hazards and global warming).[14] Pressures that alter marine and estuarine ecosystem states and biogeochemical cycles worldwide occur over a broad range of time-space scales (days-decades, local-global) and include the following:

- Commercial fishing and aquaculture;
- Sea level rise, ocean warming and ocean acidification driven by increases in atmospheric temperatures and green house gases;
- Coastal flooding driven by natural hazards (tropical storms, extra-tropical storms, and tsunami) and sea level rise;

- Natural ocean-atmosphere climate modes (e.g., El Niño-Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation);
- Basin scale migrations of large pelagic predators; and
- Land-based inputs (sediments, nutrients, contaminants, and pathogens), extraction of marine resources, habitat modification and introductions of non-native species driven by the human expansion (growth and distribution of human populations).

As these pressures indicate and as illustrated in Table 1, state changes are not only diverse and multidisciplinary, they are often expressions of larger scale pressures. Thus, although the focus here is state changes occurring in coastal marine and estuarine ecosystems,[15] **the "coastal" ocean observing system must encompass a broad range of scales from ocean basins to estuaries and coastal drainage basins**.

Within coastal ecosystems, interactions among intertidal, benthic and pelagic communities enhance nutrient cycles, primary productivity and the capacity of coastal ecosystems to support goods and services relative to deep, open ocean systems of the high seas. These interactions are, directly or indirectly, enabled or constrained by physical processes (currents, waves, turbulent mixing, pycnoclines and fronts) that structure pelagic ecosystems and resonate with biological processes over a broad spectrum of time-space scales (hours – decades, meters to thousands of kilometers).[16] In terms of the relationship between pressures and changes in ecosystem states, marine ecosystems come in many sizes and shapes from small estuaries and bays (< 10 km^2) to coastal seas, Marine Protected Areas and Large Marine Ecosystems ($1 – 5 \times 10^5$ km^2) to the ocean basins ($\sim 10^7$ km^2). Thus, small marine ecosystems are often embedded in or interact with larger ones. And, while some marine species spend their entire adult life within a single ecosystem (e.g., many small reef fish), most have larval or juvenile stages that are transported among ecosystems within larger ecosystems and many migrate on the scale of ocean basin ecosystems as adults (e.g., large pelagic fish, sea turtles, and marine mammals).[17] Thus, a pressure on one ecosystem may be a change in state for another. Together, pressures and changes in states exhibit a broad range of time-space scales of variability. **Hence the need for multi-scale (local to global), multi-disciplinary (geophysical, chemical, biological, and biophysical properties and processes), sustained, and integrated observations that can be assimilated by models in near real time to inform EBA**. These challenges can only be met through coordinated development of the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS) which underpin the Global Earth Observing System of Systems (GEOSS) of the Group on Earth Observations (GEO).[18]

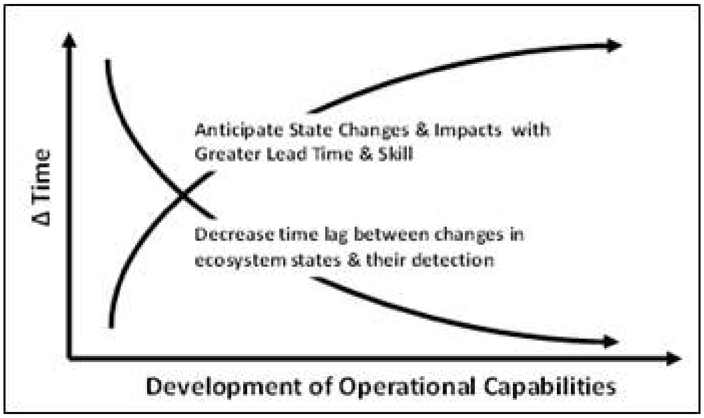

Figure 1. *The operational goal of coastal GOOS is to provide data at rates and in forms required to decrease the time lag between changes in ecosystem health (states) and their detection and to anticipate such changes and their impacts with greater lead time and skill.*

1.2 The Implementation Strategy for the Coastal Module of the Global **Ocean** Observing System (GOOS)

GOOS is developing through phased implementation of two interdependent modules: (1) an ocean-basin scale module and (2) a coastal ecosystem scale module. Basin scale GOOS is primarily concerned with more rapid detection and accurate predictions of changes in the ocean-climate system from global warming to the occurrence of natural hazards and changes in the physical environment of the ocean (e.g., sea level, distributions of temperature and salinity, current and wave fields).[19] The coastal module is primarily concerned with more rapid detection and timely predictions of the impacts of climate change, natural hazards and human activities (the primary drivers of change) on public health risks and ecosystem goods and services.[20] In this context, the primary purpose of the coastal module is to **promote and enable the routine, continuous provision of interdisciplinary observations and predictions of ecosystem states (status) and changes in states (trends) to inform the design and application of adaptive, EBAs to sustainable development** (Figure 1).

As described in detail in the implementation strategy for the coastal module,[21] timely provision of such observations and predictions on ecosystem to global scales will be achieved by expanding GOOS to include a global coastal network (GCN) with national and regional observing systems nested in it.[22] As the coastal backbone of GOOS, the GCN:

- Measures, manages and analyzes a set of essential geophysical, chemical, biological, and biophysical variables[23] simultaneously at a network of sentinel sites (stations, transects, MPAs, biodiversity "hot spots", etc.);
- Efficiently links modeling and measurements via integrated data management and communications; and

- Implements internationally accepted standards and protocols for measurements, data telemetry, data management and modeling.

Although establishing coastal GOOS is a high priority of the international community, initial requirements for global implementation have yet to be agreed upon. While observing systems for detecting and predicting state changes in the physical environment of the upper ocean are emerging on local to global scales, global implementation of coastal GOOS has been slow and uneven geographically,[24] largely as a consequence of six important technical, scientific and political challenges:

- The coastal module has a broad and complex mandate with multi-scale (local ecosystems to the global ocean) and multi-disciplinary (geophysical, chemical, biological, and biophysical) data and information requirements that differ substantially from place to place depending on the relative importance and expression of a broad diversity of ecosystem state changes.
- Most models of ecosystem dynamics and measurements of essential chemical and biological variables needed to feed them are not operational.
- International agreement on standards and protocols for quality control and interoperability of biological and chemical data;
- Implementation of the coastal module requires global coordination and collaboration among a large number of coastal nations (wealthy and developing);
- The systemic lack of observing system capacity for coastal waters of developing countries (Figure 2); and
- Funding by developed countries is inadequate, especially for capacity building (training and infrastructure)[25] and sustained implementation in the developing world.

This report addresses the first four challenges by identifying high priority state changes in ecosystem states to be targeted by the initial coastal ocean observing system of systems, by specifying observing system requirements for the initial stages of a phased implementation process, and by recommending a regional approach to development a global network of coastal observing systems. The last two bullets are matters of international ocean governance, capacity building and national policies.

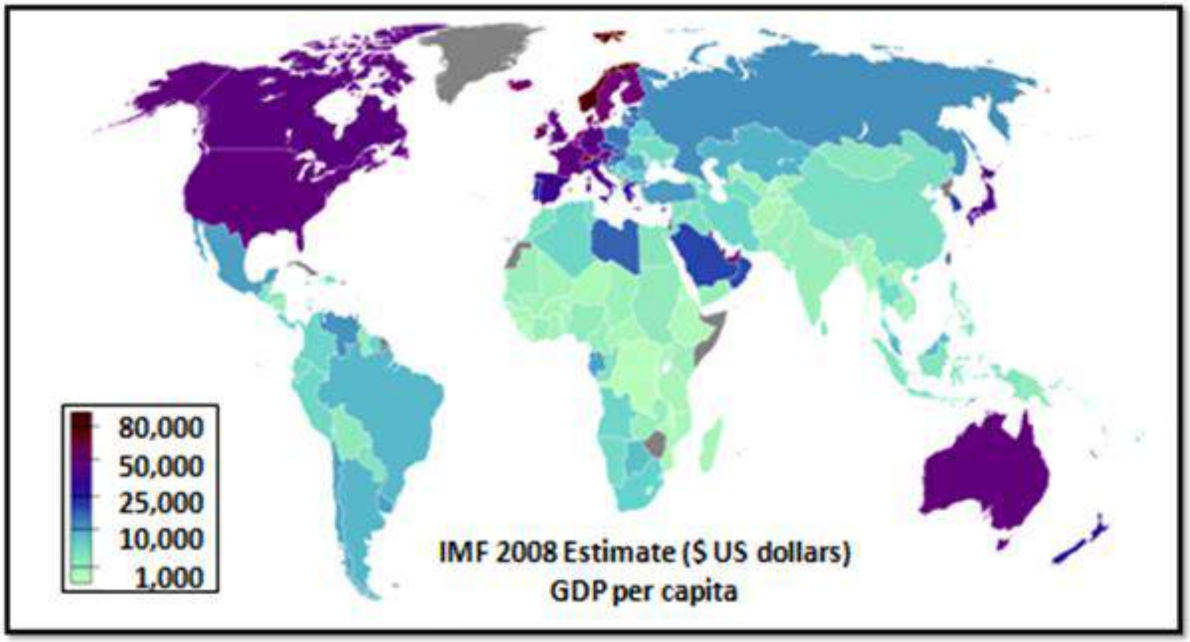

Figure 2. *Recognizing that the Exclusive Economic Zones of countries with low GDP per capita encompass most of the world's coastal ecosystems where GOOS is least developed (if at all), capacity building though partnerships between developed and developing countries is critical to the implementation and sustained operation of coastal GOOS.*

2 A FRAMEWORK FOR DEVELOPING AN INTEGRATED OBSERVING AND PREDICTION SYSTEM FOR THE COASTAL OCEAN

GOOS is developing into a globally distributed, multi-scale system of systems (SoS)[26] that routinely and continuously acquires and disseminates data and information specified by those who use, depend on, manage or study marine and estuarine systems. As such, implementation of coastal GOOS must recognize the following:

- Each component end-to-end system (Chapter 3) of the SoS must be able to perform independently of the other components and has its own unique purpose in terms of the products it supports;
- The SoS performs functions that cannot be performed by any of the component systems individually. This is the value-added result of integration (Chapter 4);
- Incorporation of component systems into the SoS is coordinated is such a way as to 'do no harm' to other component systems or to the integrated SoS as a whole (Chapter 5); and
- Implementation of the SoS is a stepwise, phased process designed to evolve as needs change and new technologies and knowledge become available (Chapter 6).

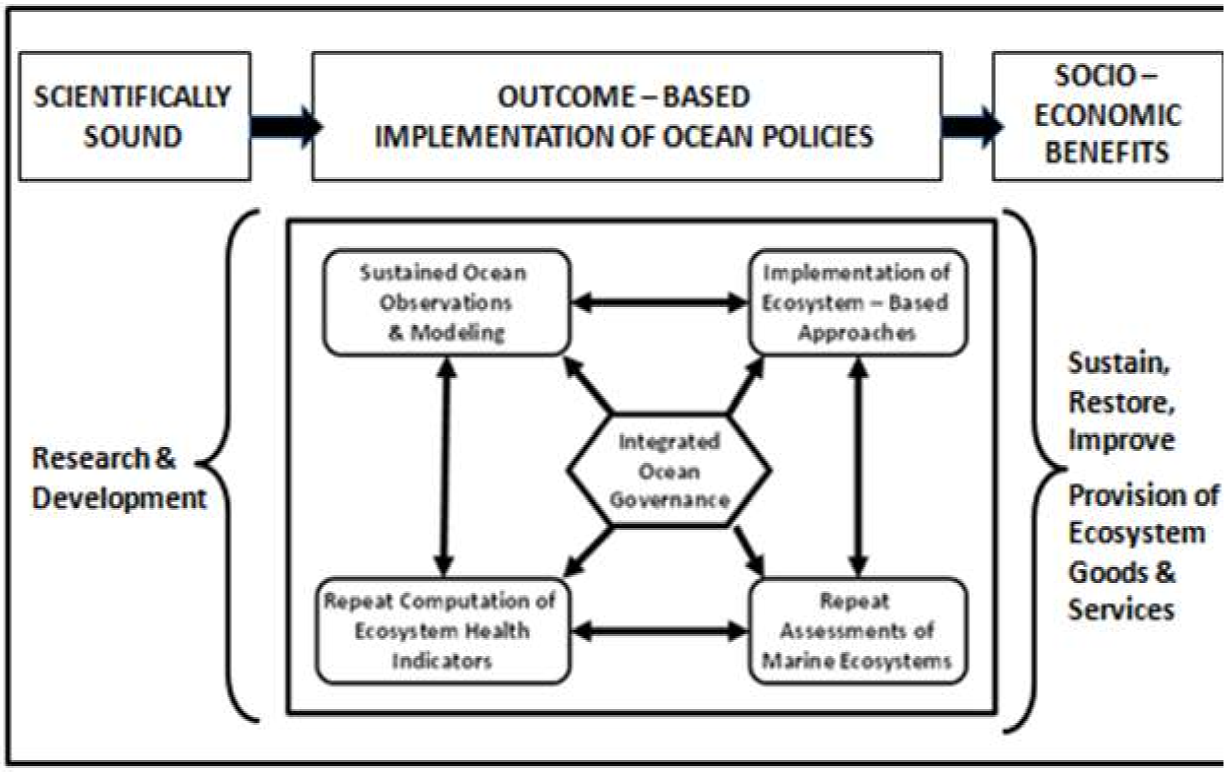

Figure 3. *Implementation of scientifically sound ocean policies for sustained development (socio-economic benefits) depends on a closely coupled system of integrated and sustained ocean observations (GOOS), repeat computation of indicators and assessments, and implementation of ecosystem-based approaches. Given that ecosystems are complex systems characterized by many interacting properties and processes that cannot all be monitored in all places at all times, it is important to identify key ecological indicators1 that enable IEAs needed to implement performance-based ocean policies and the ecosystem-based approaches called for in these policies. Coastal GOOS must evolve to provide data and information required to compute indicators routinely and continuously.*

Effective EBAs depend on scientifically credible, quantitative, robust, cost-effective and validated **indicators** (decision support tools) that can be used to enable rapid detection of changes in ecosystem states and **timely assessments** of current and future impacts of such changes on human health and well-being. Regular computation of indicators requires **sustained observations and modeling** that enable indicators to be monitored and analyzed (assessments) routinely at rates most useful to policy and decision makers responsible for sustainable use of goods and services.

Timely assessments depend on sustained delivery of frequently updated indicators of ecosystem states, changes in which are sensitive to pressures and impact the provision of goods and services and, consequently, the wellbeing of human populations. With this in mind, parties to the 2002

World Summit on Sustainable Development emphasized the importance of repeated IEAs and called for *a **regular process** under the United Nations for global reporting and assessment of the state of the marine environment, including socio-economic aspects, both current and foreseeable, building on existing regional assessments*.[27] The overarching objective of the regular process is to s*erve as the mechanism to keep the world's oceans and seas under continuing review by providing regular assessments at global and supra-regional levels*.[28]

In 2005, the UN General Assembly endorsed the need for the regular process and established an *ad hoc* Group of Experts to conduct an "Assessment of Assessments" (AoA). Their report identifies relevant existing assessment processes, provides critical appraisals of them, determines what works, and identifies regions where the required ocean observations are adequate for regular assessments and where they are not. The AoA considered six categories of information concerning ecosystem status and trends:

(1) Water quality,
(2) Living marine resources,
(3) Habitat characterizations and impacts,
(4) Lower trophic levels in the food web,
(5) Protected species, and
(6) Social and economic conditions with respect to the marine environment.

Implementing a regular process of IEAs is easier said than done.[29] In the current environment, there is a disconnect between the time scales of ecosystem dynamics and our ability to provide quantitative indicators with sufficient frequency for timely assessments of changes in ecosystem states and their impacts on society. An important first step toward tuning the required data streams to the time scales on which ecosystem state changes occur and the time scales on which decisions need to be made is to identify a set of indicators that can be used to perform IEAs based on changes in ecosystem pressures, states, and impacts.

The Driver-Pressure-State-Impact-Response (DPSIR) model provides a framework for identifying a core set of indicators.[30] The model assumes causal relationships (and feedbacks) between interacting components of socio-economic and ecological systems from primary drivers and associated external pressures on ecosystems to impacts of changes on ecosystem states and societal responses to them (Figure 4). The framework helps guide the identification of a set of indicators needed to assess and anticipate changes in ecosystem states and their impacts on local, national, regional and global scales; and facilitates analyses of which aspects and linkages are addressed by the observing system and which are not, a process that will enable the continued evolution of coastal GOOS as societal needs change and technologies advance.

For the purposes of coastal GOOS, each link in the DPSIR framework is defined as follows:

- *Drivers* are the fundamental sources of pressures on marine and estuarine ecosystems. They include growth and distribution human populations (rapid increase in the density and number of people living in the coastal zone), natural hazards (tropical and extra tropical storms, earthquakes), and climate change (due to global warming).
- *Pressures* are human interventions and external forces of nature that cause changes in ecosystems states (e.g., ocean warming and acidification, sea level rise, and basin scale oscillations; over fishing, introductions of non-native species and land-based inputs of nutrients, sediments, pathogens and chemical contaminants; storm surges, tsunami and wet deposition in coastal catchment basins).
- *Ecosystem states* are measures if the current status of properties and processes of ecosystems that are sensitive to pressures and related to the capacity of ecosystems to support goods and services.
- Changes in ecosystem states *impact* the well-being of human populations through changes in the provision of goods and services that benefit society.

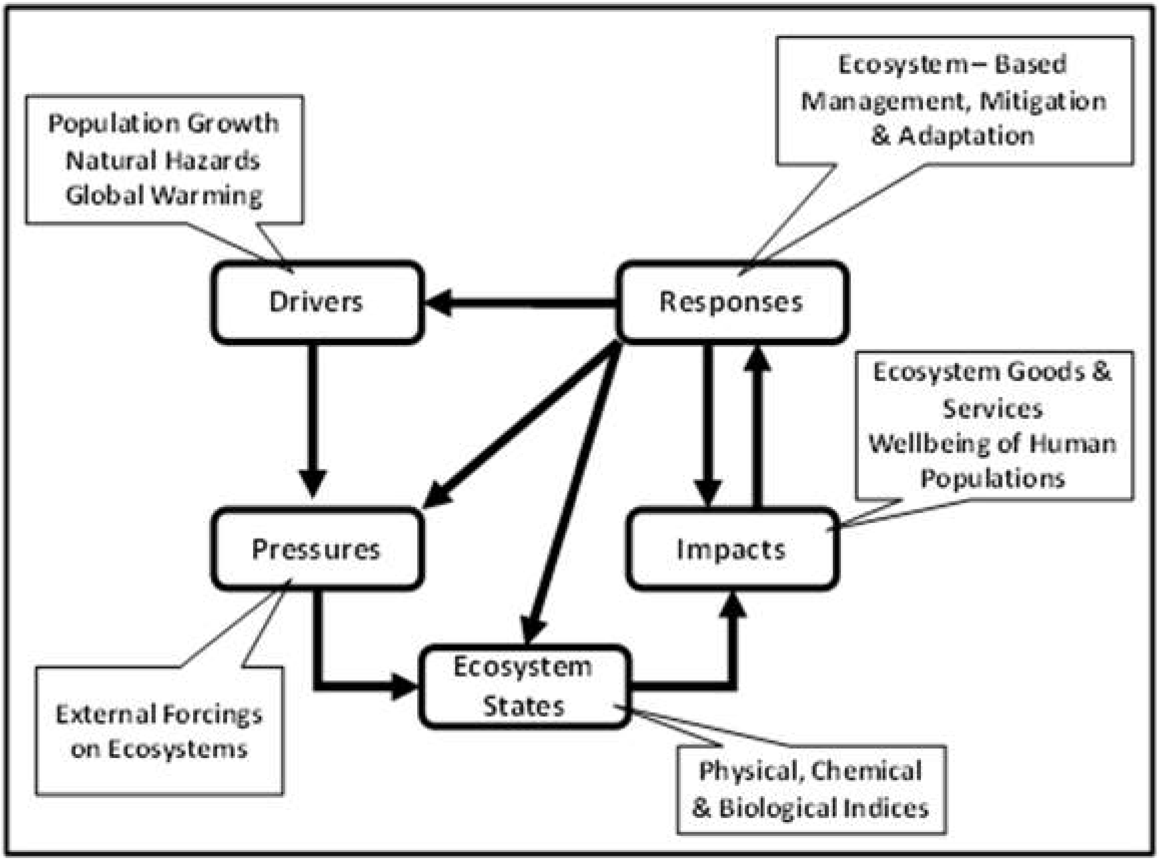

Figure 4. *The driver-pressure-state-impact-response (DPSIR) framework adapted for coastal GOOS to include both anthropogenic and natural drivers and pressures.*

- Such changes lead to human *responses* or social and political actions including the formulation and implementation of environmental policies such as ecosystem-based approaches to managing human activities and mitigating or adapting to the impacts of natural hazards and global warming.

Timely, IEAs are informed by the sustained provision of data and information on changes in ecosystems states and the relationship of such changes to ecosystem pressures and impacts. Changes in ecosystem states (Table 2) target AoA categories 1 – 5 explicitly and category 6 (socio-economic aspects) implicitly. In regard to the latter, indicators of the well-being of human populations are typically computed using metrics for human health (e.g., life expectancy), economic production (e.g., income per capita) and education (e.g., years of formal schooling).[31] Thus, the health of human populations is both a determinant and a result of wellbeing. A generally accepted measure of wellbeing is the Human Health Index (HDI) which combines these parameters of the wellbeing into a composite, dimensionless index.[32] Changes in ecosystem states directly impact life expectancy and income via changes in the goods and services provided by marine ecosystems (Table 1).

Successful implementation of the regular process of assessments depends on (1) reducing the time required to complete assessments, (2) repeating assessments on time-space scales needed to both resolve and anticipate trends in pressures and ecosystem states and to enable informed responses to impacts,[33] and (3) the continuous provision of data and information needed for rapid and frequent computation of a comprehensive set of indicators upon which assessments depend. Coastal GOOS is primarily concerned with the latter (provision of data and information on pressures, state changes and impacts). To these ends, key indicators of marine ecosystem states are identified, and end-to-end systems for selected phenomena of interest are described in **Chapter 3** for sustained provision of data and information needed to compute the indicators. A framework for integrating the end-to-end systems into a global system of systems (the GCN with nested regional ocean observing systems) is given **Chapter 4**, and **Chapter 5** describes the recommended system of systems and associated requirements. Finally, a plan for the phased implementation of this system of system is offered in **Chapter 6**.

3 THE BUILDING BLOCKS OF A SYSTEM OF SYSTEMS

Implementation of an integrated global ocean observing system of systems for marine ecosystems must occur on at least two fronts: (1) efficiently linking observations and models to build end-to-end systems based on user needs and (2) implementing and linking national and regional scale observing systems to build a global system of systems. Given that this will take a decade or more, phased implementation is recommended beginning with the integration of end-to-end systems for selected phenomena of interest: Coastal Eutrophication and Hypoxia; Human Exposure to Waterborne Pathogens; Harmful Algal Blooms; Habitat Loss & Modification; Vulnerability to Coastal Flooding; Ocean Acidification; and, Food Security.

Guided by the latest recommendations of expert panels,[34] a short list of high priority ecosystems states to target was determined based on (1) the extent to which changes in states are occurring globally in response to specific pressures (Chapter 1); (2) the importance such changes to achieving the goals of international conventions and laws (Annex I); and (3) their relevance to changes in the Human Development Index (Chapter 2) and to the regular process of marine ecosystem assessments (Table 2). Relative to the above phenomena of interest, the following priority indicators of ecosystem states (ecosystem health) meet these criteria and were identified as targets for specifying observing system requirements:

- Phytoplankton biomass and oxygen fields,

Ecosystem State Indicators	Targeted Phenomena of Interest	Assessment of Assessment Categories
Phytoplankton biomass	Eutrophication & hypoxia, species diversity food security	Water quality, LMR, Lower trophic levels
Dissolved oxygen	Eutrophication & hypoxia, species diversity, food security	Water quality, LMR, Social & economic conditions
Waterborne pathogens	Exposure to pathogens	Water quality, Social & economic conditions
Toxic phytoplankton	Exposure to toxins, species diversity, food security	Water quality, Lower trophic levels, LMR, Social & economic conditions
Spatial extent of benthic biological habitats & ecological buffers	Habitat loss & fragmentation, species diversity, eutrophication & hypoxia, food security, vulnerability to coastal flooding	LMR, Habitat characterizations & impacts, Protected species, Social & economic conditions
Calcareous plankton	Ocean acidification, species diversity, food security	Water quality, LMR, Habitat characterization & impacts, Lower trophic levels, Social &economic conditions
Fin- and shell-fish stocks	Food security, eutrophication & hypoxia, species diversity	Water quality, LMR, Lower trophic levels, Protected species, Social & economic conditions

Table 2. *Measures of ecosystem states, the corresponding phenomena of interest (as defined by the COOP[1]) targeted by end-to-end observing systems, and categories of information considered by the Assessment of Assessments (Chapter 2) impacted by changes in ecosystem states.*

- Distribution and abundance of waterborne pathogens,
- Distribution and abundance of toxic phytoplankton,
- Spatial extent of benthic biological habitats,
- Ecological buffers to coastal flooding
- Distribution and condition of calcareous organisms, and
- Distribution and abundance of exploitable fish stocks.

Each end-to-end system (1) performs independently of the others and has its own unique purpose in terms of the products and applications it supports, (2) incorporates recent advances in scientific understanding[35] and technology[36], (3) requires the integration of multidisciplinary data to anticipate changes, and (4) provides data and information that have multiple applications and significant impacts on national economies. Technologies and procedures for modeling, *in situ* measurements, remote sensing and modeling are described in Chapter 5.

3.1 Coastal Eutrophication and Hypoxia (Primary Pressures: Land-Based Inputs of Nutrients, Commercial Fishing, Ocean Warming)

3.1.1 Introduction

Eutrophication is an increase implant biomass and primary production due to nutrient enrichment. Natural inputs of nutrients from catchments (e.g., coastal rivers and streams, ground water discharge) and marine sources (e.g., coastal upwelling, vertical mixing) are vital to sustaining biodiversity and living marine resources, but excessive inputs from anthropogenic sources are now widespread in coastal marine ecosystems. The latter include increases in domestic sewage discharge (point sources) and diffuse input from agriculture (fertilizers and animal wastes) and wet precipitation.[37] Changes in ecosystem states associated with excess nutrient enrichment include accumulations of phytoplankton biomass, toxic algal blooms (section 3.3) and oxygen depletion (hypoxia or anoxia).[38] These changes can lead to fish and invertebrate kills (section 3.7) and losses of biologically structured benthic habitats (section 3.4), and biodiversity.[39]

3.1.2 Products and Applications

The management and mitigation of anthropogenic eutrophication depends on achieving reductions in diffuse and point source nutrient loads. In some cases, restoration of populations of filter feeders (e.g., bivalves, clupeid fishes) and engineering solutions to increase flushing and dispersal rates may also be effective in preventing excess accumulations of phytoplankton biomass. The cost of management actions to reduce nutrient loads can run to billions of dollars in individual catchments and affect entire agricultural sectors. In these circumstances, load reduction targets and actions must be defensible and based on sound assessment and prediction. In some cases, including natural eutrophic-hypoxic systems, mitigation may not be an option, and attention may be focused on operational forecasting to allow coastal industries and users to avoid adverse impacts.

Users and applications include (1) managers responsible for land-use in catchments (Coastal Zone Management), controlling land-based nutrient loads, and sustaining living marine resources); (2) coastal aquaculture, wild fisheries, and tourist industries(avoid or reduce impacts on aquaculture, fishing, recreation and tourism); (3) the Regular Process of the UN (input to integrated assessments of marine ecosystems); and (4) the public (ocean literacy, help guide the formulation and implementation of environmental policy, and use of coastal systems for recreation).

Products include (1) maps of the risk of eutrophication and hypoxia for each season of the year updated every 5 years (to guide the distribution of effort in observation and management) where the computation of risk is based on "climatologies" for pressures (e.g. point and diffuse land-based inputs of nutrients, over fishing), for vulnerability (flushing rates and stratification of coastal water bodies), and for potential impacts (loss of ecosystem goods and services); (2) for

Observations: *In situ*	• Continuous measurement of phytoplankton biomass, nutrients & light attenuation within the euphotic zone; • Vertical profiles of temperature, salinity & dissolved oxygen (daily to weekly prior to & during periods of hypoxia); • Point & diffuse inputs of freshwater (river flows) & associated loads of organic carbon & nutrients (inorganic & organic, dissolved and particulate N & P);
Observations: Remote	• River discharge, plumes, & salinity (direct measure or proxy); • SST & sea surface roughness & ocean surface vector winds • Ocean color radiometry: Phytoplankton biomass (chl-a), total suspended matter/turbidity, CDOM fields from water-leaving radiance spectrum • Catchment condition & land use.
Model requirements	• Coupled 4-D coastal circulation – water quality models • Catchment hydrological & load models.
Reporting	• Near real time reporting of temperature, salinity, dissolved oxygen, light attenuation, phytoplankton biomass (chlorophyll-a concentration), & river flows; • Delayed mode reporting of nutrients, biomass, dissolved oxygen, light attenuation.

Table 3. *Requirements for observations, models and data telemetry (eutrophication and hypoxia).*

regions at risk, nowcasts and forecasts (48 h to 3 months depending on flushing rates) of algal biomass (as chlorophyll-a), dissolved oxygen, and light attenuation fields (with spatial resolution sufficient to resolve gradients and address impacts).; (3) time-space extent and volume of hypoxic water ($\leq$ 2 ppm) computed annually; and (4) for ecosystems at risk, mean phytoplankton biomass (chlorophyll-a), dissolved oxygen, dissolved inorganic nutrients (N, P, Si), particulate and dissolved organic matter (C, N, P), and light attenuation (for each season and year with variances). Nutrient and chlorophyll concentrations should be integrated over the water column and averaged over the euphotic zone, and dissolved oxygen concentrations should be averaged over the oxygen minimum zone (e.g., over the bottom layer in stratified systems).

3.1.3 System Requirements (Table 3).

The observations and models needed to guide nutrient management are similar to those needed to assess and predict changes in coastal circulation, water quality and productivity. They are also likely to contribute to management of coastal habitats, living marine resources, harmful algal blooms and to the prediction of changes in ecosystem states caused by climate related pressures. *In situ* observations are not only needed to estimate pressures and ecosystem states (along with remote sensing), they are needed to calibrate and validate models and remote sensing. Priority sites for establishing end-to-end observing systems are those that are at risk. *In situ* observations should be most frequent during periods when risk is highest (e.g., daily to weekly).

3.1.4 Operational Status

The European Commission has published assessment guidelines for harmonizing eutrophication assessments by EU member states,[40] and the LOICZ Biogeochemical Budget Project developed and tested a simple low-cost assessment methodology.[41] Some assessments of the extent of coastal eutrophication have been made on national and continental scales (e.g., The National Estuarine Eutrophication Assessment for the USA[42], the Australian Land and water Resources Audit[43], and Coastal and Hypoxic Areas of Europe[44]), but these types of assessments have not been done routinely and need to be completed more frequently (e.g., annually). These efforts may help to establish a consistent information base for coastal eutrophication and to understand the causes and extent of coastal eutrophication and hypoxia in some regions (e.g., North America, Europe and Australia), but assessments currently take too long to complete to be useful for nowcasts and forecasts. Furthermore, estuarine and marine ecosystems in most coastal regions are not sufficiently comprehensive in terms of the number of systems monitored.

The required methods, technologies and models are mature and have been implemented locally (e.g., the Baltic Sea, Moreton Bay, Chesapeake Bay, and Northern Gulf of Mexico). However, fully integrated, end-to-end systems that serve the data and information needed to provide the products described above routinely have yet to be implemented on regional to global scales. To achieve this objective, integrated systems are needed that combine sustained remote and *in situ* observations (for both coastal receiving waters and catchment land-cover) with operational models (coupled catchment hydrological-hydrodynamic circulation-water quality) that routinely and continuously meet observing system requirements.

3.1.5 Gaps, Challenges and the Way Forward.

The capacity to implement observing system requirements for eutrophication and hypoxia is highly uneven. Monitoring water quality to support management of catchment loads is relatively common for many estuarine and marine ecosystems in developed countries, but even here under-sampling in time and space is a problem. There are opportunities to improve the resolution, coverage and cost-effectiveness of observations through advances in low-cost *in situ* sensors and in remote sensing. While the actions required to reduce point source loads are often obvious, and treatment costs continue to diminish, the reduction of diffuse catchment loads is more uncertain and problematic. This will require strong engagement and collaboration with catchment observing systems and managers.

Algorithms for computing the risks from climatologies as described above have yet to be developed, and short-term nowcasting and forecasting of eutrophication and hypoxia is still relatively rare and experimental. Thus, priorities for pilot projects to improve operational capabilities are:

- Develop algorithms for computing the risk of eutrophication and hypoxia from climatologies for pressures, vulnerability and potential impacts;
- Develop data assimilation for coastal hydrodynamic and water quality models, through a Coastal Ocean Data Assimilation Experiment (ecological forecasting) and establish mechanisms to ensure transition into an operational mode by the appropriate operational agencies;
- For case 2 waters,[45] develop new and improved algorithms for routinely translating ocean color into widely available regional coastal products (e.g., maps of plumes and chlorophyll-a, total suspended matter and CDOM fields) with product validation and known reliability and accuracy/uncertainties;
- Develop low cost, low power, small automated sensors that have been tested under a range of coastal environmental conditions; and
- Develop operational models for nowcasting and predicting flows, loads, phytoplankton biomass fields, and the time-space extent of bottom water hypoxia.

A staged approach is needed which provides options for investments in monitoring and modeling depending on risk and regional capacity.

3.2 Human Exposure to Waterborne Infectious Microbes (Primary Pressures: Land-Based Inputs of Untreated Human and Animal Wastes, Ocean Warming)

3.2.1 Introduction

Each year, more than 2 billion people suffer from waterborne illnesses and 5 million die from water-related diseases. *Chronic and episodic risks of exposure to waterborne infectious microbes in coastal waters via direct contact (contact recreation, fishing) and consumption of shellfish* are increasing globally as coastal waters warm,[46] point and diffuse inputs of fecal matter increase (especially in developing countries where population density is increasing more rapidly that sewage treatment capacity[47]), and population density increases along the coastline.[48] Ecosystem state is indicated by the distribution and abundance of enterococci (faecal streptococci) in areas subject to land-based inputs of fecal matter and human uses (contact recreation and harvesting shellfish). Guidelines for classifying recreational waters based on the concentration of enterococci and pressures have been published by the WHO.[49] Pressures are the inputs of infectious microbes (as indicated the concentration of enterococci in point source discharges and riverine inputs) and ocean warming. Impacts are measured in terms of beach and shellfish bed closures and outbreaks of gastrointestinal illness (including dysentery) and acute febrile respiratory illness (AFRI) among populations that come in contact with contaminated waters and shellfish consumers.[50]

3.2.2 Products and Applications

For populated coastal zones within 100 km of the coast, the product is annually updated maps of an index of potential pressure based on water temperature, salinity, location and volume discharge of rivers (seasonal climatology) and point sources (annual mean), and distance from discharges (e.g., [temperature x volume discharge x contaminant concentration] ÷ [salinity x distance]). For near shore waters frequented by people and ambient waters of shellfish beds subject to potential inputs of infectious microbes, products are near-real time nowcasts and 24-/48-hr forecasts of the distribution and abundance enterococci. Nowcasts and forecasts are updated daily during periods of recreational use and shellfish growing seasons.

Provision of data and information required for rapid detection of waterborne pathogens and timely forecasts of their distribution will improve public health and increase the economic value of beaches and shellfish beds through more accurate early warnings and reductions in the number and duration of closures. To these ends, decision-makers and applications include government agencies/ministries (manage public health risks, close and open beaches and shellfish beds, environmental protection, resource and coastal zone management); commercial shellfisheries (marketable shellfish); the World Health Organization (statistics on contaminated coastal waters, beach and shellfish bed closures); the Regular Process of the UN, and the public (beach use and shellfish consumption).

In addition to their public health applications, many of the requirements for observations and models (e.g., surface temperature, salinity, current and wave fields, land-based inputs) are also needed for eutrophication and hypoxia (section 3.1), harmful algal blooms (section 3.3), sustaining essential benthic habitats (section 3.4), managing the impacts of coastal inundation (section 3.5), and sustain exploitable fish stocks (section 3.7). Additional applications include forecasting the fate of hazardous material spills (e.g., oil spills and toxic wastes) and marine spatial planning.

3.2.3 System Requirements (Table 4)

Priority locations for establishing the end-to-end observing system are populated coastal zones where both pressures and human uses are high.

Observations: *In situ*	• Distribution & abundance of people & domesticated animals updated every 5 yr; • Location & size of public beaches & shellfish beds updated every 5 yr; • Continuous measurements of volume discharge of rivers and point sources (end of pipe); • Weekly-monthly measurements of the concentration (number of colony forming units, CFU/100 ml) of enterococci in these discharges; • Monitor ambient enterococci concentrations weekly during periods of beach use & shellfish growth; daily when CFU levels > 60/100 ml in single water samples or > 30/100 ml for geometric means of multiple samples; • Continuous measurements of surface currents, waves, temperature, salinity, & turbidity in targeted areas & during targeted periods.
Observations: Remote	• Ocean color radiometry: e.g., chlorophyll-a, total suspended matter/turbidity & colored dissolved organic matter fields from water-leaving radiance spectrum • SST fields • Ocean surface vector winds • Buoyant plumes & wave fields • Surface current & wave fields
Model Requirements	Two categories of models may be used to provide nowcasts & forecasts: (1) statistical models that estimate concentrations of enterococci as a function of salinity or turbidity & (2) coupled hydrological-hydrodynamic-particle transport models.
Reporting	Delayed mode enterococci data (< 24 hr from time of sampling); Near real-time environmental data (< 1 hr from time of sampling)

Table 4. *Requirements for observations, models and data telemetry (waterborne infectious microbes).*

3.2.4 Operational Status

Currently, beach and shellfish bed closures are based on enterococci measurements on water samples. Using thresholds established by the U.S. Environmental Protection Agency (USEPA), closures occur when enterococci exceed 61 CFU/100 ml in a single water sample or 33 CFU/100 ml for the geometric mean of multiple beach water samples. Sampling near shore waters may be repeated at regular intervals when pressures are continuous (e.g., sewage outfalls) or triggered by an event (e.g., storm water runoff). Data and information providers include government bodies responsible for marine forecasts (surface temperature, current and wave fields), public health, food safety, and environmental protection.

The concentration of enterococci is a function of distance from pressures, enterococci "half-life"[51] once introduced to coastal receiving waters, and the circulation regime (advection and turbulence) of the receiving water body. Thus, coupled hydrodynamic-particle transport models are being used to guide *in situ* adaptive sampling regimes in some locations (Box 1). Data requirements for these models are met through a combination of *in situ* and remote sensing (Table 4).

3.2.5 Gaps, Challenges and the Way Forward

Coastal circulation regimes are highly dynamic on time scales of hours and inputs of infectious microbes are often related to episodic flooding events. Actions by decision makers are currently based on estimates of enterococci concentrations using culture techniques requiring 24 – 48 hours to complete. Thus, beach and shellfish bed closures may occur too late (after exposure risk has become unacceptable) and continued too long (after exposure risk has become acceptable). This has undesirable public health and economic consequences, both of which are exacerbated by the reality that concentrations of enterococci are often unrelated to the presence or concentration of infectious microbes.[52] Even with these limitations, the operational system described above is better than nothing and should be implemented now by developing countries with the help of developed countries (funding and capacity building).

Box 1. Improving Operational Capabilities

In the U.S., Congress passed legislation in 2000 (the Beach Act) that requires coastal states to develop beach water quality monitoring and notification programs and provided federal funding to administer these programs. States are required to adopt EPA standards for determining where and when to post beaches with health advisories. Monitoring and notification programs, including websites showing current advisories,[53] have been developed by state natural resource and public health agencies, in collaboration with federal and local partners, typically county or municipal health departments. A growing number of public beaches are now being tested regularly for either *E. coli* or *Enterococci* during the bathing season (from weekly to daily for high priority beaches). Hydrodynamic models are used to provide beach managers with guidance for posting swim advisories based on current conditions at several beaches in the Great Lakes,[54] but these are limited by the time required for culture results to become available. Research is underway to (1) develop methods (e.g., rapid quantitative polymerase chain reaction) for near real-time predictions of pathogen levels as a function of current meteorological and nearshore circulation regimes and (2) develop and test a standardized Beach Sanitary Tool[55] which enables beach managers determine potential sources of bacterial contamination (onsite at the beach, and throughout the contributing watershed) and mitigate their impacts. Required observations include numbers of birds and bathers at the beach, the slope of the beach, macroalgal biomass, location of storm water outfalls and point source discharges, and land use practices in the catchment basin.

The recommended way forward for developed countries is to implement pilot (proof of concept) project to improve operational capabilities as follows:

- implement and validate adaptive *in situ* sample regimes triggered by satellite-based detection of turbid, buoyant plumes and use this capability to increase the cost-effectiveness of routine sampling protocols;
- identify more effective indicators of the presence and concentration of infectious microbes;
- develop operational *in situ* sensors for measuring these indicators (including enterococci) and near-real time telemetry of data on infectious microbe concentrations (e.g., the environmental sampling processor[56] and the autonomous microbial genosensor[57] which are approaching maturity); and
- near-real time observations of indicators and specific infectious microbes for operational nowcasts and forecasts of the distribution and abundance of infectious microbes.

3.3 Toxic Harmful Algal Events (Primary Pressures: Land-Based Inputs of Nutrients, Ocean Warming, Ballast Water Discharge, and Commercial Fishing)

3.3.1 Introduction

Harmful algae are a diverse group of organisms with only two characteristics in common: (1) they harm people and ecosystems; and (2) their initiation, development and dissipation are governed by species-specific population dynamics and oceanographic conditions.[58] There are over 200 species of phytoplankton (from 12 classes of algae) that cause harmful algal blooms

(HABs), and they exhibit a wide variety of life-cycle strategies, trophic types, physiology, behavior, morphological and harmful effects. This diverse assembly of harmful species can be organized into two broad categories (with some species in both): (1) those that cause harm through the production of toxins and (2) those that cause harm through excessive accumulations of biomass (e.g., hypoxia-anoxia, decline in food quality for filter feeders, clogged gills). Therefore, indicators of ecosystem state are fields of phytoplankton biomass (chlorophyll-a), toxic algal cells, and toxicity.

Problems associated with harmful algal blooms (HABs) are global and appear to be increasing in severity and extent.[59] The primary pressures are increases in land-based inputs of nitrogen and phosphorus from sewage, animal wastes, and fertilizers (section 3.1), increases in water temperature and vertical stratification of the upper ocean due to global warming, and introductions of invasive (non-native) HAB species with ballast water from ships. Thus, changes in oceanographic conditions most relevant to predicting where and when HABs will occur are vertical stratification, fronts and current, wave, temperature, salinity and nutrient fields.

The end-to-end system for coastal eutrophication and hypoxia targets excessive accumulations of phytoplankton biomass. Here we focus on toxic species. Negative impacts of toxins produced by HABs include illness and death in humans who consume contaminated fish and shellfish or are exposed to toxins via direct contact (swimming, inhaling noxious aerosols); mass mortalities of wild and farmed fish, marine mammals and birds; and changes in the capacity of ecosystems to support goods and services. Globally, more than 60,000 cases of human illness caused by exposure to algal toxins are report per year.[60] Based on outbreaks during 1987-2000 in U.S. coastal waters alone, HAB events are estimated to have had an economic impact of at least US $82 million/year.[61] This estimate is conservative due in part to a lack of information on individual events (unreported illness, fish kills, etc.) and socio-economic impacts that are difficult to quantify (declines in fish sales due to unfounded consumer fears, reductions in property value, etc.).

Twelve species of harmful algae (9 dinoflagellates, 2 cyanobacteria and 1 diatom) account for most toxins harmful to human health.[62] Although many of these species are pigmented and cause problems when they bloom, some bloom at depth (and do not have a surface signature), some are not pigmented, some have toxic effects at low cell densities and some exhibit variable levels of toxicity.[63] In addition, blooms tend to occur episodically over a spectrum of time-space scales (days to months, < 1 km to > 100 km). Together, these factors and the diversity of HAB species present significant challenges to specifying observing system requirements and preclude the design of an observing system for all species in all places.

Two prototype end-to-end solutions are offered, one for *Karenia brevis* in the Gulf of Mexico and one for *Alexandrium fundyense* in the Gulf of Maine. Both are dinoflagellates. *K. brevis* produces brevetoxin (causing neurotoxic shellfish poisoning [NSP] and respiratory illness), and

A. fundyense produces saxitoxin (causing paralytic shellfish poisoning, PSP). *K. brevis* was selected because it represents a group of pigmented species that can be detected from space and because an operational forecasting system is already in place for this species in the Gulf of Mexico. *A. fundyense* was selected because it represents a group of saxitoxin producing species (*Alexandrium* spp, *Pyrodinium bahamense* and *Gymnodinium catenatum*) that causes PSP in coastal ecosystems globally[64] and because a preoperational forecasting system is in place for the Gulf of Maine.

3.3.2 Products and Applications

The end-to-end systems described here will supply data and information needed to provide (1) early warnings (< 72 hr) of where and when HAB events are likely to occur updated weekly during the growth season, (2) nowcasts of location and spatial extent of blooms updated daily, and (3) 48 hr forecasts of bloom trajectories and probable locations of land-falls updated daily. Users (and applications) include decision makers from Public Health (shellfish bed closures and openings, public health advisories for beach goers and boaters), Environmental Protection (nutrient management), Natural Resource (fisheries managements), and Coastal Zone Management (land-use practices) agencies; commercial and recreational fisheries (shellfish bed closures and openings, contaminated fish, positioning of mobile mariculture operations); and the public (seafood consumers, beach goers, boaters).

In addition to the applications described above, many of the requirements for observations and models (e.g., surface temperature, salinity, current and wave fields, land-based inputs) are also needed for forecasting of waterborne pathogens and the fate of hazardous material spills (e.g., oil spills and toxic wastes) and for ecosystem based management of fisheries and coastal eutrophication, mitigation of the impacts of coastal flooding, and marine spatial planning.

Observations: *In situ*	During targeted periods and in 'hot spots': Sea surface winds, temperature, salinity, currents and waves, density of vegetative cells, species/taxa-specific diagnostic phytoplankton pigments
Observations: Remote	Ocean color radiometry: e.g., chlorophyll-a, turbidity & colored dissolved organic matter fields from water-leaving radiance spectrum; SST & SSS fields; Surface current fields Ocean surface vector wind and wave fields Buoyant plumes & wave fields
Model Requirements	*K. brevis* cell/chlorophyll-a Sea surface temperature, salinity, chlorophyll, nutrient, current, and wave fields Coupled hydrodynamic-particle transport models numerical models.
Reporting	Near real-time chlorophyll-a fields (< 12 hr), environmental data and *K. brevis* cell density (< 1 hr from time of sampling) Delayed mode *K. brevis* microscopic enumeration (< 24 hr from time of sampling);

***Table 5**. Requirements for observations, models and data telemetry for K. brevis.*

3.3.3 System Requirements

Because of their episodic, transient nature, detecting and predicting HABs require frequent, sustained, high resolution (< 10 km) observations. Thus, traditional approaches that depend solely on ships for sampling and laboratories for chemical and biological analyses are not sufficient in themselves. Remote sensing and new, autonomous, *in situ* sensing technologies with real-time data telemetry are needed to develop comprehensive observation strategies for timely detection of HAB abundance, distribution and toxicity.[65] Combined with emerging data assimilation and modeling capabilities, HAB prediction systems are emerging.[66] These systems are species-specific or target groups of species that have characteristics in common (e.g., pigmented species that cause problems when they bloom and have a surface signature that can be detected from space).

The US National Oceanographic and Atmospheric Administration (NOAA) has established a HAB Operational Forecasting System (HAB-OFS) for *K. brevis* in the Gulf of Mexico (Table 5); which demonstrates the effectiveness of the integrated use of *in situ* observations and remote sensing through modeling.[67] Coupled hydrodynamic-particle transport models ingest near-real time satellite imagery of ocean color (surface chlorophyll-a concentration), surface temperature, winds, waves and currents and *in situ* measurements of *K. brevis* cell density. Microscopic enumeration of *K. brevis* cell concentrations in samples collected from chlorophyll-a patches are used to confirm the dominance of *K. brevis*.

Observations *In situ*	Stream flows, tides, fall resting cyst maps, water temperature and salinity, currents, nitrate concentration, density of vegetative cells in the water column
Observations Remote	SST & SSS fields; Surface current fields Ocean surface vector wind and wave fields Buoyant plumes & wave fields
Model requirements	Coupled hydrodynamic-particle transport models numerical models.
Reporting	Delayed mode fall resting cyst maps, nitrate concentration , density of vegetative cells Near real-time stream flows, tides, water temperature and salinity, currents

Table 6. *Requirements for observations, models and data telemetry for A. fundyense*

The pre-operational observing and prediction system in the Gulf of Maine (Table 6) estimates the distribution and abundance of *A.fundyense* using a coupled ocean circulation-population dynamics model. A Regional Ocean Modeling System (ROMS)[68] has been configured with a high resolution (1 km) Gulf of Maine ROMS nested in a shelf-scale ROMS embedded in a data assimilating North Atlantic Hybrid Coordinate Ocean Model (HyCOM).[69] Data requirements are initial boundary conditions from HYCOM ocean forecasts, weather forecasts (6-hourly wind and heat fluxes from the US National Centers for Environmental Prediction), tides (from the NOAA Center for Operational Oceanographic Products and Services), SST from satellites, and river flows from US Geological Survey stream gauges.

The sub-model formulation includes population dynamics (cyst germination rate as function of light and temperature, vegetative cell growth rate as a function of temperature and nitrate concentration, mortality rate as a function of a temperature dependent $Q_{10,}$ and encystment rate as a function of temperature and nitrate concentration), cyst map from fall surveys (NOAA-EPA), solar radiation (NCEP EDAS), and climatology nutrient fields (Bedford Institute of Oceanography).[70]

3.3.4 Operational Status

The NOAA HAB Operational Forecast System (HAB-OFS) for *K. brevis*[71] and provides notification of bloom conditions to state and local coastal managers of the region (HAB Forecast Bulletin[72]). HAB-OFS is the first example of operational forecasting of biological events[73] and is a prototype operational system for HAB species and regions that have the following features:

- Species that produce surface blooms that can be detected and monitored from space (via ocean color radiometry – e.g., chlorophyll-a and anomaly products, spectral shape products/indices);
- Species with a specific signature of inherent optical properties that enable *in situ* detection using bio-optical sensors;

- The region has a history of monitoring that provides information on "hot spots" in time and space and a means to validate space-based observations;
- Coastal ocean circulation models for the region are operational; and
- Impacts of cloud cover on space-based observations are minimal.

In addition to the Gulf of Mexico, these conditions are met in the Baltic and North Seas and other regions where similar observing systems have been developed for cyanobacterial blooms.[74]

In the Gulf of Maine, *A. fundyense* nowcasts and forecasts are being run in a pre-operational demonstration mode with the goal of transitioning modeling capabilities to an operational agency (NOAA) once the observing system is ready for operational use.[75] This system is a prototype for other regions where PSP events are common. The population dynamics of *A. fundyense* are understood sufficiently well to allow modeling in both hindcast and nowcast modes.[76] Annual outlooks for the upcoming year are also modeled using previous autumn cyst maps and the range of physical forcings from previous years of model runs. Once NOAA's requirements for documentation and training have been met, this new capability will be transitioned into the NOAA High Performance Computing System.

3.3.5 Gaps, Challenges and the Way Forward

The challenges to establishing systems such as those described above differ for developing and developed countries. Thus, we offer two solutions. The first is for phased implementation of existing capabilities on a global scale, and the second is for improving existing capabilities (filing technical gaps) through partnerships between data providers and users in the respective regions. Success of the latter is expected to facilitate improvements of the former over time.

Implementing Existing Capabilities

Developing either system for coastal waters of developing countries will require capacity building and should begin with those countries where socio-economic impacts are clear and which have one or more coastal marine laboratories. Here we focus on the *K. brevis* prototype because it can be detected from space and a GOOS-GEOSS demonstration project (Chlorophyll Globally Integrated Network, ChloroGIN[77]) has been implemented that can be leveraged. Satellite-based remote sensing of ocean color is the only means by which biological and biogeochemical parameters can be observed synoptically through time on ecosystem to global scales. The information is useful for ecosystem-based management of fisheries[78] and for detecting and tracking HABs that have a surface chlorophyll signature. However, the information is, for the most part, limited in its use to developed countries. Thus, a global network should be utilized to disseminate this information to both developing and developed countries as described in Chapter 5.

The current ChloroGIN network consists of three primary regional centers (in Latin America, South Africa and India) with links to four northern centers (United Kingdom, European

Commission Joint Research Centre, Canada, and Japan). Two training courses on “Methods and Applications of Ocean Color Remote Sensing in African Coastal and Regional Seas” have been conducted in Mombasa and Zanzibar. Ongoing activities include (1) updates of *in situ* measurement protocols for consistency and minimum capability of all partners; identification of laboratories conducting HPLC analyses that will take samples from ChloroGIN sites for analysis; demonstrations of in situ capability on web portals; (4) updates of protocols to optimize file formats for satellite data; and establishing specifications for information system compliance and development.

Working within the framework of ChloroGIN, next steps for implementing HAB observing systems are to indentify ‘hot spots’ of HABs in time and space; formulate Chl climatologies for these regions; establish protocols for validating that Chl anomalies in ocean color images are dominated by HAB species; implement coupled hydrodynamic-HAB models to forecast trajectories and landfalls; and disseminate products to user groups.

Filling Technical Gaps

For *Karenia brevis*, sustained funding is needed to expand and maintain HAB-OFS to the entire Gulf of Mexico as an integrated component of the Gulf of Mexico Coastal Ocean Observing System (Harmful Algal Bloom Integrated Observing System, HABIOS), transitioning real-time *in situ* measurements of cell densities (e.g., flow-through spectrophotometer mounted on moorings and AUVs[79]) from research to an operational mode, and implementing 4-D hydrodynamic models to forecast environmental conditions favorable for blooms, bloom trajectories, and bloom dissipation rates. To these ends, the Regional Association for the Gulf of Mexico Coastal Ocean Observing System and the Gulf of Mexico Alliance are working together to develop HABIOS for the Gulf of Mexico. Participants in the Gulf of Mexico HABIOS planning are from U.S. local, state, and federal governments; the private and academic sectors; and various governmental groups in Mexico. Three HAB workshops[80] have been held to define the HABIOS. A final GCOOS-GOMA workshop will finish the implementation plan with a preliminary budget.

For *A.fundyense*, sustained funding is needed for transitioning this pre-operational demonstration project to operational status, developing automated *in situ* capabilities for monitoring the abundance of *A.fundyense* (e.g., the Environmental Sample Processor[81]), and global implementation in coastal waters of developing countries. Partners include NOAA’s National Ocean Service, Northeast Regional Association for Coastal Ocean Observing System (NERACOOS), Woods Hole Oceanography Institution (WHOI), Massachusetts Department of Marine Fisheries Shellfish Sanitation Program, Maine Department of Marine Resources Biotoxin Monitoring Program, andNew Hampshire Department of Environmental Services Shellfish Monitoring Program.

Pressure	Warm, Shallow Water, Coral Reefs	Cold, Deep Water Coral Reefs	Oyster Reefs	Kelp Beds	Seagrass Beds	Salt Marshes	Mangrove Forests
Coastal development					X	X	X
Land-based inputs	X		X	X	X		
Aquaculture						X	X
Natural hazards	X		X	X	X	X	X
Over fishing	X	X	X	X			
Destructive fishing	X	X			X		
Dredging & Channelization			X		X	X	
Sea level rise	X				X	X	X
Ocean warming	X			X			
Ocean acidification	X	X	X				

Table 7. *Pressures that have major impacts on biologically structured habitats.*

3.4 Loss and Modification of Biologically Structured, Benthic Habitats (Primary Pressures: Table 7 below)

3.4.1 Introduction

Major benthic habitats include abiotic substrates (e.g., hard bottoms, soft bottoms, mud flats, rocky intertidal) and biologically structured habitats (live cover). The latter support high species diversity and economically important living marine resources and are the focus here. **Knowledge of distribution patterns of live cover (coral reefs, oyster reefs, kelp beds, seagrass beds, salt marshes, and mangrove forests) is essential information for fisheries management, conservation of species diversity, and assessing vulnerability to coastal flooding.** These habitats are also being lost and modified (e.g., fragmented) at an alarming rate due to coastal development (e.g., urbanization, agriculture, hardening shorelines), land-based inputs of sediments and nutrients, aquaculture, over fishing, destructive fishing (dynamiting, dredging), channelization (e.g., flood “control” and channels for marine commerce), sea level rise, ocean warming and ocean acidification (Table 7).

The magnitude of the problem is indicated by the rates of shoreline development (1 km per year) and global habitat losses (20% of coral reefs, 29% of sea grass beds, and 35% of mangrove forests) between 1960 and 1995.[82] Such losses result in declines in species diversity, disrupt natural biogeochemical cycles, and threaten the survival of living resources that use these habitats for spawning, nurseries, food and protection from predators.

3.4.2 Products and Applications

In terms of the capacity of ecosystems to support goods and services, the most useful indicators of ecosystem state are the distribution and condition of sentinel species or functional group (those that are sensitive to particular ecosystem pressures and portend of losses of habitat and biodiversity): species of hard coral of the order Scleractinia (both the iconic warm, shallow-water and cold, deep-water coral species) mangrove forests, tidal marshes, sea grass beds, and kelp forests. Priority ecosystem state indicators are as follows:

- The spatial extent and condition of living warm and cold water coral reefs, sea grass beds, mangrove forests, and tidal marshes;
- Spatial extent of dead cover; and
- The abundance and species diversity of living resources occupying each habitat.

Interannual trends in these indicators and the pressures described above (products) will inform integrated assessments of the effects of anthropogenic pressures and changes in environmental conditions. Timely computation and delivery of priority ecosystems state indicators will enable effective protection of critical habitats that possess innate value (such as supporting high biodiversity) as well as the allocation of areas for managed exploitation (e.g. MPAs). Such information is of value to organizations responsible for management action (including managing marine protected areas, sanctuaries and parks; fisheries management, nutrient and sediment management in watersheds), local communities and fishers that depend on the resources these habitats provide (e.g., seafood, income from tourism), and tourists attracted to these habitats. Knowledge of the extent of habitat loss and modification will guide actions such as the establishment of marine protected areas and identifying alternative sites for development and exploitation. It will also help provide appropriate boundaries and parameters for the rehabilitation or restoration of degraded sites if this is a feasible and desirable option (e.g., establishing networks of MPAs). Specific applications include the following:

- Assessments (status and vulnerability) of threatened habitats under specific pressures;
- Designation of marine protected areas (location, spatial boundaries, spacing in networks);
- Marine spatial planning[83] including designation of areas open for exploitation of resources, development, restoration , limited use, and no-access zones and fishing activities;
- Management of land-based inputs to these habitats;
- Management of living marine resources that depend on these habitats; and
- Assessments of the vulnerability to coastal erosion and flooding.

3.4.3 System Requirements

Observations: *In situ*	• Annual surveys of the extent & species composition of biologically structured benthic habitats & dead cover (including validation of remote sensing images) • Environmental conditions o Water temperature, salinity, water level • Environmental conditions o Sediment & freshwater inputs (salt marshes & mangrove forests) o Nutrient & chlorophyll-a concentrations, light attenuation (seagrass beds & kelp forests) o Aragonite saturation state, nutrient & chlorophyll concentrations, sedimentation, light attenuation (coral reefs)
Observations: Remote sensing	• Spatial extent of warm water coral reefs, sea grass beds, kelp beds, mangrove forests, and salt marshes & land-cover of adjacent catchment basins updated annually • Spatial of extent of cold coral reefs updated annually • SST fields • Ocean color radiometry: Chlorophyll-a, total suspended matter/turbidity & colored dissolved organic matter fields from water-leaving radiance spectrum • Digital, high resolution maps of topography & near shore bathymetry updated at regular intervals
Modeling & Analysis	• Statistical, geospatial models of habitats (GIS) • Statistical models relating o Habitat extent to time (temporal trends) o Temporal changes in habitat extent & species diversity to relevant environmental parameters o Coral bleaching to SST anomalies o Calcification rates to aragonite saturation state and temperature
Reporting	• Near real-time (< 12 h) for near-surface environmental parameters • Delayed mode (< 1 month) for environmental conditions near sea mounts (cold corals); (< 1 week) for annual in situ surveys; (< 1 month) for near shore topography-bathymetry and for cold water coral reef imaging

Table 8. *Requirements for observations, data telemetry and models (habitats).*

3.4.4 Operational Status

Technological developments in recent years have made it possible to obtain synoptic, large-scale images of coastal habitats and changes in their areal extent over time. Observing system requirements can be met using remote and *in situ* sensing combined with on sight measurements by trained personnel (above ground surveys, divers, towed cameras and acoustic instruments). The main challenges are access to and integration of data to compute products and complete integrated assessments.

Data providers include scientists in academic, research or government institutions; NGO's such as Conservation International; government bodies responsible for monitoring water quality, living resources; and volunteer networks. While many of the technologies needed to establish operational networks are at mature readiness levels, implementation is limited to North America, Europe, Australia and Japan. Only two mature networks are global in scope: the Global Coral Reef Monitoring Network (GCRMN)[84] and the SeaGrass Monitoring Network (SeagrassNet).[85] GCRMN is well established network in terms of duration, spatial extent, continuity and engagement of a large network of volunteer scientists. It is implemented by volunteers in a number of countries who carry out *in situ* surveys of their coral reef resources on a fairly regular basis. The results are integrated every few years into a global assessment of the status of coral reef ecosystems. An emerging program that is becoming global in scope has been initiated by NOAA. This program uses both remote and *in situ* sensing to monitor SST, spatial extent of warm water coral reefs, bleaching and spawning.[86] Since 2003, NOAA has operationally delivered synoptic satellite-derived products for coral reefs globally to provide current reef environmental conditions to quickly identify areas at risk for coral bleaching.[87] SeagrassNet is also a volunteer program for regular monitoring of sea grass beds in selected coastal sites worldwide. Begun in 2001 in the western Pacific, SeagrassNet now includes 115 sites in 32 countries with a global monitoring protocol and web-based data reporting system. The ultimate aim is to preserve seagrass ecosystems by increasing scientific knowledge and public awareness of this threatened coastal resource.

The Ramsar Convention has established a global network of protected wetlands that include mangrove forests and salt marshes (Ramsar sites).[88] To date, 160 counties have signed the convention and there are 1929 sites with a combined area of 187,989,389 hectares. One of the major goals of the convention is to maintain an inventory of sites and monitor their extent and condition (Goal 1, Strategy 1.1 Wetland inventory and assessment). However, sustained monitoring programs have yet to be established for most of these sites.

Regional monitoring is limited. Regional Seas Conventions monitor habitat extent and condition, but sustained monitoring is conducted in only a few places (e.g., the Mediterranean, Baltic Sea, North Sea, and Black Sea). Under the auspices of IOC-WESTPAC, a coastal habitat mapping working group is currently operating in Indonesia and Malaysia using a combination of satellite data and echo sounder methods complemented by SCUBA diving.

3.4.5 Gaps, Challenges and the Way Forward

The significant challenges include the need for sustained funding and for capacity building in developing countries globally. Many developing countries possess a critical mass of scientists and skilled personnel who have been educated in-country, or who have been sent overseas for advanced training. However, implementation of sustained coastal observations of habitats depends on training programs that provide specific training for nationals in recipient countries to update their skills and learn requisite methods for implementation.

A possible pilot project is the collation of all available, validated remotely sensed images to document trends for selected coastal sites around the world, focusing on warm water coral reefs, seagrass beds, salt marshes and mangrove forests. This information could be related to known environmental threats and to changes in the abundance and diversity of living marine resources to provide integrated assessment that enable appropriate and timely management action. As more information becomes available, one could consider a pilot project which aims to provide the best feasible audit of the state of coastal habitats globally. Such an audit should be updated at annually. As a start, candidate regions may be selected where local scientific capacity is known to be in place and where there is a reasonable amount of supporting infrastructure and technical capability. A pilot project would involve a combination of regions, preferably from both northern and southern hemispheres.

3.5 Ecological Buffers to Coastal Flooding (Primary Pressures: Table 7)

3.5.1 Introduction

The effects of tropical cyclones, extratropical storms and tsunami on coastal populations will be exacerbated by climate-driven sea level rise and the loss of ecological buffers to coastal flooding (tidal wetlands, seagrass beds, kelp beds, coral reefs, sand dunes and barrier islands).[89] Flooding events will become more frequent and severe; tidal wetlands, sand dunes, river deltas and other low lying land forms will be gradually inundated and eroded; coral reefs and seagrass beds will receive less light compounding the effects of ocean warming, acidification, and destructive human activities; salinity will increase in estuaries; and aquifers will be contaminated with salt. Flooding and subsequent runoff events will increase risks of public exposure to waterborne pathogens and chemical contaminants, degrade the health of coastal marine and estuarine ecosystems, and impair their ability to support goods and services, including the sustainability of living marine resources. Improving the reliability of model-based predictions of (1) climate-driven sea level rise and hazard-driven (e.g., tropical cyclones, extratropical storms, tsunami) coastal flooding and (2) the effects of sea level rise and coastal flooding on coastal populations and marine ecosystems are high priorities for adapting to climate change and mitigating the effects of natural hazards.

Given the emphasis of the ocean-climate module of GOOS on detecting and predicting flooding events (storm surge) and sea level rise, our recommendations focus on observing system requirements for the following:

- Documenting changes in ecosystem states in terms of the spatial extent and fragmentation of ecological buffers that influence the vulnerability of coastal populations to flooding; and
- Estimating impacts of changes in ecosystem states on the vulnerability of coastal populations to flooding and water quality.

The socio-economic impacts coastal flooding can be assessed in the short term based on the number of deaths, injuries, homelessness, economic losses, insured losses, and government expenditures[90] and in the long term by changes in the Human Development Index (HDI)[91] of coastal nations.

3.5.2 Products and Applications

Of the external pressures on coastal ecosystems, coastal flooding caused by tropical and extratropical storms is among the most significant in terms of impacts on ecosystem goods and services and on coastal communities. Sea level rise and coastal urban development will combine to more than triple the number of people vulnerable to coastal flooding by 2070.[92] In the absence of informed ecosystem-based coastal zone management, environmental protection and resource management in near shore lands and waters, this will have major socio-economic consequences globally. The following products for targeted coastal zones will inform ecosystem-based decision making:

- Digital, high resolution (≤ 1 km) maps of vulnerability[93] to flooding updated at 1 – 5 yrs intervals depending on coastal geomorphology and frequency & magnitude of flooding events in targeted regions;
- Scenario predictions of 5 – 10 yr changes in vulnerability based on projections of sea level rise, erosion, habitat change, and land-use in targeted regions; and
- Post – event digital maps of ecological buffers and water quality indicators (waterborne pathogens, suspended sediments, nutrient concentrations, phytoplankton biomass, dissolved oxygen, methylmercury, and polycyclic aromatic hydrocarbons) updated daily until the event signature in the salinity field has dissipated.

Users and applications include coastal land-use managers and developers (use assessments of vulnerability to guide the sustainable development of coastal communities, agriculture and infrastructure), insurance and re-insurance industries (Insurance rates guided by the probability of flooding), emergency responders (determine safe and efficient evacuation routes in advance of anticipated flooding events), and the public (awareness of vulnerability).

Box 2

The Insurance Industry and Coastal Inundation

From The Geneva Reports (2009, No. 2, 138 pp.) <www.genevaassociation.org>

Some of the first and most severe impacts of climate change will come through greater storm surges caused by a combination of higher sea levels and stronger storms in some regions. In the absence of storm surge, a 20-80 cm rise in mean sea level will place 7 – 300 million additional people at risk of being flooded each year (Stern, 2007. The cast for action to reduce the risks of climate change, In *After the Stern Review: Reflections and Responses*, Office of Climate Change, U.K.). Increases in storm surge will increase these numbers substantially. The Organization for Economic Cooperation and Development (OECD) estimates that, in the absence of adaptation, the population in 136 major port cities exposed to storm surges could increase from 40 million in 2005 to ~150 million in the 2070s with exposed assets rising from US $3,000 billion to US $35,000 billion (Nicholls et al., 2008. Ranking port cities with high exposure and vulnerability to climate extremes: exposure estimates, OECD Environment Working Papers, 1). As a proportion of GDP, economic losses from flooding are much higher for developing countries that for developed countries (Ramsharan, 2007. Does the exchange rate regime matter for real shocks? Evidence from windstorms and earthquakes. J. International Economics, 73: 31-47.) Financial losses from weather events are currently doubling every 12 years at an annual rate of 6% (UNEP Finance Initiative, 2006. Adaptation and vulnerability to climate change: the role of the finance sector, CEO Briefing, November, 2006, Geneva).

To adapt to greater storm surges, one option for at-risk regions is to invest in hard defenses such as flood barriers or in the maintenance and restoration of **natural ecological buffers** such as tidal wetlands, seagrass beds, kelp beds, coral reefs, and barrier islands that retain floodwater, dampen storm surges and/or prevent coastal erosion. Building codes can be strengthened by incorporating flood and storm proofing measures (e.g., property elevation, engineered foundations, reinforced cladding). Drainage systems can be improved or installed to handle larger volumes of water. Managed retreat from the shoreline can be implemented in regions deemed to be too costly to protect. Critically, early warning observing and prediction systems and sound strategies for adaptation (from evacuation to land-use practices) are needed to reduce exposure risks. This is especially important in the developing world here human exposure is often substantial, vulnerabilities are high, and investment available for other options is low.

The use of risk-based pricing for insurance can stimulate adaptation that reduces risk. Where observations are of sufficient granularity, insurers can often differentiate between risks. The presence of risk reduction methods can be indicative of lower claims which justify lower premiums. Conversely, a regulatory regime that does not allow risk-based pricing can lead to responses by the public and business that exacerbate coastal flooding risks. Insurers that provide liability insurance can also motivate professionals to give climate-risk advice to their clients recognizing that those who do not are open to legal challenges that may lead to professional indemnity or errors and omissions claims.

Observations *In situ*	• Sea level along the land sea-interface at representative locations • Rain fall & river flows • Validate remote sensing images of the extent of ecological buffers • Post event distributions of water quality parameters (dissolved nutrients, waterborne pathogens, turbidity, dissolved oxygen, chlorophyll-a, methylmercury, polycyclic aromatic hydrocarbons)
Observations Remote	• Coastal zone patterns of land-cover/use & geospatial boundaries of low lying areas susceptible to flooding updated at 5 year intervals • Spatial distribution of natural ecological buffers (tidal wetlands, seagrass beds, kelp beds, coral reefs, sand dunes & barrier islands) updated annually • Digital, high resolution maps of near shore topography and bathymetry updated at 5 year intervals & after major flooding events • Wet precipitation & river flows • Spatial extent of flooding • Post event temperature, salinity and chlorophyll fields
Model Requirements	• High-resolution digital elevation models of topography, shoreline position, bathymetry, & spatial extent of floods • Algorithms to compute levels of vulnerability as a function of o Current & predicted seasonal & annual mean sea level, o Coastal zone topography & bathymetry, & o Spatial distributions of ecological buffers • Geographic Information System maps of levels of vulnerability (current & projected) & water quality
Reporting	• Delayed mode for boundaries, land-use/cover, ecological buffers, coastal zone topography-near shore bathymetry& validation • Near real time for water quality parameters, tides, river flows & wet precipitation

Table 9. *Requirements for observations, models and data telemetry (coastal inundation).*

3.5.3 System Requirements (Table 9)

Priority locations for establishing the end-to-end observing system are coastal zones that have a history of flooding, are vulnerable to sea level rise and flooding events, and have high population densities, extensive infrastructure and/or agricultural activity, e.g., major river deltas, low lying estuarine and coastal land forms, small island developing states. Observing system requirements are summarized in the Table 9.

3.5.4 Operational Status

Our ability to provide timely assessments of vulnerability and realistic long-term scenarios of changes in vulnerability on spatial scales needed for ecosystem-based management of the impacts of flooding events and adaptation to sea level rise is limited at best. The technology exists to map the extent and condition of ecological buffers (GPS linked tide and river flow gauges, satellite remote sensing [MODIS bands 1 and 2, radar altimetry, InSAR & gravity][94] and airborne LIDAR and photography). The primary limiting factors are the lack of calibrated and validated algorithms for computing levels of vulnerability based on relationships between the spatial extent of floods, topography-bathymetry across the land-sea interface, land-use, and ecological buffers. The problem is exacerbated by current limitations and the reliability of real-time predictions of local mean sea level and long-term predictions of absolute sea level rise on local-regional space scales.

3.5.5 Gaps, Challenges and the Way Forward

Managing and mitigating the impacts of coastal inundation require high resolution, digital, geospatial 5 – 10 year forecasts of vulnerability to coastal inundation that are updated at 1 – 10 year intervals depending on coastal geomorphology and the rates of coastal development and changes in land- and water-use practices. Such maps must be grounded in observations and capture the effects of changes in shoreline position, near shore bathymetry and topography (e.g., from 50 m below to 100 m above local mean sea level relative to a single internationally adopted vertical datum), the extent and condition of near shore ecological buffers, human population density along rural-urban continuum, and spatial extent of impermeable surfaces and hardened shoreline. Algorithms for computing levels of vulnerability based on relationships between the spatial extent of floods, topography-bathymetry across the land-sea interface, land-use, and ecological buffers are in development as are models for generating geospatial maps of levels of vulnerability. The main challenges are data integration and the development and validation of the required algorithms. Pilot projects should focus on the development and validation of algorithms for computing vulnerability and on scenario-based predictions of the consequences of near-shore land-use practices and changes in the distribution of ecological buffers.

3.6 Distribution and Condition of Calcareous Organisms (Primary Pressure: Ocean Acidification, Table 7 for Coral Reefs)

3.6.1 Introduction

Since the beginning of the industrial revolution, ocean pH has decreased by 0.1 units on average, and model projections suggest even greater reductions by the end of this century.[95] Of particular concern are decreases in the saturation levels of the carbonate minerals calcite and aragonite which are expected to be greatest at high latitudes as under saturated waters shoal.[96] Such changes in seawater carbonate chemistry may result in decreases in calcification rates of calcareous organisms.[97] Lower calcification rates would lead to losses of coral reef habitats and declines in the abundance of plankton species, both of which would have profound effects on the capacity of marine ecosystems to support living marine resources.[98]

Pressures associated with ocean acidification include increases in pCO_2, decreases in pH and associated changes in aragonite and calcite saturation levels. Biological indicators of ecosystem state include the distribution and abundance of calcareous organisms most likely to be affected by these pressures, e.g., coral reefs, coccolithiphores, foraminifera, and pteropods. Recognizing that the effects of ocean acidification vary among species of calcareous organisms,[99] and much remains to be determined regarding how best to monitor and assess these effects, the end-to-end system described below is likely to evolve rapidly as new knowledge and technologies become available.

3.6.2 Products and Applications

Indicators (products) of pressures associated with ocean acidification are (1) regional to global scale maps of surface pCO_2 and pH and the depth of the aragonite saturation horizon (seasonal means updated annually); and (2) temporal variations in these parameters at sentinel and reference sites (section 5.5). Biological indicators of ecosystem state (products) are as follows:

- Spatial extent and condition (species diversity, coral skeletal density) of warm and cold water scleractinian (stony) corals updated annually; and
- Abundance and distribution of the sentinel species (coccolithophore *E. huxleyi* and the thecosomate pteropod *Limacina* spp.) during their seasonal maxima.

Users and applications include marine resource and MPA managers (marine spatial planning); shellfish mariculture (siting and targeted species); recreation and tourism (location of biodiversity hotspots); the public (promoting efforts to reduce carbon emission); environmental scientists (development of new tools and capabilities to better assess and monitor ocean chemistry and ecosystem changes and impacts); and the Regular Process of the United Nations.

3.6.3 System Requirements

Basin and regional-scale changes in carbon chemistry can be monitored synoptically through both satellite remote sensing and *in situ* measurements. For effective use of *in situ* assets, sites that are most likely to provide early warnings of the ecological impacts of ocean warming should be targeted (section 5.5). Observing system requirements are summarized in Table 10.

Observations: *In situ*	• Temperature, Salinity and O_2 • Primary carbonate chemistry parameters (pCO_2, pH, Total alkalinity, DIC, aragonite saturation horizon) • Skeletal density of stony corals • Abundance of the pteropod *Limacina* spp., & the coccolithophore *Emiliania huxleyi* • Spatial extent & condition of coral reefs at sentinel sites • Shellfish aquaculture production
Observations: Remote	• Sea surface temperature (SST) & salinity (SSS) • Ocean color radiometry (OCR) • Ocean surface vector winds (OSVW)
Model Requirements	• Coupled circulation, biogeochemical and ecological models (global and regional) • Atmospheric CO_2 mole fraction • Calcification rate versus aragonite saturation state
Reporting	Delayed mode: weekly to monthly for remote observations and physical and biogeochemical modeling output; monthly to annually for *in situ* observations

Table 10. *Requirements for observations, models and data telemetry (calcareous organisms)*.

3.6.4 Operational Status

Observations and assessments of ocean acidification are still largely a research activity, although efforts are underway to implement national and international observational networks.[100] These are primarily concerned with ocean acidification per se, but assessments of impacts on ecosystem states are increasing. A variety of in situ and satellite measurements are available in various stages of operational maturity. Protocols for ship-based sampling have been established for measuring carbonate chemistry parameters but not for sampling regimes in time and space. Commercial sensors are available for pCO_2 and pH that can be deployed on moorings, gliders and floats, but there is a need to develop new/improved autonomous sensor measurements for DIC and total alkalinity (required to compute aragonite saturation state).[101]

Shellfish bed and coral reef surveys and assessments are routinely made, and coral skeletal density is readily measured in the lab. Massive colonies of the order Scleractinia typically deposit layers of skeleton in varying densities, as determined by environmental parameters such as temperature and pH. These layers may be resolved to annual temporal scales, and may be correlated with time-series measurements (on the order of decades, as these become available) of pH to determine possible effects of increasing acidification. The CPR program is operational and is providing data on the distribution and abundance of calcareous plankton, but more CPR lines employing species-specific molecular probes for identifying organisms collected with the CPR are needed.

Satellite derived measurements of SST, OSVW and OCR are either operational or being transitioned into operations. Operational, satellite-derived basin-scale ecosystem products are presently being implemented, including global maps illustrating calcite concentration as well as the presence of *E. huxleyi* blooms. In combination, these two products can be used to monitor the areal extent, timing and calcite produced by blooms of this biogeochemically important phytoplankton species. Additionally, an experimental ocean acidification product suite is presently available for the greater Caribbean region and is being assessed by users.[102] SSS is an emerging space-based parameter, presently being measured at coarse-scales on an experimental basis.

3.6.5 Gaps, Challenges and the Way Forward

Monitoring pressures associated with ocean acidification and their effects requires large-scale and sustained programs of in situ measurements. International cooperation to develop a coordinated, global network of ocean observations that could leverage existing infrastructure and programs will be required. As recommended by Gruber et al.,[103] an observing system for ocean biogeochemistry is needed to determine, understand, and predict the past, present, and future oceanic sinks for anthropogenic CO_2 and associated changes in ocean biogeochemistry. The system would consist of an expanded SOOP network for surface measurements (air-sea fluxes), regular ship-based survey network for the ocean's interior, the OceanSites network for time-series observations, and Lagrangian networks. Such coordinated effort is also needed for the coastal ocean on a global scale.[104] Potential ocean acidification monitoring sites need to be identified for both open-ocean and coastal regions.[105] A pilot project linking basin-scale climate change assessments with regional-local impact assessments, insuring the use of sentinel locations in tropical, temperate, and polar-regions (section 5.5), is highly desirable.

Participants in the Second International Symposium on The Ocean in a High CO_2 World[106] made the following recommendations for observational networks for tracking acidification and its impacts:

- Develop new instrumentation for autonomous measurements of CO_2 system parameters, particulate inorganic (PIC) and particulate organic carbon (POC), and other indicators of impacts on organisms and ecosystems;
- Maintain, enhance, and extend existing long-term time series that are relevant for ocean acidification;
- Establish new monitoring sites and repeat surveys in key areas that are likely to be vulnerable to ocean acidification;
- Develop relaxed carbon measurement methods and appropriate instrumentation that are cheaper and easier, if possible, for high-variability areas that may not need the highest measurement precision;
- Establish a high-quality ocean carbon measurement service for those unable to develop their own measurement capabilities;

- Establish international collaborations to create a data management and synthesis program for new ocean acidification data and data mining and archival for relevant historical data sets;
- Work on developing an ocean acidification index (perhaps saturometry using a standard carbonate material); and
- Initiate specific activities for education, training, and outreach.

New autonomous, small, low power sensors are needed for in situ measurements of DIC and total alkalinity in both Eularian and Lagrangian modes. Existing profiling float, VOS and SOOP programs need to be expanded to include more pCO_2 and pH sensors. Time series measurements and more sentinel sites are needed, especially in highly productive coastal and estuarine systems (section 5.5). New and improved remote sensing capabilities (algorithms, product development, suitable proxies et al.) are needed especially for more accurate estimates of SSS and for estimating the abundance of coccolithophores.

In terms of recommendations for future research, five priorities have been identified:[107] (1) understand processes affecting acidification in coastal waters; (2) assess the potential for calcareous organisms to acclimate and adapt to changes in the carbonate system; (3) investigate the responses of individuals, populations and communities; (4) understand ecosystem level consequences; (5) investigate the interactive effects of multiple stressors; and (5) understand the socioeconomic impacts and inform decisions.

3.7 Abundance of Exploitable Fish Stocks (Primary Pressures: Fishing, Loss of Habitats & Species Diversity, Ocean Warming and Acidification)

3.7.1 Introduction

Increased demand for fish and shellfish (for human consumption and aquaculture production) is threatening food security since the survival of many fish stocks as biomass has dropped below maximum sustainable yield (the traditional single species management target) for over 60% of fish stocks for which stock assessments are available.[108] Together, fishing and changing environmental conditions (e.g., chemical contamination, hypoxia, toxic algal blooms, ocean warming and acidification) are placing wild fish stocks under unprecedented stress.[109] As discussed in chapter 1, this problem is being addressed by transitioning from traditional single species management of capture fisheries to an EBA to fisheries management in which fishing is managed in the context of interactions of fish stocks with other organisms (prey, predators, and competitors) and their environment.[110] The success of this approach depends on (1) simultaneously monitoring multiple pressures and ecosystem states; and (2) rapid detection and timely predictions of changes in ecosystems states and their impacts on carrying capacity.

Given previous sections on ecosystem pressures and states, monitoring and assessing the status of exploited fish stocks is addressed here. Integration into a system of system for EBAs is addressed in Chapters 5 and 6.

3.7.2 Products and applications

Major pressures on harvestable fish stocks include fishing, land-based inputs of chemical contaminants and nutrients, ocean warming and ocean acidification. Indicators of ecosystem states most relevant to sustainable fisheries are temperature and salinity fields; the distribution and abundance of food (phytoplankton, zooplankton) and natural predators; hypoxia and loss of essential fish habitats;[111] toxins produced by harmful algae; and species diversity.

Priority products are seasonal and annual stock assessments[112] based on catch statistics (species, biomass, numbers, size) and fishery independent surveys (catch per unit effort, abundance and diet of spawning stock year classes) and maps showing the number and location of active fishing vessels. Users include fishers, living marine resource managers, fisheries scientists and oceanographers, coastal marine conservation managers and conservation agencies, compliance enforcement agencies, fisheries ministries, FAO, regional and international fishery commission, and the Regular Process. Applications include setting fishing quotas (or total allowable catch) for subsistence, recreational, and commercial fisheries and permissible bycatch levels; documentation of illegal fishing; allocation of aquaculture licenses, associated regulations and enforcement of quotas; annual "State of the Stocks" reports with trend assessments and projections of changes in spawning stock abundance and maximum sustainable yield for both local management applications and fulfillment of international reporting requirements (e.g. LME Commissions, FAO databases, Regular Process, etc.).

Observations: *In Situ*	Fisheries dependent catch statistics (observers & landings) • Species, biomass, numbers, size & mean trophic level • Bycatch Fisheries independent surveys of harvestable fish stocks • Distribution & abundance of fish eggs, larvae, juveniles & year classes (cohorts) of adult spawners (age structure) • Migration routes between feeding & spawning grounds Environmental data • Water temperature & salinity • Chlorophyll-a • Zooplankton (macro- & meso-) abundance • Abundance of predators
Observations: Remote	• Sea surface temperature, salinity, wind & current fields • Phytoplankton biomass (chlorophyll-a), primary productivity, and frontal products (ocean color radiometry derived) • Spatial mapping of fishing vessels
Model Requirements	• Computation of phytoplankton productivity from chlorophyll-a, photosynthetically active radiation and temperature. • Stock assessments o Virtual population analysis (VPA) requiring data on the number of fish in each cohort & algorithms for relating the variable of interest to the variable measured (e.g., stock size estimated from CPUE) and estimating errors; o Multi-species virtual population analysis (MSVPA) requiring additional data diet (stomach contents) and predation rates. • Ecosystem & trophic dynamics o Ecopath with Ecosym o Atlantis, SEAPODYM, GADGET
Reporting	• Delayed mode (≤ 1 month) for stock assessments used to set annual & seasonal total allowable catches & quotas • Near real-time (< 12 hours) for monitoring compliance & anomalies from historical trends during the fishing season to support adaptive management

Table 11. *Requirements for observations, models and data telemetry (living marine resources).*

3.7.3 System requirements

Specification of observing system requirements is guided by the data and information needed for stock assessments (Table 11).

3.7.4 Operational status

Although observations and models that inform single species fisheries management have been operational for years, there are very few fisheries for which EBAs are used to support management decisions operationally.[113] Management systems, be they via international fisheries commissions or coastal states, tend to presume that there are sufficient data on the state of fish stocks and their environment to make informed and defensible management decisions. However, data on fish stocks relies heavily on fish landings as fishery independent surveys are limited in terms of both the number of fish stocks surveyed and the frequency and scope of the surveys themselves. In regard to the former, increasing numbers of industrial scale fisheries are subscribing to accreditation and certification by the Marine Stewardship Council[114] as consumer pressure increases on suppliers to demonstrate sustainable fishing practices (using eco-labeling of fish products). This approach uses individual evaluation of fisheries from a technical and economic point of view and audits management approaches from the scientific, assessment and marketing (traceability) aspects of each fishery (i.e., target species). Participation by commercial fisheries is voluntary and the number of certified fish stocks (91) is a small fraction of the total number of harvestable fish stocks in the ocean.

3.7.5 Gaps, Challenges and the Way Forward

Traditional fisheries management has failed to halt the global decline in wild fish stocks and many examples of over-exploited fisheries and impacted marine systems exist. In this regard, major limitations to operational implementation of EBAs include the sparse availability of data needed to conduct comprehensive annual stock assessments for all commercial stocks; lack of information on the migratory patterns of exploited fish populations; and the lack of sufficient data on ecosystem states that are provided in near-real time at rates required to make timely assessments of the effects of environmental variability on fecundity, recruitment, natural mortality and migration patterns.. Some nations have invested much time and money in routinely monitoring fish populations to underpin stock assessments to fisheries management. However, implementation of EBAs requires a much broader and data-rich information-base for decision making.

Operational delivery of data and information on the status of the ecosystem requires greater time-space resolution than can be provided by ships and *in situ* sensors alone. While additional sampling from these platforms (ships and sensors on moorings, gliders, and pelagic animals) are clearly needed, these observations by themselves will not provide the time-space resolution of essential biological variables required for EBAs. To address this limitation, additional sampling platforms and autonomous sensors are needed, e.g., satellite-based remote sensing and automated acoustic sampling of the oceans interior.

<u>Satellite-Based Remote Sensing</u>

A recent IOCCG report[115] has documented the critical role that satellite-based remote sensing is and will play in providing data with sufficient time-space resolution to elucidate linkages between climate-driven changes in marine ecosystems and the dynamics of fish and phytoplankton productivity. Quantifying stock-recruitment relationships and identifying the environmental factors modifying them is not possible using traditional oceanographic methods by themselves. Satellite-derived estimates of ocean surface currents and frontal zones, temperature (SST), salinity (SSS), ocean color radiometry (e.g., phytoplankton biomass and phytoplankton productivity estimates) have made these objectives achievable, and the results can be used to inform ecosystem-based stock assessments. The challenge is in quantifying relationships between these satellite-derived estimates of the distributions of SST, SSS and phytoplankton productivity and the abundance and distribution of higher trophic levels from zooplankton to fish. Four general approaches are available to estimate the production and biomass of fish and other high trophic level organisms from primary production: statistical models (e.g., regressions of fish landings on primary production), size spectra models, energy mass-balance models and 'end-to-end' or 'physics-to-fish' ecosystem models. All depend on or benefit from the provision of satellite data.

The SAFARI (Societal Applications in Fisheries and Aquaculture using Remotely-Sensed Imagery) project is a Canadian contribution to GEOSS and of particular significance to the development of this end-to-end system.[116] The goal of SAFARI is to identify and implement a suite of ecological indicators computed using data from satellite-based ocean observations for detecting changes in marine ecosystem states caused, for example, by climate change and overfishing. Such indicators would also be responsive to seasonal and interannual changes in the ecosystem, and thus be of use to fisheries research and management.

In addition to stock assessment applications, remote sensing can be used to help fishers locate target species through the detection of hydrographic features, such as fronts. This approach has the advantages of improving the efficiency of the catch, reducing fuel use and thereby greenhouse gas emissions, as well as potentially reducing bycatch. However, it also risks increasing the potential for over-exploitation of fish stocks. Clearly, implementation needs to be considered alongside other conservation-based management tools, such as quota systems and using remote sensing to enumerate and track fishing vessels for enforcement purposes.

Automated Acoustic Sampling

Combined with satellite-based remote sensing and CPR surveys,[117] acoustic technologies have the potential to provide an observing system for marine food webs from phytoplankton to fish. The goal of the proposed Mid-Trophic Automatic Acoustic Sampling (MAAS) Network is to implement a network of platforms (ships of opportunity and fixed platforms) equipped with multi-frequency acoustics that can monitor the distribution and abundance of macrozooplankton (1 – 1000 mm in size) basin wide.[118] The Ocean Tracking Network (OTN) is a GOOS pilot project that combines technologies developed for tagging apex pelagic predators with those developed for smaller animals.[119] The former uses satellites to determine where large animals travel in the oceans and monitors the environment (temperature, salinity and chlorophyll) they experience while the latter uses "curtains" of acoustic receivers across continental shelves and near islands to monitor fish migrations and receive and transmit data from larger animals. Thus, once fully deployed, the OTN will have the capability of tracking the movements of spawning populations that represent three upper trophic levels of the ocean's food webs.

Sustaining Time-Series Observation of Spatial Distributions on Local to Global Scales

A major challenge to sustainable fisheries is maintaining long term and consistent data sets on the vital statistics of population dynamics in order to quantify trends in pressures, states and impacts. The regular collection and acquisition of consistent data (in terms of geographical distribution and methods of collection) for establishing long term time series of essential variables requires a consistent technical capacity in terms of platforms, sensors, skills and budget. Temporal and geographical gaps and changes to data specifications can cripple and weaken assessments, analyses and model outputs. This remains a challenging problem for managing fisheries and other LMRs, especially in developing countries with limited resources. As data are collected from autonomous instruments such as those describe above, careful consideration must be given to data compatibility and capacity to maintain, service and operate them cost-effectively. The latter will require cost benefit analyses (in particular, their potential saving of ship-time). For successful implementation of EBA, restructuring of institutions (in many instances) and the implementation of ecosystem modeling capacity, multi-species model development and the improvement of relationships among scientific communities, fishing industries and relevant authorities will be required in many instances.

The recognition that ecosystem boundaries transcend national boundaries, that several commercially exploited stocks have transboundary distributions, and that the forcing and drivers of ecosystem dynamics occur over a range of scales has given rise to the Large Marine Ecosystem (LME) program. Some of these are becoming institutionalized at the level of regional commissions. These efforts are critical to the development of the operational, end-to-end systems needed to inform ecosystem-based approached to fisheries management. Collaboration among coastal states (including the pooling of resources and capacity) to achieve the required quality of observations, analyses and model outputs is the most efficient means of establishing EBA for LMRs.

4 DEVELOPING AN INTEGRATED SYSTEM OF SYSTEMS

4.1 Ecosystem-Based Approaches in the DPSIR Framework

As discussed in Chapter 1, the purpose of ecosystem-based approaches (EBAs) is to effectively manage anthropogenic pressures on ecosystems and mitigate or adapt to changes in ecosystem states and their impacts (Figure 4). EBAs are stakeholder-driven, place-based, integrated processes that consider interactions among species and strive to balance diverse societal objectives. IEAs inform EBAs by considering the following:[120]

- Ecosystem **states** and changes in states that reflect interactions among organisms (including humans) and their environment;
- External **pressures** on ecosystems (both natural and anthropogenic) that influence these interactions and lead to changes in states;
- **Impacts** of ecosystem state changes on ecosystem goods and services and the health and wellbeing of human populations; and
- Human **responses** to changes in states and their impacts (e.g., actions to manage human pressures, mitigate impacts of tropical storms, or adapt to climate-driven sea level rise).

The goal is to maintain healthy ecological and socioeconomic systems by sustaining the structure, function and biodiversity of ecosystems.

The end-to-end systems offered in Chapter 3 reflect traditional approaches to managing natural resources, water quality and public health in that they focus on particular phenomena and associated pressures, states and impacts in isolation. In effect, such “stove pipe” approaches take a simple slice through complex socio-ecological systems ignoring other processes and interactions. However, as a group, they provide a framework for identifying common observing system requirements across phenomena of interest (PoI), a first step toward building an integrated system of systems for observing and predicting changes in the states of marine ecosystems and their impacts (Table 12).

PoI	Pressure Metrics	State Indicators	Impact Indicators
Eutrophication & Hypoxia	**Land-based inputs** of nutrients, **Ocean warming, Over fishing,** Aquaculture, Coastal flooding	Chlorophyll, dissolved oxygen & nutrient fields; Distribution & abundance of toxic HAB species	**Food security,** Mass mortalities of marine animals, **Loss of habitat & species diversity,** Loss of aesthetic value & tourism
Waterborne Pathogens	**Land-based inputs** of pathogens **Ocean warming** Coastal flooding	Distribution & abundance of enteric bacteria	**Human illnesses & death,** Beach & shellfish bed closures
Toxic Phytoplankton	**Land-based inputs** of nutrients **Ocean warming** **Over fishing** Introductions of non-native species	Distribution & abundance of toxic phytoplankton species, Species diversity	**Human illness & death,** Beach & shellfish bed closures, **Food security,** Mass mortality of marine animals
Loss of Benthic Habitats & Ecological Buffers to Coastal Inundation	**Land-based inputs** of nutrients & sediments Coastal flooding River overbanking **Ocean warming** Ocean acidification Land reclamation Introductions of non-native species **Over fishing,** Destructive fishing	Water level; Extent & fragmentation of habitats and ecological buffers; Chlorophyll dissolved oxygen and nutrient fields	**Loss of habitat & species diversity,** Vulnerability to flooding, Loss of real estate, Loss of aesthetic value & tourism, **Food security, Human illness & death**
Ocean Acidification	pCO_2, pH, alkalinity, aragonite saturation level	Coral skeletal density, Abundance & distribution of coccolithophores, pteropods & benthic bivalves	**Loss of habitat & species diversity,** Loss of aesthetic value & tourism, **Food security**
Food Security	**Over fishing** & by-catch Destructive fishing **Ocean warming** **Land-based inputs** of nutrients & contaminants Ocean acidification Introductions of non-native species Fish landings (food) for aquaculture	Catch statistics; Mean trophic level fish landings; Distribution, abundance & biomass of spawning stocks, eggs & year classes; Fat content & parasite burden of selected species; Abundance & distribution of selected macrozooplankton species; Biomass of apex predators; Proportion of large apex predators; Species diversity; Aquaculture production	**Loss of habitat & species diversity, Human illness & death**

Table 12. *Synthesis of pressures, states and impacts from the end-to-end systems described in Chapter 3 (PoI – Phenomenon of Interest). The most common pressures and impacts are highlighted in bold.*

Based on the number of PoIs affected, the most significant pressures and impacts on a global scale are:

- Pressures: Land-based inputs, ocean warming, and over fishing
- Impacts: Loss of habitat and biodiversity, food security, and human illness and death.

This result points to efficiencies to be gained by designing integrated observing systems that address multiple pressures and impacts. When indirect links from states to pressures and impacts are included, the potential for strong interactions across phenomena becomes obvious. Thus, as anthropogenic pressures on marine ecosystems have intensified, ignoring interactions among pressures, states and impacts across the phenomena of interest can no longer be justified. Integrated, ecosystem-based observing systems are required on the grounds of both effectiveness and efficiency.

4.2 Challenges of Detecting, Anticipating and Managing Changes in Ecosystem States and Their Impacts

Apart from serving raw data, all products of ocean observing systems will come from models, the main value of which is to estimate pressures, states and impacts that cannot be measured directly.[121] Modeling and observing marine ecosystems are mutually dependent activities. Models of marine ecosystems cannot function without observations that specify initial and boundary conditions and help set model parameters. Conversely, models can be used to help design determine what to measure, where to make measurements, monitor the quality of real time data streams, detect problems with sensors and data telemetry, and design more effective ocean observing systems

4.2.1 Designing Integrated Observing Systems for Adaptive EBAs

Although the need is clear, the design and implementation of effective EBAs remains a substantial theoretical and practical challenge. An important step toward addressing this challenge is to engage in adaptive decision-making (responses) based on sustained monitoring and analysis of key indicators. This reduces reliance on accurate predictions in a complex and uncertain world and is commonly used for single sector management purposes, e.g., species- or stock-specific fisheries management, the management of land-based nutrient loads to reduce coastal eutrophication, or closing shellfish beds to prevent human consumption of contaminated shellfish.

While the concept of adaptive management is understood in the context of sector-specific decision-making, EBA introduces a host of new challenges, including multiple conflicting objectives, multiple classes of potential management responses and actions, and multiple chains of cause and effect linking actions to future impacts. In particular, the problem of diagnosis and attribution looms large. If it is not possible to correctly diagnose the reasons underpinning observed changes in impact indicators, it is quite likely that management responses will be inappropriate and have undesirable consequences. While there are currently no universal rules prescribing the choice of indicators for EBA observing systems, it seems likely that they will require at minimum the key indicators from the relevant component sectors and phenomena of interest, and may well require additional indicators to support diagnosis and attribution.

The first requirement of a monitoring strategy to support adaptive EBAs is the provision of data and information needed for regular evaluations of performance against management objectives, generally measured in terms of indicators of impacts. Interpretation of changes in impact indicators and the choice of appropriate management actions and responses depend on knowledge of (1) changes in ecosystem states underpinning impacts and (2) changes in pressures and their relationship to state changes. Thus, the establishment of an effective adaptive strategy that supports learning and improvement over time requires sustained monitoring and analyses of key indicators of pressures, states and impacts synoptically in time and space.

The adoption of an adaptive management strategy does not guarantee the achievement of management objectives. Even in simple "one-dimensional" problems, noise and bias in indicators, and lags in changes in ecosystem states and responses to impacts, can result in management failure. In engineering terms, this is a problem of controllability. Successful adaptive strategies require observations and models on appropriate time and space scales to provide robust and reliable indicators in a timely fashion. Again, given the additional challenges of diagnosis, it seems likely that requirements for statistical reliability of indicators for EBA will be more stringent than for sector-specific adaptive management.

The choice of spatial and temporal scales for observations, models and indicators needs to reflect both human and natural ecosystem scales. The scales of impact indicators may be partly at our discretion, and reflect the time and space scales of human interest and activity, and the institutions and agencies responsible for management and response. But the choice of scales for state observations, models and indicators must also reflect the scales of ecosystem processes, if they are to allow meaningful interpretation and diagnosis. The following two subsections consider ecosystem scales and human system scales, respectively.

4.2.2 Ecosystem Scales of Time-Space Variability

Coastal ecosystems are constrained by irregular coastlines and a relatively shallow and variable bathymetry. Within coastal ecosystems, physical, chemical and biological interactions between intertidal, benthic and pelagic communities enhance nutrient cycles, primary productivity and the capacity of coastal ecosystems to support goods and services relative to oceanic systems. Changes in ecosystem states, upon which the provision of goods and services depend, reflect the interplay between these interactions and external pressures that impinge upon them (Figure 5). Thus, observations and models must capture variations and trends in both pressures and states.

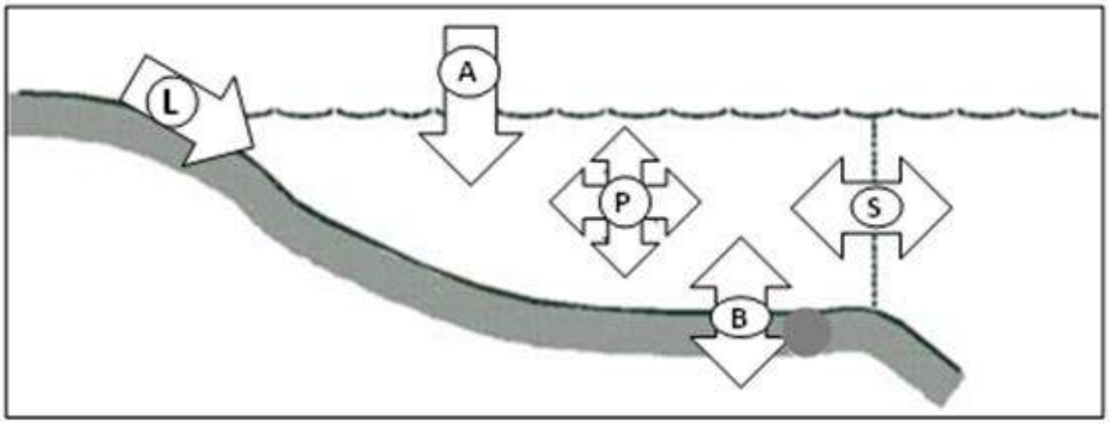

Figure 5. *A schematic of pressures and interactions that govern coastal ecosystem states and state changes. Pressures include land-based inputs (L); net atmospheric inputs (A); and oceanic influences (S). Within coastal ecosystems, interactions between benthic and pelagic systems (B) and interactions within the pelagic environment (P) are influenced by pressures that lead to changes in states. Not shown are interactions among coastal ecosystems that propagate along the coast*

Resolving long term trends and large spatial patterns from variability are big challenges. Physical processes (turbulent mixing, currents, fronts, pycnoclines, etc.) have a significant influence on the structure and function of marine ecosystems.[122] Consequently, physical, chemical and biological processes exhibit scales of variability that resonate over a multidimensional continuum of time, space and ecological complexity, e.g., large space scales tend to be associated with long time scales, larger animals, and greater species diversity; and small space scales tend to be associated with short time scales, smaller organisms and less species diversity.[123]

This scale-dependent linkage of biological and physical processes is fundamental to understanding and predicting spatial and temporal variability and patterns in ecosystem states and their impacts. For example, on the scale of the ocean basins and their circulations, the distribution and abundance of species are related to water mass distributions and large scale current regimes (the central gyres). At smaller scales, the abundance and distribution of organisms are more influenced by turbulence and small scale circulations (e.g., eddies and fronts). The result is a hierarchy of physical-chemical-biological interactions within and among marine ecosystems that span a broad spectrum of time-space scales (Figure 6). In addition, marine ecosystems exhibit high variance at low frequencies underscoring the importance of longer time and larger space scales. Thus, understanding relationships between pressures and state changes and anticipating state changes and their impacts requires observations and models that capture key interactions over a broad spectrum of time-space scales.

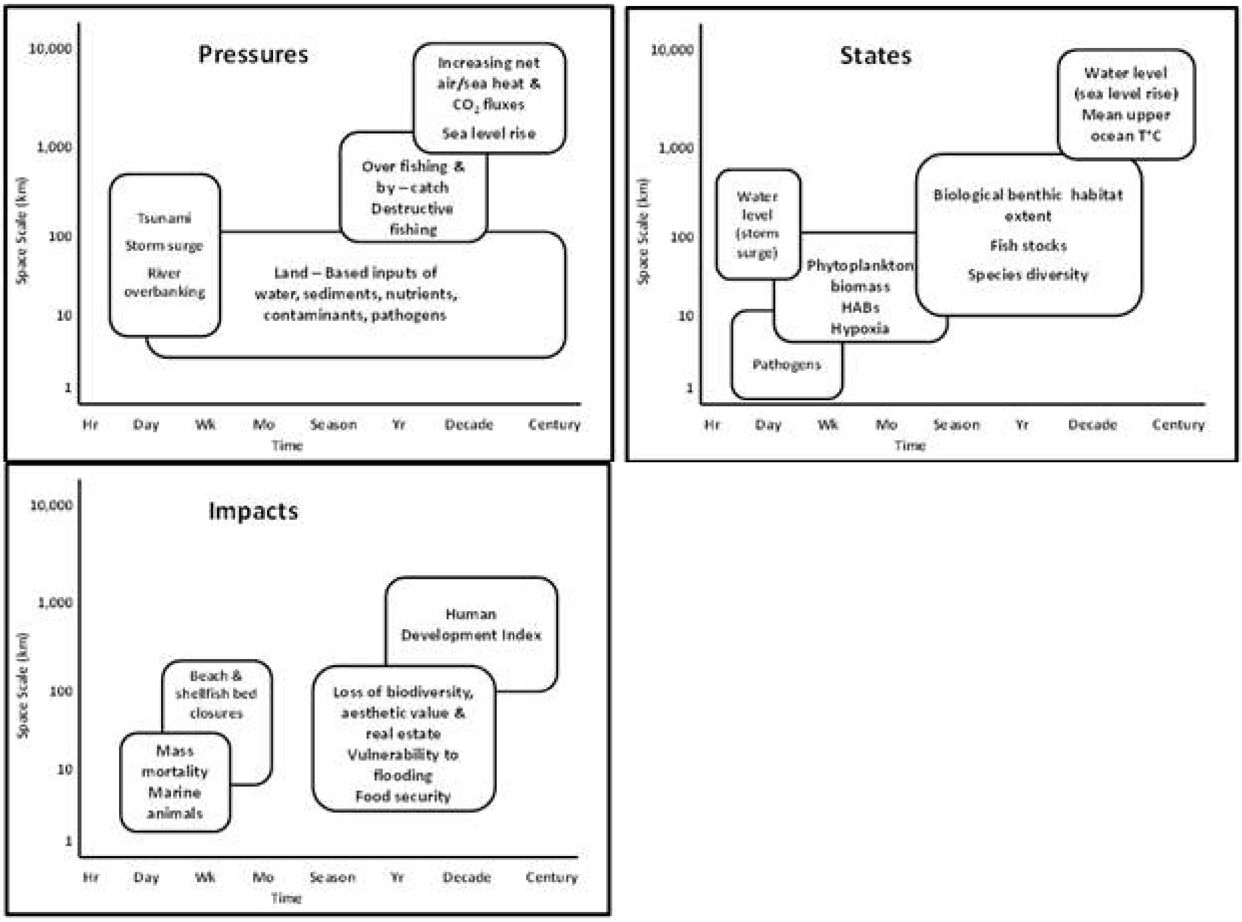

Figure 6. *Pressures on ecosystems, ecosystem states and impacts of changes in states exhibit broad spectra of time-space variability*.

4.2.3 Scales of Impacts and Human Responses

Historically, human responses have driven by environmental catastrophes and institutional constraints rather than by the timely provision of scientifically sound data and information on ecosystem state changes and their impacts.[124] The time frames in which decision-makers need to respond to changes in ecosystem states should be driven by the time scales on which actions need to be taken to achieve their mission and objectives most effectively (Table 13).

	Indicators and Metrics	(1)	(2)	(3)
Pressures	Land-based inputs: pathogens, sediments, nutrients, & contaminants	X	X	X
	Coastal flooding (Storm surge, River overbanking, Tsunami)	X	X	X
	Ocean warming		X	X
	Over fishing		X	X
	Introductions of non-native species		X	X
	Sea level rise		X	X
	Ocean acidification		X	X
	Land reclamation		X	X
	Destructive fishing	X	X	
	Aquaculture production		X	
States	Water level	X	X	X
	Temperature, salinity, wave and current fields	X	X	X
	Light attenuation	X	X	X
	Nutrient fields	X	X	X
	Distribution & abundance of enteric bacteria	X	X	X
	Phytoplankton biomass fields	X	X	X
	Distribution & abundance of sentinel species of macrozooplankton	X	X	X
	Distribution & abundance of toxic HAB species	X	X	X
	Dissolved oxygen fields	X	X	X
	Extent & fragmentation of habitats (live, dead and abiotic substrates)		X	X
	Species diversity & composition		X	X
	Coral skeletal density		X	X
	Abundance and distribution of coccolithophorids, pteropods, & benthic bivalves		X	X
	Catch statistics	X	X	X
	Distribution, abundance & biomass of spawning stocks, eggs & year or size classes of exploited stocks		X	X
	Fat content and parasite burden of selected species		X	X
	Biomass of large apex predators		X	X
	Aquaculture production		X	X
Impacts	Human illness & death	X	X	X
	Mass mortalities of marine organisms	X	X	
	Beach & shellfish bed closures	X	X	
	Vulnerability to flooding		X	X
	Coastal erosion & loss of real estate	X	X	X
	Loss of aesthetic value & tourism	X	X	X
	Food security		X	X

***Table 13**.* *The time scales on which pressures, states and impacts need to be reported, predicted or assessed fall into one or more of three categories: (1**) nowcasts and short-term forecasts,** (2) **periodic (1-5 year) assessments,** and (3) longer-**term (years to decades) projections or scenarios of trends**. Note that human responses to all pressures, state changes and impacts benefit from periodic assessments.*

For some state changes, near real-time operational **nowcasts and forecasts** are needed in the short-term to guide actions that must be taken on time scales of hours to days. These kinds of responses typically occur at fine spatial scales. They require high spatial resolution observations and numerical predictions that are able to capture variability and resolve trends in pressures, states and impacts on scales that depend on the phenomenon of interest. For most state changes, periodic (1 – 5 year) **integrated assessments** of pressures, states and impacts are needed to inform management strategies for mitigation or adaptation and measure progress against management objectives (e.g., the Regular Process of assessments of marine ecosystems described in Chapter 2). Finally, longer term (years – decades) **predictions or scenarios**[125] of future pressures, states and impacts are needed to anticipate changes and inform strategic plans for managing human uses of ecosystem goods and services and adapting to impacts of climate change. Integrated assessments and scenarios involve a range of spatial scales, from local estuaries and bays, to regional seas and continental shelves, to ocean basins.

Increasingly, the need to match management scales to the natural scales described in 4.2.2 (and to develop appropriate institutional and governance structures to support this) is being recognized. Thus, observing system requirements[126] for an end-to-end SoS must address both the scales of variability that characterize ecosystem state changes and the scales of decision-making.[127]

Many ecosystem state indicators and some pressures and impacts are relevant to all three response time scales, and responses to all pressures, state changes and impacts are informed by periodic assessments (Table 13). This suggests that some requirements for observations, data management and/or modeling may be similar across response time scales (e.g., observations and models used for near term weather and ocean forecasting and long term predictions of climate change) and provides a framework for harmonizing the scales of ecosystem variability and change with the scales of decision-making.

4.2.4 Linking Ecosystem Pressures to State Changes and Impacts

IEAs used to guide adaptive responses are based on sets of indicators that provide information on state changes, the pressures that cause them and their impacts. Indicators are computed from data provided by observing systems using statistical and diagnostic models. IEAs depend on how well linkages between pressures, changes in states, and impacts can be identified, monitored and predicted. Although changes in coastal ecosystem states (by definition) tend to be local in scale, they are globally ubiquitous suggesting they are, more often than not, local expressions of larger scale pressures of natural origin, anthropogenic origin, or both. Three approaches are available to provide the data and information required to inform the ecosystem models underpinning IEAs: (1) experimental manipulations of ecosystems in controlled environments such as mesocosms, (2) observing and modeling natural ecosystems, and (3) comparative analyses of ecosystems.

Unfortunately, marine ecosystems are both complex and complicated,[128] and changes in states are typically responses to multiple pressures from both anthropogenic (those that can be managed) and natural sources. Consequently, experimental and ecosystem-specific approaches do not provide the required data and information by themselves.[129] Controlled experiments are limited in terms of the extent to which they can capture the complexity needed to develop realistic models of ecosystem dynamics on the scale of natural ecosystems.[130] Time-series observations and models of a given ecosystem may provide useful information on specific issues for that ecosystem but rarely lead to robust, generally transferable products. Comparative analyses of marine ecosystems have a long history[131] and, building on the first two, may be the most effective approach.

Implementation and evolution of IEAs will be enabled by comparing and contrasting pressures, changes in states and impacts across a range of similar ecosystems (e.g., upwelling systems along the western continental margins, coral reefs, high latitude fishery systems) and ecosystem types (e.g., from coral reefs to boreal environments).[132] Such comparisons are needed on regional to global scales to (1) provide a broad range of indicator values that can be used to rank ecosystems in terms of their relative status (health) and capacity to sustain goods and services (especially important given the natural succession of ecosystems and the absence of baselines), (2) determine the relative importance of anthropogenic and natural pressures as agents of change, and (3) anticipate local state changes and impacts by analogy with pressure-state-impact relationships in other ecosystems.[133] Data and information provided by the end-to-end systems offered in chapter 3 will enable the computation of a set of indicators that can inform IEAs; enable ecosystems to be ranked in terms of their relative condition or health; guide the implementation and evolution of EBAs; enable analyses of the efficacy of ocean policies when implemented; and help create a more ocean literate society.

From a regional or global perspective, the comparative analyses of marine ecosystems can be thought of as the operation of a complex ecosystem-based adaptive strategy across multiple nested scales. Management actions and interventions perturb ecosystems at ‘whole-of-system’ scales, and offer opportunities to learn about system dynamics at those scales, and test understanding and prediction based on experiments at smaller scales. However, these opportunities currently often go begging, through lack of adequate investment in monitoring and analysis. An appropriate set of nested integrated observing systems, together with appropriate models for interpretation and diagnosis, will accelerate learning from management successes and failures, not only locally within a system and sector, but across comparable systems and sectors. By exploiting partial replication across comparable systems, it will be possible to design and implement active adaptive or experimental management approaches at the ecosystem scale. Given the urgency of many current environmental issues, delaying management responses until scientific knowledge and predictive capacity improves may not be an option, and active adaptive management may be the most promising way forward.

4.2.5 Linking Observations and Models

Indicators of ecosystem states cannot be observed directly. They are computed from models that provide predictions of states based on observations where “predictions” include nowcasts, forecasts, and scenarios future states that are not directly observed (e.g., estimates of species diversity or the spatial distribution of an essential variable). Models include simple statistical relationships (e.g. multiple and multivariate regression models), more sophisticated statistical constructs (e.g. geospatial information systems, neural networks, network analysis), dynamical models based on first principles (e.g. numerical circulation, storm surge and ecosystem models in Lagrangian or Eulerian forms) and, coupled models of the biotic and abiotic components of the marine ecosystem (e.g. coupled atmosphere-ocean circulation-trophic dynamical models).

Observing marine ecosystems and modeling them are mutually dependent processes. Of central importance for the provision of nowcasts, forecasts, in IEAs and scenarios of future pressures, states and impacts is the computation of gridded reconstructions of past and current ecosystem states using data assimilation techniques that also provide estimates of the errors associated with interpolation and extrapolation.[134] Data assimilation techniques are most advanced for numerical predictions of weather and physical oceanographic states (sea surface temperature, currents and waves) and least advanced for predictions of chemical and biological ecosystem states.

For the purposes of coastal GOOS, an analysis is the computation of accurate images of ecosystem states at a given time based on a set of observations that typically under sample the ecosystem. An analysis must be informed by “background” information such as a climatology that provides an a priori estimate of the mean ecosystem state. Knowledge of mean states of marine ecosystems over specific periods is fundamental resolving short term variability from longer term trends and to predicting changes in ecosystem states and their impacts. Thus, an application of hindcasting that is especially relevant to GOOS is the computation of means and first moments of variability (climatologies) for the essential variables in selected marine ecosystems. Unfortunately, historical data on essential variables (especially the non-physical variables) are grossly inadequate for most marine and estuarine ecosystems, and it is essential that observations required to compute seasonally and annually resolved interannual climatologies for key essential variables and sentinel ecosystems begin immediately.[135]

Analyses can be used to provide comprehensive and internally consistent diagnostics of ecosystem state, as input data to another operation, (e.g., as the initial state for a numerical forecast of a current field), as a reference against which observations can be compared for quality control, and as a data retrieval for an observing system simulation experiment (OSSEs). The latter is particularly important for optimizing sampling schemes for observing marine ecosystems on regional and global scales. The importance of current *in situ* measurements and remote sensors to the accuracy of a prediction can be assessed by Observing System Experiments in which existing observations (e.g., variable-specific data from selected locations, data on a particular variable) are removed from a standard data base. The impact of future instruments can be assessed using hypothetical data in Observing System Simulation Experiments (OSSEs). OSSEs use data assimilating models to specify the optimal mix of observations (locations, spatial extent and variables measured) for model-based predictions and can accelerate the transition of observations from newly developed instruments to operational use. In fisheries, and increasingly in coastal management, model-based scenarios may be used to assess the likely performance of adaptive management strategies, combining observing strategies and management decision rules.

5 AN INTEGRATED SYSTEM OF SYSTEMS FOR ESTUARINE AND MARINE ECOSYSTEMS

5.1 Introduction

As reviewed in previous chapters, the primary purpose of GOOS is to enable routine provision and continuous integration and analyses of multidisciplinary data to help guide decisions on three time scales (real-time nowcasts, short-term forecasts and long-term scenarios) all of which benefit from or are informed by periodic (1-5 years) IEAs. The latter includes developing and incorporating quantitative models of pressure-state-impact relationships that (1) enable adaptive ecosystem-based responses, (2) provide periodic evaluations of the efficacy of such responses in achieving their objectives; and (3) identify crucial knowledge and data gaps that guide future research and the evolution of integrated ocean observing systems.

Coastal GOOS is envisioned as a multi-scale, interdisciplinary system of systems consisting of a Global Coastal Network (GCN) with national and regional coastal ocean observing systems (RCOOSs) embedded in it. A set of building blocks for an initial system of systems and a framework for integrating them on regional and global scales are offered in Chapters 3 and 4, respectively. Existing capabilities for building the initial system of systems is described here with the understanding that the primary purpose of the GCN is to provide a larger scale framework (grid) for RCOOSs to achieve their objectives by providing data required to (1) compute indicators for IEAs on regional to global scales (comparative analyses of the causes and consequences of changes in ecosystem states) and (2) formulate long-term, large scale, climate-driven scenarios. In short, the GCN provides the larger scale perspective needed to understand and anticipate the causes and consequences of ecosystem state changes on local to regional scales.

As the ‘backbone’ of coastal GOOS, the GCN (1) measures, manages and analyzes a set of essential geophysical, chemical, biological, and biophysical variables at a network of sentinel sites and selected ecosystems, (2) efficiently links modeling and measurements via integrated data management and communications; and (3) implements internationally accepted standards and protocols for measurements, data telemetry, data management, and modeling. Given the data and information provided by the GCN (and by the open ocean, climate and terrestrial components of GEOSS), RCOOSs are able to focus on locally relevant nowcasts, forecasts and long-term scenarios within their respective regions, i.e., the provision of data and information needed to conduct IEAs that inform adaptive, ecosystem-based management of human activities within the region and mitigation of sub-regional impacts of larger scale pressures.

5.2 Modeling Requirements, Status and Gaps

Given its broad scope and multi-disciplinary nature, it is inevitable that the development of Coastal GOOS will depend on multiple communities and draw on a spectrum of modeling disciplines and capabilities. Each modeling community has its own history and established approaches, methods and challenges. These modeling components and capabilities differ in terms of maturity and readiness for incorporation into operational systems. There are major review papers and texts devoted to each of these areas. Our purpose here is to give a brief introduction and overview of modeling capabilities most important to the implementation of coastal GOOS and provide a road map to these capabilities. In parallel with moves towards integration through EBA, there is an important emerging trend towards convergence and integration of what have been disparate modeling approaches and communities. This offers exciting opportunities, not only for synergies, but for modeling communities to benefit from each other's strengths.

5.2.1 Models of ocean circulation and biogeochemical cycles.[136]

Ocean modeling has seen rapid advances over the last two decades, driven initially by investments in the science to underpin assessment and prediction of climate variability and change, coordinated by international programs such as the World Ocean Circulation Experiment (WOCE), Joint Global Ocean Flux Study (JGOFS) and Climate Variability and Predictability (CLIVAR). Climate prediction through coupled climate and earth system models continues to be a major driver and user of models of ocean circulation and carbon cycling. With growing concern about the potential impacts of ocean acidification, ocean biogeochemical models are also being used to project the likely evolution of ocean pH, alkalinity and carbonate saturation under different CO_2 emission scenarios.

With the establishment of GODAE[137] in 1997 (Box 3), ocean circulation modeling entered a new era, developing and implementing operational, eddy-resolving, data-assimilating circulation models at global, ocean basin and regional scales. This highly successful program has seen the establishment and demonstration of operational ocean circulation models by a number of groups around the world, and (critically) the establishment of the key observing infrastructure needed to support them.

Box 3
The Global Ocean Data Assimilation Experiment
<http://www.godae.org/>

GODAE was a 10-year international project to demonstrate the feasibility and utility of real-time, global ocean forecasting. The broad objectives were to (1) apply state-of-the-art ocean models and assimilation methods for short-range open-ocean forecasts, for boundary conditions to extend predictability of coastal and regional subsystems, and for initial conditions of climate forecast models; (2) provide global ocean analyses for developing improved understanding of the ocean and improved assessments of the predictability of ocean systems; and (3) serve as a basis for improving the design and effectiveness of the global ocean observing system.

Legacies of GODAE include the routine provision of estimates of the physical state of the ocean that are publically available through data servers. State estimation products have been used to study a wide range of topics in physical oceanography and climate science as well as in geodesy and biogeochemistry. Ocean state estimation products and tools have been applied to studies over a wide range of topics in physical oceanography including the nature of sea level variability, water-mass pathways, estimating surface fluxes and river runoff, and interannual and decadal variability of the upper-ocean and heat content (Lee et al. 2010. Ocean state estimation for climate research. In Proceedings of OceanObs'09, Vol. 2, ESA Publication WPP-306, Paris, 13 pp.)

These models play a similar role to operational numerical weather prediction models, and a key challenge now for this community is to transition the global operational ocean forecasting capability from its current demonstration status to the permanent, sustained and continuously improved status established for numerical weather prediction. While the immediate products are nowcasts and short-term forecasts of 3-dimensional ocean state, these programs have also provided extremely valuable information for climate and marine ecosystem research through multi-decadal hindcasts of ocean state and improvements to circulation models that can be transferred to climate models.

The success of GODAE has led to the establishment of GODAE OceanView which has a broader mandate and scope as encapsulated in four goals:[138]

- The consolidation and improvement of global and regional analysis and forecasting systems (physics).
- The progressive development and scientific testing of the next generation of ocean analysis and forecasting systems, covering bio-geochemical and eco-systems as well as physical oceanography, and extending from the open ocean into the shelf sea and coastal waters.
- The exploitation of this capability in other applications (weather forecasting, seasonal and decadal prediction, climate change detection and its coastal impacts, etc).
- The assessment of the contribution of the various components of the observing system and scientific guidance for improved design and implementation of the ocean observing system.

For the most part, the work plan represents an evolution of GODAE models and capabilities, including improvements in the spatial resolution of circulation models from 10 km to 3 km (at global and regional scales), and development of prototype data-assimilating (pelagic) biogeochemical models at global and regional scales. Quasi-operational higher-resolution data-assimilation regional and shelf circulation models exist now, and one might expect to see demonstration operational systems within 3 years. Data-assimilation into biogeochemical models is an active research area, but the establishment of operational data-assimilating biogeochemical models is likely to take longer.

The further downscaling of circulation models to bay and estuary scales and the extension of biogeochemical models to end-to-end ecosystem models do not figure largely in these national and regional plans, with the exception of the US National Ocean Service (NOS). NOS applies hydrodynamic models for the development, transition and implementation of Operational Forecast Systems (OFS) in U.S. estuaries, ports, lakes and the coastal ocean. The inshore extension of ocean models must address the rapid decrease in the spatial scales of variation approaching the coast. This poses challenges for models (increased spatial resolution, requiring nested, flexible or adaptive grids, and imposing significant computational loads), but also poses major challenges for inshore observing system design and implementation (section 5.4).

To help achieve the goals of GODAE OceanView, research will be encouraged to improve operational oceanography systems in areas such as "high-resolution physical modeling, downscaling (to coastal regions), biogeochemical and ecosystem modeling, ocean-wave-atmosphere coupling, data assimilation and coupled data assimilation, error estimates, long-term reanalyses, use of new observations." GODAE OceanView has also established five task teams. The teams for *Intercomparison and Validation* and *Observing System Evaluation* are addressing generic issues that are critically important for any operational coastal or ecosystem modeling system, including the definition of metrics to assess the quality of analyses and forecasts (e.g. forecast skills), and the use of Observing System Experiments (OSEs) and OSSEs to provide objective evaluation of alternative observing system designs. The *Coastal Ocean and Shelf Seas Task Team* is focusing on the problems of downscaling global and basin models to address cross-shelf interactions, primarily for physics and the interaction between physics and biogeochemistry, including the fate of terrestrial inputs. Because international coordination and collaboration are less well developed for coastal modeling (see below), the task team plans to focus on convening discussion forums and developing international coordination. The Task Team for *Coupled Atmosphere-Ocean Prediction* is focused on short to medium range time scales. The *Marine Ecosystem Monitoring and Prediction* Task Team is working closely with the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program to develop and integrate models and assimilation methods for ocean biogeochemistry and marine ecosystem monitoring into operational ocean models. Initiatives such as the Advances in Marine Ecosystem

Modeling Research (AMEMR) Symposia are helping to bring the ecosystem modeling community together, and to document progress.[139]

5.2.2 Inshore Coastal Modeling[140]

Models of inshore marine systems are well-established with a long history of development and application to local coastal management issues. We can distinguish five broad classes of applications:

- Coastal inundation and changes in sea level
- Coastal circulation
- Sediment dynamics and transport
- Water quality and the fate and impact of pollutants;
- Coastal Ecosystem impacts and responses.

Coastal models of inundation and changes in sea level, including surface waves, tides, tsunami, storm surge and river flooding, are typically 2-D depth-averaged. The Advanced Circulation Model (ADCIRC) is a hydrodynamic circulation numerical model that simulates water level and current over an unstructured gridded domain.[141] ADCIRC can be run as a two-dimensional or three-dimensional (2-D or 3-D) model for modeling tidally driven and wind and wave driven circulation in coastal waters; forecasting hurricane storm surge and flooding; and for modeling inlet sediment transport/morphology change studies, and dredging/material disposal studies. Because applications of these models address high priority threats to human life and infrastructure, they are widely used operationally and are arguably more mature than other classes of coastal models.[142]

Coastal hydrodynamic models predict currents, mixing and transport, and underpin models of water quality, biogeochemical cycles and ecosystems. The spatial resolution, accuracy and skill of 3-D coastal circulation models have all increased with improvements in computational power and numerical methods. Greater attention is now being given to wave-current interactions and coupled wave-hydrodynamic models.[143]

A distinguishing feature of coastal systems is the importance of interactions between the water column and the benthos. Models of sediment dynamics represent the dynamic processes controlling exchanges of tracers between the water column and the seabed, and may be used to predict changes in benthic geomorphology[144], changes in the concentrations of suspended fine sediments, and modeling of other tracers adsorbed to sediment particles or dissolved in interstitial pore waters.[145] Models of sediment dynamics rely on semi-empirical parameterizations of small-scale processes. While these semi-empirical process formulations are relatively mature and stable, model applications require parameter calibration against observations. The prediction of changes in benthic geomorphology has proven more challenging

than prediction of turbidity, and specialized geomorphological models may be used in engineering applications, especially in zones of wave breaking and swash on open coastlines. Representing the effects of structure and relief due to living benthos on bottom stress and sediment exchanges continues to be a challenge.
Receiving water quality models (RWQMs) have been developed to address the fate and impact of pollutants, including sediments, nutrients and toxins, in coastal systems. Biological process representations in RWQMs have changed from simple semi-empirical representations of biological oxygen demand (BOD), to full biogeochemical process models, representing the cycling of multiple elements (eg nitrogen, phosphorus, carbon) through pelagic and benthic primary producers and consumers.[146] Most RWQMs produce products and indicators related to water quality, specifically indicators such as turbidity, nutrient levels, phytoplankton biomass and dissolved oxygen. Benthic primary producers such as seagrasses and macroalgae have been included as needed.

Most recently, end-to-end ecosystem models (primary producers to top predators), involving full food webs, and benthic habitats, have been implemented for a number of coastal systems.[147] These are discussed further in Section 5.2.3.

The operational status of these coastal models is uneven. With the exception of ecosystem models, the models are now relatively mature, and have been very widely applied to support tactical and strategic management decisions. There are well-known commercial packages such as the DELFT-3D and Danish Hydraulic Institute (DHI)-MIKE series of models,[148] which are widely applied, often by commercial consultants and engineers. There are other open research and community modeling platforms which have also been used in many applications.[149]

While this subsection and the previous one have focused on more sophisticated modeling approaches, especially data-assimilating dynamical models, there is an ongoing role and need for simpler models, especially for assessment and diagnosis. The LOICZ biogeochemical budget methodology is an important example.[150] This allows users to infer information about flushing, production and nutrient fluxes from limited data sets using simple inverse techniques. It has been widely applied to estuaries and coastal systems globally. There is again a need to develop better statistical techniques to put confidence limits around outputs from coastal inverse models.[151]

In summary then, some coastal modeling for inundation is already operational. Coastal circulation models and RWQMs might be said to be quasi-operational in the sense that modeling platforms and tools exist that are routinely applied to support coastal management. However, there is an opportunity and need to radically improve these tools by adopting some of the techniques and methods already demonstrated for ocean circulation models by GODAE. One can expect this development to be encouraged and supported by GODAE OceanView, but it will require a genuine partnership and integration of the existing ocean modeling communities (GODAE and IMBER) with coastal modeling communities. Coastal physical and biogeochemical models are not simply inshore, high resolution extensions of ocean models. They include processes and components absent from ocean models, particularly those related to benthic components and benthic-pelagic coupling. This collaboration has already commenced in a number of nations and groups, and it would be reasonable to expect prototype data-assimilating inshore coastal models to be running in a number of locations after 3 years, with demonstration operational systems in 5 years.

Coastal RWQMs are used to predict and assess the impact of diffuse loads from catchments. The state of observation, modeling, assessment and prediction for catchment flows and loads offers strong parallels with the state of RWQMs. There is a strong history of catchment modeling, with a mix of physical process-based and empirical approaches. Observations have typically been sparse and under-sampled in space and time. With the exception of hydrological models for flood prediction, catchment models have been primarily used for assessment and management scenario evaluation. There are currently moves to implement more sophisticated automated observing systems, and to develop data-assimilating catchment models for prediction and assessment. While this report is not directed at observing systems for coastal catchments, it is well recognized that the development of coastal terrestrial and marine observing systems must proceed in an integrated manner.

5.2.3. Fisheries and Ecosystem Models

From a modeling standpoint, fisheries management has historically relied primarily on single species population models. It is generally not possible to directly observe the indicators used to make fisheries management decisions, such as stock size and structure, fishing mortality and recruitment rates. Observations typically consist of catch and effort data from commercial fisheries, sometimes including the structure of the catch such as age or size composition, potentially augmented by fishery-independent surveys and/or larval or egg recruitment surveys. Stock assessment models are used to convert these observations into management indicators such as stock biomass or fishing mortality rate.

Stock assessment modeling for single stocks is a very mature and technically sophisticated field.[152] The approaches can be divided into two classes. Inverse methods are used to directly convert observations into hindcasts of key indicators. The most widely applied inverse approach is known as Virtual Population Analysis (VPA). Alternatively, dynamical population models may be statistically fitted to time series of observations. These yield hindcasts of indicators, estimates of population parameters and forecasts of future population under specified catch or effort regimes. Sophisticated statistical procedures, including Bayesian inference for stochastic models, have been developed and are now widely applied.[153] Indicator estimates are routinely accompanied by quantitative error estimates.

Stock assessment models are now widely operationally implemented for fisheries, wherever the required observations and resources are available. Fisheries scientists have also put considerable effort into developing robust management strategies for fisheries where data and resources are limited. In those cases, stock assessment models may be replaced by simple statistical indices based on catch composition and trends.

A sophisticated framework for using models to inform fisheries and, increasingly, ecosystem-based management strategies, has been developed by fisheries scientists. The approach, referred to as Operational Management Procedures (OMP) or Management Strategy Evaluation (MSE),[154] assumes that an adaptive management strategy will be informed by a set of observations (a monitoring program), an assessment procedure or model, and a decision rule that specifies actions to be taken based on the assessment. If the strategy can be formally specified, then it is possible to simulate its application to a fishery or an ecosystem and evaluate the (simulated) performance of the strategy by comparing outcomes to management objectives and targets. Note that this approach has much in common with the twin experiment approach adopted by ocean modelers in OSSEs, although here the evaluation goes beyond model skill, to address management objectives, actions and impacts.

Models play two distinct roles within the MSE/OMP framework. **Assessment models** are used to convert observations into the indices or indicators that feed directly into the decision rule. Assessment models can be as simple as statistical averages of noisy observations, or as complicated as multi-species dynamical models, fitted to time-series of observations. However, because the outputs are used to inform actions, it is typically required that they are amenable to formal statistical treatment, to provide quantitative confidence limits or statistical distributions on the outputs. This requirement places a strong constraint on the complexity of assessment models, and they are typically restricted to single stock models, or the first two classes mentioned above: single-species extensions, and minimum realistic models.

MSE or OMP requires a capability to simulate the application of the strategy or procedure (including the assessment model) to an underlying ecosystem or fishery. The model used for this simulation is called the **operating model**. An operating model should ideally predict plausible and realistic changes in the underlying system state in response to management actions, and provide simulated “observations” of these state changes with realistic observation errors. Increasingly, the operating model is being extended to include socioeconomic aspects, both to provide indicators of performance against social and economic objectives, but more importantly to predict the responses of human agents, such as fishers, to changes in system state and management actions.[155] To allow for uncertainty in the knowledge and understanding of the underlying system, it is recommended practice to consider many possible realizations of the operating model with varying structural assumptions and parameters, so that MSE or OMP considers an ensemble of simulated outcomes or realizations, rather than a single outcome. However, with some exceptions, operating models are not subject to formal statistical treatment, and probabilities are not attached to different realizations. Instead, strategies are sought that are robust across a wide range of assumptions about the underlying system.

The lack of requirement for a formal statistical analysis allows the operating model to be considerably more complicated than the assessment model, and both dynamic system models and whole of ecosystem models have been used as operating models. In practice, the need to explore a wide range of operating model assumptions still imposes formidable computational requirements and constraints. The curse of dimensionality means that there is an explosive (exponential) growth in the number of simulations required to fully explore the operating model behavior, as the number of structural choices and uncertain parameters grows. For complex models, the choice of operating model scenarios must be strongly guided by heuristic experience.[156]

The data requirements for these models differ enormously according to their complexity and purpose. Data requirements are much less for simple (minimalistic) models representing a small number of species aggregated in space compared to complex ecosystem models involving many species or functional groups and explicit spatial distributions. The needs are more exacting for assessment models, where there is a formal statistical treatment, and errors in model outputs depend explicitly on the data quantity and quality.

For ecosystem models, gaps in data may be partly overcome by making plausible assumptions guided by experience. But knowledge of population sizes, life histories and trophic interactions is still required to allow an adequate approximation of the system structure. For some modeling systems, particularly Ecopath with Ecosim (EwE), tools are provided to allow inference of trophic structure from incomplete information, and even some dynamical fitting to time series of observations. However, there are risks involved, particularly in the adoption of default parameter values or structures by inexperienced users with inadequate information.

FAO (2008) highlights some particular modeling platforms, based on their wide adoption and/or particular strengths:

- Ecopath with Ecosim (EwE)[157] is by far the most widely implemented ecosystem modeling platform, because of its strong support base, and user-friendly interface and tools for implementation. The wide user base and large number of case studies for EwE also support comparative studies across ecosystems.
- The Atlantis model[158] is recommended because of its strengths in connecting bottom-up and top-down pressures in a spatially-resolved framework.
- The SEAPODYM model[159] has been developed to support ecosystem-based management of pelagic tuna fisheries, and is noteworthy for its connection to ocean circulation models and strong bottom-up spatial approach.
- The community model GADGET[160] is recommended because it handles multiple species in a spatially-resolved context, provides strong statistical inference procedures, and offers a flexible choice of structural assumptions.

5.2.4 Informing Observing System Design

ESSENTIAL ECOSYSTEM STATE VARIABLES			
Geophysical	**Chemical**	**Biological**	**Biophysical**
Water temperature	Dissolved inorganic nutrients (N, P, Si) concentrations	Phytoplankton biomass (chlorophyll-a)	Water leaving radiances
Salinity	Dissolved oxygen concentration	Toxic phytoplankton abundance	Diffuse attenuation coefficient (downwelling irradiance)
Currents	pH, fCO_2 & total alkalinity (Aragonite saturation state)	Calcareous plankton abundance	
Surface wave height & direction	Colored dissolved organic matter	Abundance of copepod indicator species	
Absolute sea level		Abundance of waterborne pathogens	
Shoreline Position		Extent of living benthic habitats	
Bathymetry		Species diversity of communities associated with living benthic habitats	
Sea surface roughness		Coral skeletal density	
Total suspended matter		Abundance of eggs, larvae & size classes of exploited fish stocks	
		Bycatch	
		Diet of exploitable fish species	
		Abundance & size of apex predators	

ESSENTIAL PRESSURE VARIABLES		
Land – Based	**Atmospheric**	**Deep Sea & Ocean Basin Scale**
Volume discharge of rivers & associated inputs of sediments, nutrients, pathogens & chemical contaminants	Ocean surface vector winds, air temperature & pressure, heat flux, precipitation & associated inputs of chemicals	Inputs of plankton, non-native species, nutrients, hypoxic & acidic water masses; & migrations of straddling & highly migratory fish stocks
Fin- and shell-fish harvests	Incident solar radiation	Changes in sea surface height & fields of temperature, salinity, currents & waves

Table 14. *The provisional essential (common) variables for the Global Coastal Network used to compute indicators of ecosystem states (e.g., fields, indices) and pressures on coastal marine ecosystems. The list, an update of Table 1.3, includes additional essential variables identified in the end-to-end systems described in Chapter 3.*

Improved metrics and objective statistical procedures for model-data fusion together provide an opportunity to use models to help evaluate and inform observing system design. The ocean forecasting community now uses OSEs[161] and OSSEs[162] to estimate changes in model skill likely to be achieved through the assimilation of data following changes to observing systems. These techniques are likely to be transferred to coastal models and biogeochemical models over the next decade.

5.3 Observing Subsystem Requirements, Status and Gaps

5.3.1 Updating the List of Essential (Common) Variables

When the provisional essential variables were identified by the Coastal Ocean Observations Panel (COOP), the Panel recommended that the list be updated periodically as new knowledge and technologies become available and priorities evolve.[163] Accordingly, observing system requirements for the end-to-end systems offered in Chapter 3 were used to update the list of essential variables (Table 14).

Note that many of these variables can be used to compute indicators of states or, when states change, as pressures depending on the phenomenon of interest and the spatial scale of the ecosystem. For example, the extent of benthic habitats is an indicator of ecosystem state while habitat loss is a pressure on biodiversity as an index of state. Likewise, a state change in an ocean basin ecosystem (e.g., ocean acidification, declines in large, migratory predators such as tuna) may be a pressure on an LME within the basin (Figure 7).

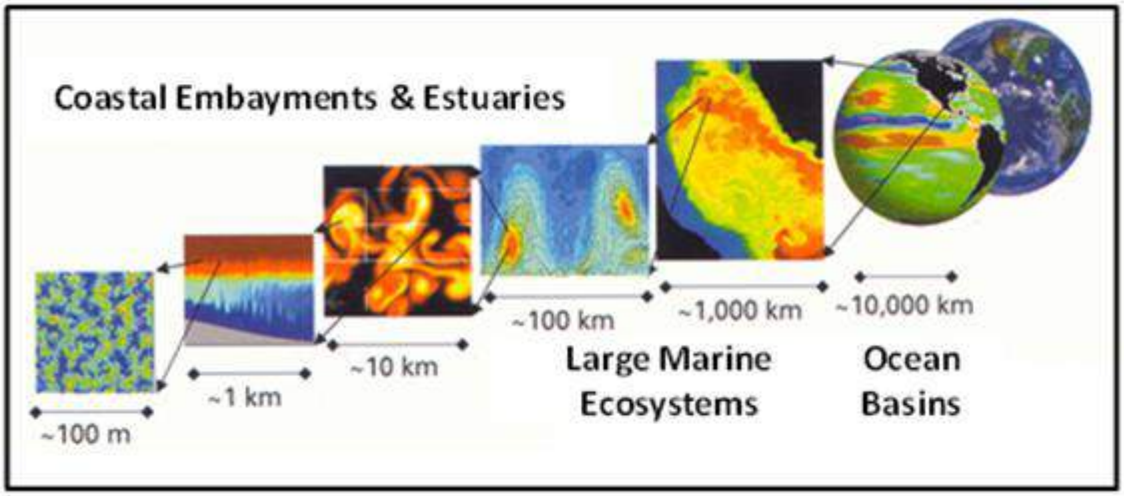

Figure 7. *Ecosystems come in many sizes and shapes from small estuaries and bays to LMEs and ocean basins so that a state change in a large ecosystem may be a pressure to a smaller ecosystem.*

5.3.2 Remote Sensing

Opportunities and Challenges

Capturing the dynamics of coastal ecosystems requires an integrated approach with remote sensing and *in situ* observations. Observations from satellite-based remote sensing are critical to addressing the chronic problem of under-sampling by complementing and enhancing the value of *in situ* observations (sections 5.3.3 and 5.3.4). Advantages of remote sensing include the ability to provide synoptic observations of spatial distributions on local to global scales; long-term time series of changes in these distributions as well as short-term temporal variability (e.g., from geostationary orbit); and, the capability to observe geophysical and biological variables simultaneously and cost effectively. Disadvantages include the inability to detect subsurface distributions, measure contaminants directly, and adequately resolve changes and events on small-scales (although improvements continue to be made in this area). A persistent challenge is frequent cloud cover, leading to gaps in SST coverage and ocean color radiometry in particular. Additional challenges for detecting changes in coastal ecosystem states include the optical complexity of coastal waters, sub-optimal imaging conditions (e.g., sun-glint or too high/low winds), contamination of pixels by land, and problems of comparing and integrating data for the same variable from different sensors. Given the potential of ocean observations from space, two primary observational challenges from the GOOS perspective must be addressed in the coming decade and beyond, maintaining continuity and increasing resolution and coverage.[164] Continuity issues are addressed below. Resolution and other issues are primarily addressed in section 6.3.2.

For the purposes of GOOS, platforms for remote sensing include satellites, aircraft (e.g., Lidar for nearshore bathymetry and topography) and ground-based platforms (e.g., High Frequency radar for surface current and wave fields). Although aircraft- and ground-based remote sensing capabilities are currently being employed by many developed countries, emphasis here is on satellite-based remote sensing since it has the potential to benefit both developed and developing countries cost-effectively worldwide. Significant efforts are underway to resolve both technical and programmatic challenges to the provision of satellite data that will enable more rapid detection and timely prediction of changes in coastal marine and estuarine ecosystem states to support sustainable development.

Essential ecosystem state and pressure variables (Table 14) that can be estimated remotely include the following:

- Sea surface temperature (SST);
- Water leaving radiances, chlorophyll-a, total suspended matter, colored dissolved organic matter, and diffuse attenuation coefficient et al. from ocean color radiometry (OCR);
- Ocean surface vector winds (OSVW);
- Sea surface height (SSH);
- River discharge;
- Sea surface roughness, e.g., surface waves, buoyant plumes, high resolution wind fields, ship detection, bathymetric features, marine slicks (from synthetic aperture radar);
- Ocean surface currents;
- Surface wave height and direction;
- Sea surface salinity (SSS);
- Land cover and living benthic habitats (e.g., coral reefs, seagrass beds, mangrove forests and tidal salt marshes);
- Nearshore bathymetry and topography.

Existing Observations, Operational Maturity, and the Need for Continuity

As ocean and coastal remote sensing evolves to become an important tool for both research and operational oceanography, ensuring the continuity of satellite-based observations has become an increasingly high priority. Most existing space-based oceanographic measurements are already either being generated operationally (e.g., SST from the Advanced Very High Resolution Radiometer: AVHRR; sea surface height from Jason-2; ocean surface vector winds from the Advanced Scatterometer: ASCAT) or are being utilized for operational purposes (e.g., ocean color radiometry from research sensors such as the Moderate Resolution Imaging Spectroradiometer, MODIS; sea surface roughness data from the Advanced Synthetic Aperture Radar, SAR). Upcoming operational missions will ensure continuity of ocean color radiometry (e.g., from Sentinel-3 and JPSS-1) and synthetic aperture radar (SAR) data (e.g., Sentinel-1 and the RADARSAT Constellation). Emerging measurements such as sea-surface salinity show great promise. However, there is increasing concern that there could be a break in continuity of some essential variables due to schedule, funding and/or data quality issues, with the potential for a gap in satellite data records that could impact research as well as near-real time operations and ecosystem and climate applications. While this remains a risk, recent efforts to coordinate priorities and assets across national and international space agencies show promise to ensure that such breaks in the climate-quality satellite time series do not occur.

Remotely Sensed Observations	**Phenomena of Interest**						
	Coastal Eutrophication and Hypoxia	Exposure to Waterborne Pathogens	Toxic Algal Blooms	Habitat Loss and Modification	Vulnerability to Coastal Flooding	Ocean Acidifi-cation	Food Security
Sea Surface Temperature[a]	X	X	X	X	X	X	X
Ocean Color Radiometry[b]	X	X	X	X	X	X	X
Ocean Surface Vector Winds[c]	X	X	X			X	X
Sea Surface Height[d]				X	X		X
Sea Surface Roughness[e]	X	X	X	X	X		X
Ocean Surface Currents[f]		X	X	X	X		X
Sea Surface Salinity[g]	X	X	X	X	X	X	X
Coastal Habitats/Land Cover[h]	X			X	X		X
Nearshore Bathymetry/ Topography[i]				X	X		
Optical Imagery[j]		X		X	X		X

Table 15. *Remotely-sensed observation requirements for priority coastal phenomena of interest. Present-future sources include: [a]Advanced Very High Resolution Radiometer (AVHRR), Along Track Scanning Radiometer (ATSR); Visible Infrared Imaging Radiometer Suite (VIIRS), Advanced Microwave Scanning Radiometer 2 (AMSR-2), Moderate Resolution Imaging Spectroradiometer (MODIS); [b]Medium Resolution Imaging Spectrometer (MERIS), MODIS, Ocean Colour Monitor (OCM-2), Second Generation Global Imager (SGLI); [c]Advanced Scatterometer (ASCAT), Oceansat-2 Scatterometer (OSCAT); [d]Jason-2, Jason-3, Surface Water Ocean Topography (SWOT); [e]Advanced Synthetic Aperture Radar (ASAR), RADARSAT Constellation Mission (RCM); [f]shore-based High-Frequency (HF) radar, Jason-2, ASAR, TerraSAR-X and TanDEM-X; [g]Soil Moisture and Ocean Salinity (SMOS), Aquarius; [h]MODIS, Landsat Enhanced Thematic Mapper Plus (ETM+), Hyperspectral Imager for the Coastal Ocean (HICO), Hyperion, Hyperspectral Infrared Imager (HyspIRI); [i]airborne LIDAR, QuickBird, Landsat ETM+; [j]MERIS, MODIS, Satellite Probatoire de l'Observations de la Terre (SPOT), IKONOS, Landsat ETM+, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), HICO.*

As documented in Chapter 3 and summarized in Table 15, remote sensing data can be utilized for a diversity of applications including monitoring coastal eutrophication (3.1), fate and transport of pathogens (and pollutants) (3.2), harmful algal blooms (3.3), habitat modification and loss (3.4), ecological buffers to coastal flooding (3.5), distribution of coccolithophores and other calcareous organisms (3.6), and distribution of living marine resources (3.7).

Sea-surface temperature and ocean color radiometry are the most widely utilized satellite data streams as they support a diversity of coastal applications. SST measurements are routinely acquired from both Low Earth Orbit (LEO) as well as Geostationary Earth Orbit (GEO) satellites. The latter provides significantly improved temporal resolution which is quite important in dynamic coastal regions and regions that experience frequent cloud cover.

SST measurements from satellite sensors in both LEO and GEO have been operational for years. These sensors use thermal infrared bands to provide global and high temporal resolution regional SST measurements for such uses as identifying and detecting changes in circulation features (e.g., upwelling zones, fronts, and eddy fields), indicating spatial patterns and temporal trends in coral bleaching, estimating changes in the heat content of the upper ocean, and determining boundaries of marine protected areas (MPAs). Continuity of passive microwave SST capabilities (e.g., the Advanced Microwave Scanning Radiometer for EOS, AMSR-E, via the upcoming AMSR-2) is also a priority given the ability of these sensors to penetrate clouds. For microwave SST observations, improvements are needed in both spatial resolution and the ability to acquire data closer to the coastline.

Satellite ocean color radiometry (OCR) data have been acquired as part of various research missions dating back to the Coastal Zone Color Scanner (CZCS) in 1978. Uninterrupted OCR measurements have been available since 1997 when the SeaWiFS mission was launched; this successful and ground-breaking mission ended in early 2011. MODIS and MERIS continue to provide OCR data (but are beyond design life and aging). Ocean color radiometry measurements have been utilized for ocean monitoring and coastal applications over the past decade, and will soon be acquired routinely as part of several upcoming operational missions as previously noted, as well as from a series of current and planned polar orbiting research missions. However, there remain data acquisition, access and distribution issues (e.g., free, open and timely exchange of Level 0, 1, and 2 data) that need to be addressed to ensure both the near-real time and delayed mode data needs of coastal users are met from existing as well as future ocean color sensors. In terms of ocean color radiometry data needs, a well-documented and compelling need is for higher temporal, spatial and spectral resolution data[165]. Regarding improved temporal resolution, Korea's Geostationary Ocean Color Imager (GOCI) launched in 2010 on the COMS platform. GOCI is the first ocean color sensor in geostationary orbit, providing frequent temporal revisits for coastal waters adjacent to Korea. This emerging ocean color capability will significantly improve our understanding of coastal marine ecosystem dynamics.

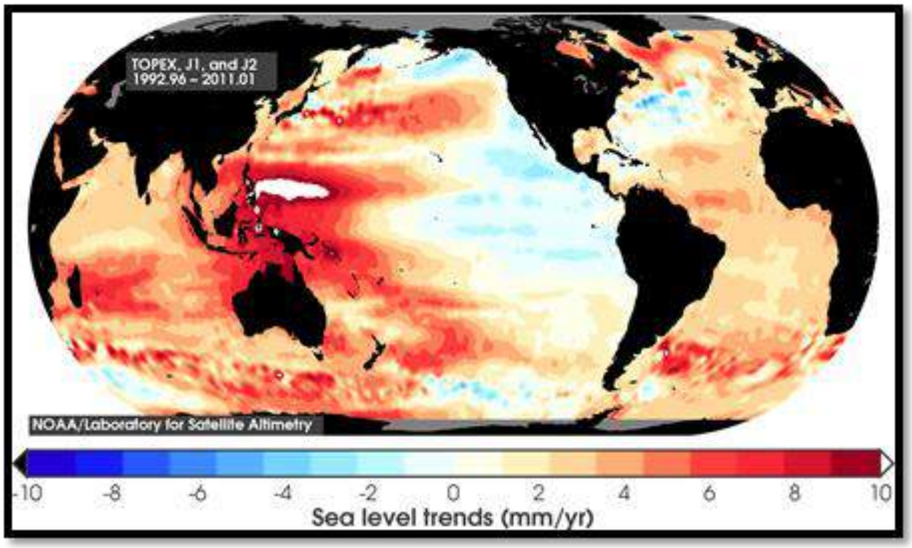

Figure 8. *Trends in sea level from 1992-2011 (1993-2010 complete) as measured by TOPEX/Poseidon, Jason-1, and Jason-2.*

For sea surface height measurements, the multi-mission, Topex-Poseidon/Jason satellite altimetry time series starting in 1992 shows global mean sea level increasing at a rate about 3 mm/year.[166] However, there is substantial spatial variability with some regions showing large increases and some showing decreases in sea level (Figure 8).

The presence of large regional variations has significant implications for coastal inundation and flooding as discussed in section 3.5. Efforts are underway to improve our ability to utilize existing satellite altimetry capabilities from the Jason series to provide enhanced coverage in coastal regions (Figure 9) toward better understanding trends in regional sea level and variability, as well as for other applications.

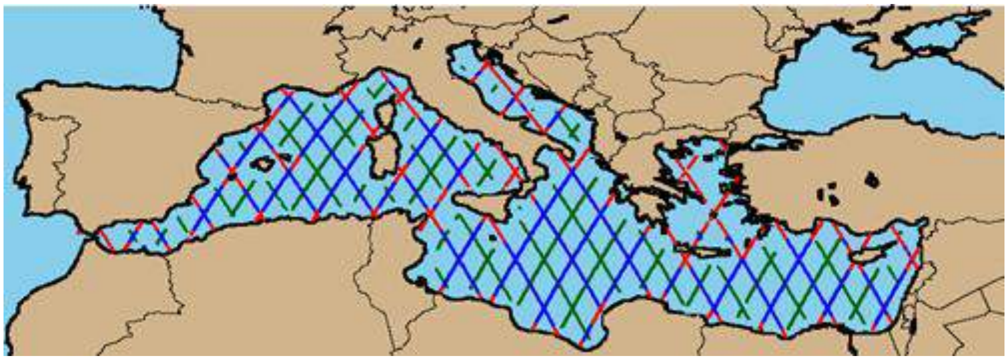

Figure 9. The hardware design and algorithm improvements for the Jason-2 Advanced Microwave Radiometer (AMR) have greatly improved coastal sea level monitoring over its predecessor altimetry missions, Jason-1 and TOPEX/Poseidon. In particular, the spatial resolution of the wet troposphere correction derived from radiometer observations has nearly doubled. The coverage of the Jason-1/TOPEX references missions was limited to areas greater than 50 km from coasts and islands (blue), while Jason-2 additionally covers areas up to 26 km away (red dots). In 2009 Jason-1 was maneuvered into a ground track interleaved with Jason-2, and this coverage area is in green. Note that the AMR from Jason-2 is more important than the interleaved phase in providing coverage of the Adriatic and Aegean Seas. Courtesy of the NOAA Laboratory for Satellite Altimetry.*

Sea surface height observations are now operational from satellite altimetry missions (e.g., the Jason-2 and upcoming Jason-3 and Jason-CS), and critical for sustained and accurate global monitoring of sea level rise on global to regional scales. Additional information is needed regarding coastal zone dynamics, including improved characterization of mesoscale and submesoscale circulation, tides, and bathymetry, as well as estimates of river discharge and distribution of terrestrial surface water. Future swath altimeter missions will address many of these needs (see section 6.3.2).

Ocean surface vector wind measurements support operational surge forecasting and provide operational inputs for Numerical Weather Prediction (NWP) of winds, wave forecasting, marine nowcasting (high seas et al.), tropical and extratropical cyclone forecasting, ocean model forcing and ocean current forecasts.[167] Ocean surface vector wind measurements also provide valuable information on surface wind fields and wind driven wave and current fields (e.g., coastal upwelling, fronts, and surface currents) that govern the transport and distribution of nutrients, sediments, chemical contaminants, and plankton. Operational ocean surface vector winds are presently only available from the ASCAT sensor as the SeaWinds Instrument on the QuikSCAT mission is no longer collecting synoptic ocean surface vector wind data. There are other existing and planned scatterometers, but their operational utility is still uncertain. In general, continuity of this key measurement remains a significant concern.

Complementing satellite altimetry and scatterometry data with High-Frequency (HF) radar data (short and long range) can help improve the resolution and accuracy of estimates of sea surface current and wave fields. Ocean surface currents in the coastal zone are currently best derived from shore-based HF radar, but deployment is currently limited to developed countries. There are active efforts in Australia, Europe and the U.S. to implement coastal HF radar networks that provide surface ocean current velocity fields in near-real time, supporting a wide range of applications including oil spill response, search and rescue, water quality monitoring, navigation, HAB forecasts, fisheries and ecosystem monitoring, and hydrodynamic modeling. Ocean surface currents can be derived from satellite altimeter measurements, but this is limited to the coarse-scale geostrophic current field. An emerging direction with greater utility for coastal waters is the use of SAR Along-track interferometery (ATI).[168] Other methods to estimate velocity include the use of across-track Doppler Shift and through feature tracking.[169]

Sea surface roughness observations from SAR sensors provide the ability to monitor, with high spatial resolution, oil spills, waves (surface and internal), coastal wind fields, current gradients, buoyant plumes from land-based sources (rivers, storm drains, runoff following coastal floods, etc.) and a variety of other oceanic and atmospheric phenomena.[170] Adequate coverage and access to these data from SAR sensors remains a persistent challenge for many regions and users. However, it is anticipated that these data will become more routinely available in the coming years with the launch of several operational systems (e.g., Sentinel-1 and RADARSAT Constellation Mission).

Sea surface salinity is the newest ocean parameter to be measured from space. Two missions, i.e., Soil Moisture and Ocean Salinity (SMOS) and Aquarius, currently provide global and basin-scale estimates of sea surface salinity fields which will improve our ability to monitor and predict changes in the ocean's impact on the Earth's water cycle and to better understand ocean circulation and climate. A challenge for next generation missions would be to provide space-based ocean salinity data on time-space scales that are more useful for coastal research and coastal GOOS (e.g., monitoring the sources and fates of river-discharged contaminants).

Observations and characterizations of biologically structured near shore habitats (coral reefs, seagrass beds, mangrove forests, salt marshes) and land-use/cover in coastal catchment basins are currently possible via satellite-derived low (e.g., MODIS), moderate (e.g., Landsat, SPOT, HICO) and high (e.g., IKONOS, QuickBird) spatial resolution multispectral imagery.[171] Future directions include routine global mapping using high-quality hyperspectral imagery to assess and monitor changes in the health and extent of nearshore benthic and adjacent coastal terrestrial habitats; missions such as the proposed Hyperspectral Infrared Imager (HyspIRI) would provide suitable data for this purpose.[172]

Coastal and nearshore bathymetric and topographic maps are provided at the highest resolution via airborne LIDAR. Satellite-derived observations using altimetry, SAR, and/or multispectral imagery can also provide additional useful information in this context.

Future Directions and Community Activities

Moving forward, the focus will be on expanding the use of satellite-based ocean remote sensing for both research and operational applications, ensuring continuity in data streams for essential variables, and facilitating their utilization by a broad spectrum of users. [173] There will also be continued development and implementation of new and improved sensors and platforms to provide increased spatial, spectral and temporal resolution and coverage for coastal regions, as well as measurement of new parameters from space. Algorithm development efforts will continue to provide new and improved data streams and products. Likewise, associated efforts in calibration, validation, inter-sensor comparisons and error/uncertainty analyses are critically needed, particularly to facilitate blending and merging of data to address gaps in coverage and data drop out due to clouds et al., and develop robust climate data records for a diversity of research and application efforts. Integrated data information products and environmental predictions using data assimilation techniques and numerical models (e.g., nowcasts and forecasts) will increasingly depend on the blending of remote sensing and *in situ* data.

There are numerous community activities underway that bring together satellite data providers and coastal users to advance the use of satellite data for coastal research and applications. These include the following:

- The Group for High-Resolution Sea Surface Temperature (GHRSST) provides global high-resolution (<10 km) SST products to the operational oceanographic and meteorological communities as well as the climate and oceanographic research communities.[174]
- The IOCCG, through its member agencies, partners and contributors, provides regional, basin scale and global chlorophyll-a and other ocean color radiometry products, and likewise works to advance ocean color science and its applications (e.g., a geostationary ocean color working group for coastal research and applications).
- The coastal altimetry workshop series brings together scientists from many nations who are helping to advance the use of altimetry for regional and coastal applications in the coastal zone.
- The GEO Inland and Near-Coastal Water Quality Remote Sensing Working Group are working to facilitate the widespread use of space-based OCR data for water quality monitoring.[175]
- The Chlorophyll Global Integrated Network (ChloroGIN) project of GOOS-GEOSS promotes dissemination of ocean surface chlorophyll and temperature fields along with associated *in situ* measurements of chlorophyll-a, temperature, and light penetration.[176]
- The Societal Applications in Fisheries and Aquaculture using Remotely-Sensed Imagery (SAFARI) initiative is advancing the use of satellite-based remote sensing to inform fisheries management, the fishing industry and aquaculture operations.[177]
- The GEO-CZCP[178] is working to advance the use of Earth observations for coastal applications such as managing and mitigating the effects of coastal inundation on coastal communities and ecosystems.

These efforts support development of robust ecosystem indicators for management of the oceans, including regional algorithm development for phytoplankton biomass and primary production and are needed to more effectively link the development of coastal GOOS to user groups.

5.3.3 *In Situ* Measurements

Over the last decade, autonomous technologies for measuring essential geophysical variables (Table 14) have revolutionized our ability to observe the ocean's interior. By integrating data from both remote sensing (satellite-based sensors and land-based HF radar) and *in situ* measurements (from ships of opportunity, research vessels and automated moorings, profiling floats, gliders, and surface drifters), observations of atmospheric and upper ocean geophysics are now made continuously in 4-dimensions; data are transmitted to data assembly centers in near real-time via satellites, fiber optic cables, and the internet; and predictions (nowcasts and forecasts) of atmospheric and upper ocean "weather" are made routinely using data assimilation techniques and coupled atmospheric-hydrodynamic models.[179] While much remains to be done in terms of capacity building, minimizing problems of under sampling, and improving models and *in situ* sensors (continue the development of small, inexpensive, stable, low power sensors that have long endurances, are accurate at low concentrations, and less prone to biofouling),[180] this end-to-end system of systems has rapidly advanced our understanding and forecasting skill of changes in upper ocean and near-shore geophysical states from local to global scales.

Similar capabilities are needed for observing essential chemical and biological variables synoptically (simultaneously on the same time-space scales) with the essential geophysical and biophysical variables.[181] *In situ* measurements of essential chemical and biological variables fall into two classes (Table 16): (1) autonomous, near-real time measurements and (2) delayed mode measurements made under controlled laboratory conditions after samples have been collected (by divers, from vessels and piers, etc.). Our focus here is on the former as the best means to decrease time lags between changes in ecosystem states and their detection (Figure l). Three categories of autonomous capabilities are considered (Table 16):

(1) Commercially available, operationally mature sensors that have been field tested under a broad range of conditions, are stable over extended periods (≥ 1 month) and are deployable on fixed or mobile platforms;
(2) Commercially available sensors that are undergoing pre-operational field testing (for deployment and maintenance costs, endurance, stability, accuracy, etc.); and
(3) New and emerging technologies under research and development.

These are roughly equivalent to the three categories of readiness recommended by the Integrated Framework for Sustained Ocean Observing Task Team.[182] Here we address category 1 and delayed mode variables. Categories 2 and 3 are addressed in section 6.3.

Category		Essential Variable
Near-Real Time	1	Dissolved oxygen, nitrate, ammonium, & phosphate; *f*CO_2, pH, spectral attenuation of downwelling irradiance, phytoplankton biomass (chlorophyll-a); spatial extent of coral reefs, seagrass beds, mangrove forest and salt mashes
	2	Abundance of size classes of exploited fish stocks & apex predators
	3	Aragonite saturation state, toxic phytoplankton species, waterborne pathogens, macro- & meso-zooplankton, species diversity of coral reef communities
Delayed Mode		All of the above (increase the number of sites surveyed, calibrate, validate, improve resolution & accuracy) Species diversity, calcareous plankton, copepod indicator species, fish eggs & larvae (filtered water, towed nets, CPR or settling plates followed by DNA barcoding, microchips, microscopy); coral skeletal density (weight in air & water)

Table 16. *Essential variables may be measured and reported in near-real time or delayed mode. Autonomous near-real time measurements fall into three categories in terms of their operational maturity.*

As defined in *A Framework for Ocean Observing* (end note 5), category 1 corresponds roughly to a "mature" readiness level, category 2 with a "pilot" readiness level and category 3 with a "concept" readiness level.

Category 1 Variables

- **Dissolved Oxygen**

Two types of dissolved oxygen sensors are available for deployment on profiling floats, gliders and moorings:[183] an electrochemical sensor[184] and a fiber optic oxygen sensor.[185] Relative to the electrochemical sensor, the latter is preferred because of its faster response time, longer stability, resistance to biofouling, and lack of interference from exposure to sulfide. In addition, the sensor does not consume oxygen and can be calibrated *in situ*.

- **Dissolved Nutrients** (Nitrate, Ammonium, Phosphate)

Most *in situ* sensors fall into two categories, those that depend on wet chemistry and those that depend on UV absorbance.[186] Criteria for an ideal *in situ* nutrient sensor include self-calibration, multiple-analyte capability, resistance to biofouling, low life cycle cost, reliable, real-time data transmission, low maintenance, and interoperability with other sensors.[187] With the important exceptions of biofouling and long-term reliability, much progress has been made toward meeting these criteria. Optical sensors for dissolved nitrate are now available[188] and, in combination with autonomous platforms, can be used to monitor changes in nitrate fields.[189] The Adaptive and Integrated nutrient Monitoring System (AIMS) employs wet chemistry to measure urea, ammonium, nitrate and phosphate and provides near real-time data telemetry for 1-2 month deployments in turbid estuarine waters.[190] The comparatively large size of wet chemical sensors, power requirements, reagent degradation, storage, and waste generation, limit long-term effectiveness of wet chemical sensors. The UV technique provides a rapid response and does not require reagents or waste storage, but sensitivity is lower than wet chemical techniques.

- **Dissolved Inorganic Carbon System**

Byrne et al. outline strategies for observing the CO_2 system, the status of autonomous in situ sensing, appropriate pairings of sensors and platforms, and potential new technologies.[191] Measurable variables include total dissolved inorganic carbon (DIC), total alkalinity (A_T), CO_2 fugacity (fCO2),[192] and pH. Comprehensive characterization of system requires the measurement of at least two of these variables. Pair combinations that provide optimum results are pH–A_T, pH–DIC, fCO_2–A_T, and fCO_2–DIC. Shipboard methods are well established. A variety of sensors are available for measuring components of the inorganic carbon system.[193] Autonomous sensors for long-term subsurface measurement of fCO_2 on fixed platforms, surface drifters and AUVs have been commercially available for some time. Two techniques have been developed: (1) equilibration of a pH indicator dye solution (with specifically adjusted alkalinity) through a silicone membrane tube with ambient seawater with the change in pH measured spectrophotometrically and (2) membrane-based air-sea water equilibration with subsequent measurement of CO_2 concentration in the equilibrated gas by non-dispersive infrared detection (NDIR). Power requirements, size, and response time have made it problematic to use CO_2 system sensors on Argo floats and gliders. Ion-sensitive field-effect transistor (ISFET) pH sensors appear to have sufficient stability (<0.01 pH) for multi-year operation on profiling floats, but the chip packaging that enables long-term stability is not tolerant to high pressure.[194] Until this technical problem is solved, autonomous, *in situ* pH measurements using this technology will be limited to shallow waters. The Multiparameter Inorganic Carbon Analyzer can measure pH, fCO_2, and total inorganic carbon,[195] and the Spectrophotometric Elemental Analysis System (SEAS) can measure pH[196] as well as nitrate and phosphate.[197] Sensors sans pumps, valves, and other moving parts need to be developed (e.g., the O_2 optode), to enable widespread use of CO_2 system sensors on profilers and gliders.

- **Downwelling Irradiance**

The field of miniature, low power bio-optical and biogeochemical sensors is rapidly evolving.[170] Deployments of small, autonomous radiometric optical sensors (multi-wavelength spectrometers, bioluminescence detectors, multispectral and hyperspectral upwelling and downwelling radiometers, etc.) on moorings, floats, and gliders have been highly successful over the last decade, e.g., OCR-507 irradiance sensor. The diffuse attenuation coefficient (K_d), derived from downwelling irradiance (E_d), is used to compute the depth of the euphotic zone and serves as a proxy for colored dissolved organic matter (CDOM), turbidity, total suspended solids, and phytoplankton biomass (in waters with low concentrations of detritus).

- **Phytoplankton Biomass**

Chlorophyll a (indicator of phytoplankton biomass and a key variable in the biogeochemistry of the oceans) can be measured by fluorescence. Miniature fluorescence sensors can be mounted on a variety of platforms (e.g. moorings, gliders, profiling floats, pelagic animals).[198] Turbidity and light attenuation coefficients (transparency) can be estimated using backscattering-meters and transmissometers, respectively. In waters where POC is the primary source of turbidity and light attenuation and coccolithophores are not abundant, the concentration of POC can be computed from both measurements with acceptable accuracy.[199]

- **Mapping Biologically Structured Benthic Habitats**

Side scan and multibeam sonar are effective for seafloor characterization and habitat classification when combined with extensive ground-truthing with under water video.[200] The spatial extent and fragmentation of coral reefs and seagrass beds can be mapped using autonomous underwater vehicle (powered AUV). AUV surveys provide a synoptic view of these habitats at scales from cm to 10s of km, can include depth ranges not easily attained by divers, and can reduce the cost per datum for seafloor mapping by reducing or eliminating the need for expensive ships. AUV surveys enable rapid mapping of coral reefs and seagrass beds at the landscape scale complementing aerial and satellite remote sensing.[201] AUVs can be deployed from small boats or from shore. Flying in close proximity over the habitat in bathymetry-following mode, a single AUV can image and map several km^2/day (using side scan sonar, multibeam sonar, and high resolution digital cameras) while simultaneously measuring currents, conductivity, temperature, dissolved oxygen, pH, and chlorophyll-a concentration.[202]

- **Multi-Sensor Instrument Packages for Monitoring Water Quality in Coastal Waters**

Some of the technologies described above have been incorporated into a single instrument package for deployments on ships and moorings. The Ferry-Box project in Europe has demonstrated the value-added and operational capability of multi-sensor packages deployed on ships of opportunity.[203] The project used four core sensors to provide synoptic measurements of temperature, salinity, chlorophyll-a, and turbidity. In addition to Europe, ferry-boxes are now deployed on ferries in Australia, Japan and the USA. The next step is to expand these efforts into a globally coordinated contribution to GOOS.[204]

The Water Quality Monitor (WQM) has been developed for real-time observations of temperature, salinity, dissolved oxygen, chlorophyll-a and turbidity.[205] Equipped with a copper faceplate and copper Bio-wiper™ for the optical window and anti-foulant cartridges for the sensor plumbing, the WQM is capable of long-term deployments (months) on fixed platforms in potentially high biofouling coastal waters (e.g., nutrient rich coastal estuaries).

- **Biofouling**

Finally, biofouling is a chronic problem in productive coastal waters since many of the sensors for chemical and biological variables rely on optical systems. A modular servo-controlled anti-biofouling shutter system for open-faced optical sensors has been developed and used extensively.[206] A newer design uses a coupled copper shutter and face-plate to protect the optical window and to wipe it clean just prior to making a measurement. Other anti-fouling techniques for flow-through optical systems include air purging and bleach injection.

Delayed Mode Variables

- **Species Diversity**

Four communities of organisms are targeted that represent a range of expected response time scales from rapid to slow: microbial communities (relatively rapid response), open water zooplankton communities, epiplankton associated with warm water coral reefs, and nearshore benthic communities (relatively slow response).

(1) Microbes

The development of massively parallel DNA sequencing technology has enabled scientists to assess the diversity of bacterial and viral communities in the oceans.[207] This technology has also been applied to analyses of the gene expression of environmental samples of marine bacteria[208] making it possible to detect responses of entire microbial communities to changes in physical conditions of the ocean. Given cost of these technologies, water samples could be delivered central laboratories for advanced antibody analyses (enzyme labeled immune-sorbent assay, ELISA) and/or DNA analysis (e.g., quantitative polymerase chain reaction, Q-PCR; fluorescence in situ hybridization, FISH).

(2) Open water zooplankton (including calcareous plankton species)[209]

The CPR Survey is a contribution to GOOS and the longest (1931 – present), most geographically extensive (North Sea, North Atlantic, North Pacific, Southern Ocean, Australian coastal waters) marine biological survey in the world with a unique dataset on the species diversity of macrozooplankton (> 500 taxa to date).[210] The CPR is a high-speed plankton recorder towed behind volunteer ships of opportunity (SOOP) at a depth of ~10 m. Plankton samples collected on a slow moving silk (mesh size 270 μm) are reeled into a tank containing 4% formaldehyde and sent to processing center where plankton species are enumerated microscopically. Given the importance of macrozooplankton in marine foodwebs and as indicators of ocean warming, this program should be expanded to establish a coordinated global CPR program consisting of regional surveys that utilize common international standards for sampling, analysis, data processing and sample storage, and that is closely associated with SOOP and Volunteer Observing Ship operations.

The zooplankton project of CoML has developed DNA chips that recognize ~ 10,000 species from their DNA barcodes,[211] and it has been demonstrated that DNA sequencing can be used to identify zooplankton species in formalin-preserved CPR samples.[212] These advances and the proposed global expansion of this program would provide an unprecedented data set on time-space variations in the species diversity of key members of marine food webs on coastal ecosystem to global scales.

(3) Coral reef communities

The coral reef project of CoML has deployed Autonomous Reef Monitoring Structures (ARMS) in most of the world's tropical and subtropical coral seas and has developed DNA barcode catalogs for all of the juvenile species that have settled on these structures.[213] Recolonization of reefs occurs primarily from meroplanktonic larvae and juvenile forms that settle on ARMS. A years' worth of species can be collected from the settlement plates and analyzed for DNA without involving months of labor intensive microscopic analyses once the relationship between traditional morphometric descriptions and DNA barcodes are established and recorded in online databases.

(4) Near-shore benthic communities

The Natural Geography of Inshore Areas (NaGISA) project is being established to observe changes in the species diversity of benthic communities from the high intertidal to 20 m from pole to pole and around the equators.[214] The standardized protocol include photography (estimates of percent cover of sessile colonial invertebrates, seagrass beds and rhizoidal macroalgae and abundance of solitary faunal species within quadrates), core samples of sea grass beds, samples of organisms from small quadrants within macroalgal sites, visual classification of substrata, and measurements of surface and bottom temperature. The information is sent to the global headquarters of NaGISA (the University of Kyoto, Japan). All of this information is then collated in the Ocean Biogeographic Information System. NaGISA is moving toward DNA barcode approaches that can provide near real-time results about changing patterns and invasive species in the places people care about most. This will be a powerful new tool for linking local physical and chemical observations to changing biodiversity.

- **Abundance and Distribution of Calcareous Plankton and Coral Skeletal Density**

The Continuous Plankton Recorder (CPR) survey is currently monitoring these vulnerable organisms in the North Atlantic and Southern Ocean in case these organisms begin to show negative effects of ocean acidification. This information is periodically compiled in an Atlas of Calcifying Plankton.[215] Skeletal density of whole corals is measured uses Archimedes' Principle. The coral is weighed in air and then while suspended in water.[216]

5.3.4 Platforms and the Problem of Under Sampling

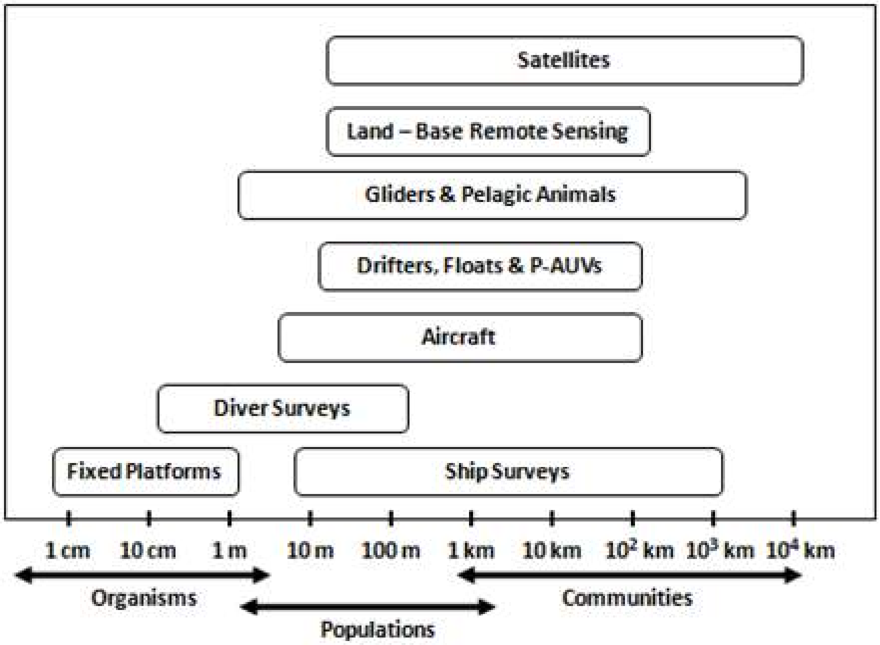

Figure 10. *Changes in ecosystem states reflect the physiology and behavior of organisms, interactions among organisms within species populations, and interactions among populations within communities that constitute the biotic elements of ecosystems. Such interactions occur over a spectrum of space scales that span 10 orders of magnitude from < 1 cm to > 10,000 km that can be captured using a mix of platforms (P-AUV, Powered Autonomous Underwater Vehicle).*

Ideally, data on essential variables are collected synoptically in time and space over a wide range of time-space scales. For pressures and state changes related to global population growth, natural hazards and climate change, this means sampling and modeling a spectrum of time-space variability that encompasses 8 – 10 orders of magnitude (Figure 10).

Given the temporal dynamics, volume, and ecological complexity of the oceans, addressing the problem of under sampling will always be challenging, especially for those variables that cannot be estimated from remote sensing and in the ocean's interior where satellite based observations are not possible. However, the problem can be addressed through the **strategic and simultaneous use of a mix of platforms that enable both remote (section 5.3.2) and *in situ* (5.3.3) sensing and synergies between modeling and observations (section 5.2) optimized to minimize errors and maximize the skill of model-based predictions**. In short, the evolution of a cost-effective system of systems depends to a great extent on leveraging synergies among models, sensors (e.g., synoptic measurements of geophysical, chemical, biological and biophysical variables; calibration and validation of sensors), platforms (e.g., Eularian and Lagranian), and sampling regimes (e.g., resolution in all four dimension, scale-dependent mix of sentinel and reference sites). The challenge is to achieve, sustain and evolve an optimal mix of remote sensing, autonomous *in situ* sensing, ship-based observations, and modeling to deliver quality data streams that exploit synergies between satellite and *in situ* observations cost-effectively.[217]

As reviewed in section 5.3.2, satellites are most useful for providing time-series observations of spatially synoptic surface fields for some essential variables (volume discharge of rivers, vector winds, rainfall, temperature, salinity, currents, waves, shoreline position, chlorophyll-a, salt marshes, mangrove forests, turbidity, and light attenuation). The main challenges here are continuity, validation and increasing temporal, spatial and spectral resolution.

Historically, *in-situ* observations have depended on ships, moorings (including bottom stationed ocean profilers), small boats, piers and divers. Moorings and piers equipped with *in situ* sensors can provide multidisciplinary, long-term (months-years), high resolution time series. However, spatial resolution is generally poor unless large numbers of moorings are deployed simultaneously (which is too expensive for most countries to do routinely). Research vessels provide controlled laboratory environments for precise and accurate measurements of all essential variables and serve as platforms for underway measurements, vertical profiling, and benthic surveys. But ship surveys are slow and expensive. Small boats and ships of opportunity are important exceptions. Small boats are relatively inexpensive and useful for sampling nearshore and estuarine ecosystems. The primary goal of the Ship-of-Opportunity Program (SOOP) is to fulfill upper ocean data requirements established by GOOS and GCOS.[218] Ferries and other ships of opportunity are especially important for deploying sensors with relatively high power requirements and accuracy and for providing data on boundary conditions for numerical modeling. The SOOP Implementation Panel[219] is establishing itself as an operational program and is participating in the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) and its Ship Observations Team (SOT).[220]

While these platforms can support multidisciplinary measurements, they do not provide the required 4-D resolution by themselves. Clearly, programs such as OceanSITES,[221] Repeat Hydrography,[222] Ships of Opportunity (including CPR and Ferry-Box Programs) are critical contributions to GOOS and should be maintained and expanded. But, it is also clear that resolving temporal from spatial patterns of variability with sufficient resolution to minimize problems such as aliasing requires an integrated mix of platforms, i.e., ships, moorings, gliders, pelagic animals, and satellites. At the same time, autonomous *in situ* robotic instruments and sensor networks that enable multidisciplinary observations in 4-D are emerging that will help address these problems. Coordination and integration with ship-based and moored platform observations will enable more effective monitoring (less under sampling) of pressures and changes in the chemical, biological and biophysical indicators of ecosystem states. Major advances are expected over the next decade by expanding the sampling domains of autonomous platforms (to high latitudes and into coastal marine and estuarine ecosystems); through the development of multidisciplinary suites of small, stable sensors with low power requirements; and through data integration from multiple platforms. While additional ships and networks of moorings will be needed, the greatest advances in temporal and spatial coverage will come through cabled observatories, profiling floats, autonomous underwater vehicles (gliders and powered AUVs) and the use of pelagic animals as platforms.

Cabled Observatories[223]

Cabled ocean observatories provide unprecedented amounts of power and two-way bandwidth to access and control instrument networks and platforms and to serve data in real time. Observatories are able to provide support for surface moorings, water column profilers (which can also transmit data via satellite links), benthic boundary layer sensors, powered AUVs and gliders. The latter enable repeat mesoscale observations.

Cabled observatories are being established by Canada (North East Pacific Time-series Underwater Networked, NEPTUNE), Europe (European Seas Observatory NETwork-Network of Excellence, ESONET-NoE and European Multidisciplinary Seafloor Observatory, EMSO), Japan (Dense Oceanfloor Network system for Earthquakes and Tsunamis, DONET), Taiwan (Marine Cable Hosted Observatory, MACHO), and the USA (Ocean Observatories Initiative, OOI). An International Association of Sub-Sea Observatory Operators (IASSOO) is being established to implement expert working groups on sensor interface standards, data exchange formats, quality control procedures, procedures for deep-sea interventions, tests and calibration procedures, contribution to GOOS.

Profiling Floats[224]

The international Argo program is providing the first high volume data coverage of temperature, salinity and circulation in the upper 1000 to 2000 m of the world ocean. Each float transmits data on temperature, salinity and location about every 10 days, and the current global array of ~3,000 profiling floats provides a horizontal resolution (average distance between floats) of ~ 300 km, which is adequate to estimate monthly mean temperature, salinity and heat content of the upper ocean in the ocean basins. In its current configuration, the array does not provide data on coastal ecosystems and is limited to physical measurements for the most part. However, this is likely to change as small, low power biological, biogeochemical and biophysical sensors are developed and groundings are prevented through bidirectional communications via Iridium and Argos-3.[225]

Gliders[226]

Gliders are able to sample areas where high spatial resolution is required including fronts and coastal marine ecosystems. They are relatively small, intelligent, and inexpensive platforms that can be deployed and recovered by small vessels; carry payloads of 2-5 sensors; perform sawtooth trajectories from the surface to depths of 1000-1500m; travel along reprogrammable routes (using two-way communication via satellite) at speeds of up to 40 km/day (25 cm/s); operate during extreme weather (e.g., hurricanes); and operate for up to 8 months with a range of nearly 10,000 km (depending on power requirements of sensors and biofouling). Although gliders are relatively slow, the challenge of obtaining synoptic observations over large areas can be addressed by flying them in coordinated fleets and using them in conjunction with profiling floats and moorings. Gliders operating over continental shelves are equipped with altimeters to avoid grounding. Gliders are able to carry out high resolution measurements of essential variables (e.g., temperature, salinity, dissolved oxygen, chlorophyll-a, toxic algal species, and turbidity) colored dissolved organic matter, and particle size spectra. They can also be used to monitor the travels of large pelagic animals such as whales.[227] At each surfacing, they transmit data and receive new commands via the bidirectional iridium satellite phone system. GPS data can be used to compute average velocities between transmissions.

Repeat transects ("endurance" lines ~ 300 km long) perpendicular to the isobaths from nearshore to the open ocean should be established (Figure 11). In addition to 'small' scale information for regional forecasting models, gliders could then also provide a number of profiles at the boundaries between nested models to be shared by regional and global models. Access to glider-ports is critical. At the same time, transects should be far enough apart to maximize the space-time coverage when considered in the context of remote sensing and other *in situ* observations. Given ~ 120,000 km of global coastline (or shelf break), it has been estimated that about 800 endurance lines are needed to enable more accurate estimates of boundary conditions and fluxes of momentum and properties (nutrients, oxygen, plankton, etc.) across boundaries among coastal ecosystems and between coastal ecosystems and the open ocean. This will also help bridge the gap between basin scale GOOS-GCOS and coastal GOOS.

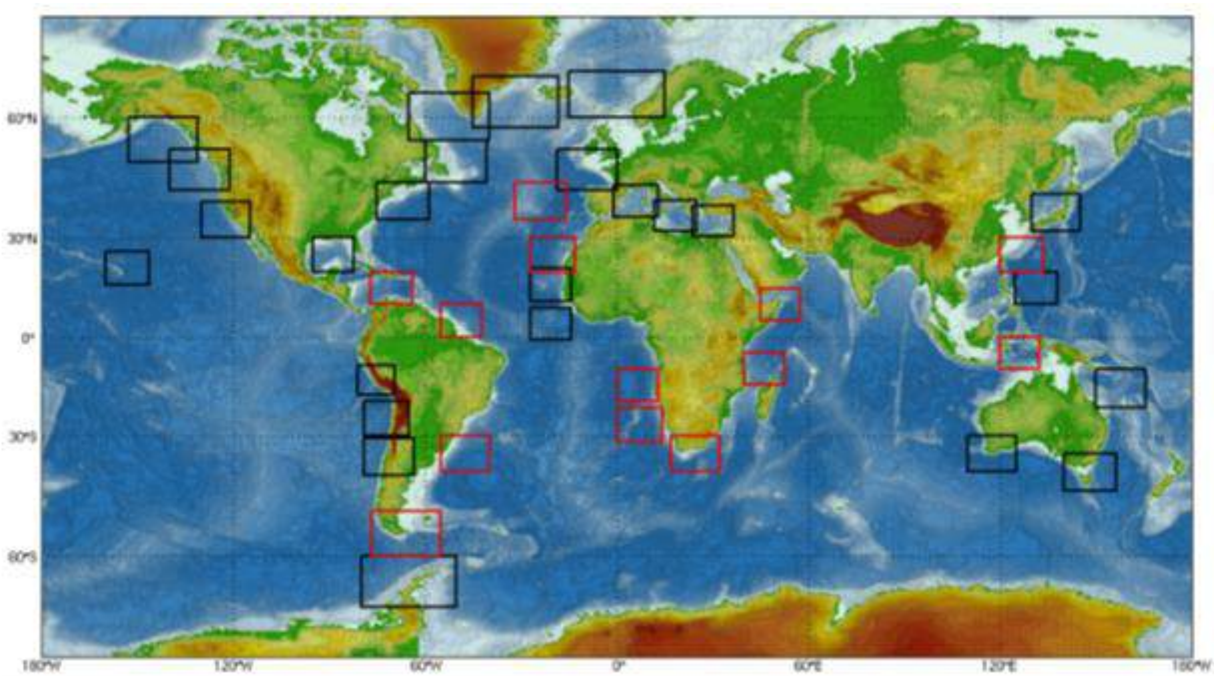

Figure 11. *Map of regions where gliders have been deployed (black boxes) and additional sites of interest for glider transects (red boxes).*[1]

The main drawback of gliders is that they are complex systems and need to be serviced between deployments by highly proficient marine engineers and technicians. Periodic maintenance includes exchange of the batteries, calibration of sensors, updating the hard- and soft-ware. This task requires experts and dedicated facilities (e.g. pressure and calibration tanks). There will always be problems related to corrosion, biofouling, sharks, and collisions with ships. Even so, a global network of gliders would provide a cost-effective, value added contribution to GOOS, and it is recommended that the following actions be taken over the next 10 years:

- Use gliders to enhance the value of key time series observations from moorings, repeat hydrography sections, CPR and VOS lines, fish stock surveys, and acoustic curtains;
- Develop gliders for both multidisciplinary sensing, downloading data from *in situ* sensors (from thermisters to acoustic curtains), and transmitting data to data assembly centers via satellites and fiber optic cables;
- Establish a global network of centers to share resources and expertise, establish standard endurance lines and glider ports, adopt standards and protocols for glider operations and establish a common portal for rapid access to glider data

<u>Powered Autonomous Underwater Vehicles</u>

Powered AUVs are likely to become important platforms for observations in estuaries and other relatively shallow semi-enclosed bodies of water. The "EcoMapper" is an example of such a platform.[228] It has been developed and field tested in estuaries and nearshore marine ecosystems. The vehicle has an endurance of 8-14 hours (depending on the power requirements of the sensor package), can be deployed by one person from the shore or from a small boat, and has can operate at depths of up to 50 m. It can be equipped to measure water quality parameters (temperature, salinity, dissolved oxygen, chlorophyll-a, phycocyanin, phycoerythrin, pH, turbidity), currents and dept. Once deployed, the vehicle communicates while at the surface and acquires a GPS fix at waypoints in the cruise track.

Pelagic Animals (Bio-Logging)

The emerging OTN and GTOPP[229] programs will provide observations that not only complement those supported by man-made platforms; they provide direct observations of the movements of pelagic animals on local to global scales. GTOPP sensors are implanted in highly migratory, apex predators and large organisms, which, unlike Argo floats and gliders, move rapidly along paths that often transect frontal regions as they travel between spawning and feeding grounds.[230] Thus, they adaptively sample their environment based on experience and often retrace previous tracks thereby providing repeat sections over a range of time scales. Some species penetrate deep into polar, ice-covered areas where profiling floats and ships cannot operate.[231] OTN acoustic curtains target migratory corridors over continental shelves (Figure 12) while GTOPP animal migrations cover the ocean basins and polar seas.

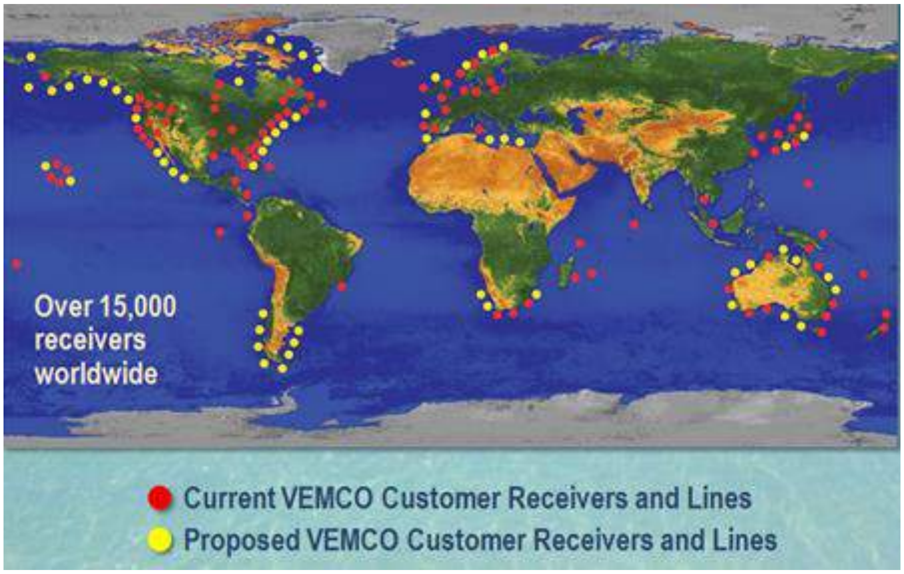

Figure 12. *The emerging Ocean Tracking Network will monitor the passage of tagged fish and receive and transmit data on where larger fish have been, who they have encountered and the environmental conditions they have experienced. VEMCO[1] designs and manufactures underwater acoustic transmitters and receivers for data telemetry*.

Ultimately, an integrated network of sensors on Argo floats, gliders, pelagic animals and remote platforms (satellites and HF radar), coupled with models of ecosystem dynamics and associated biogeochemical cycles, will provide an unprecedented capability to nowcast and forecast changes in the capacity of marine ecosystems to sustain goods and services from coastal estuaries to the global ocean.

5.4 A Global Coastal Network for GOOS

5.4.1 Spatial Considerations for a Provisional Network of Sentinel Sites

In situ measurements of the essential variables (Table 14) are to be made at a global network of sentinel sites (in the form of fixed stations, transects, grids and benthic habitats). These, in concert with remote sensing, are intended to populate the GCN and thereby enable rapid detection of state changes for regional to global scale assessments of ecosystem health, quantification of relationships between pressures and state changes, and evaluations of the efficacy of ocean policies and management actions on local to global scales – all of which are required to anticipate potential impacts with sufficient time to respond appropriately.

Six phenomena of interest have been identified as high priorities for coastal GOOS, and eight related indicators of the state of marine ecosystems were used in Chapter 3 to illustrate end-to-end observing systems (Table 2). Here we offer a provisional set of indicator-based, sentinel sites as a framework for specifying the initial GCN. Sentinel sites were identified based on the following criteria: (1) their ability to monitor key pressures, state changes and impacts as described in Chapter 3; (2) their potential for providing data on multiple indicators for early warnings of impacts and comparative ecosystem assessments on regional to global scales; (3) the presence of monitoring programs and historical time-series of observations that can be used for retrospective analyses (e.g., reanalysis) and (4) their potential for providing observations that can be used to trigger and guide timely adaptive sampling programs in response to episodic events.

Quantifying relationships between pressures and changes in ecosystem states also requires spatial boundaries that define the target ecosystem. Coastal ecosystems come in many sizes and shapes from small estuaries (< 10 km^2) and MPAs to LMEs (1 – 5 x 10^5 km^2). For coastal ecosystems that are not semi-enclosed (topographically bounded) such as LMEs and the open ocean, satellite-based imagery of SST and chlorophyll-a on local to global scales has provided information critical to specifying ecologically relevant boundaries. [232] Given these considerations and the criteria above, estuaries, MPAs and LMEs were targeted in the selection of the provisional set of sentinel and reference site for monitoring ecosystem states given below.

Pressures on Marine and Estuarine Ecosystems

Based on the number of PoIs affected (Table 12), the most significant pressures on coastal marine and estuarine ecosystems are (1) land-based inputs (water, nutrients, sediments and contaminants), (2) over fishing (including destructive fishing practices such a dredging and dynamiting), (3) sea level rise, (4) ocean warming, and (5) ocean acidification.

- Land-based inputs to coastal waters

Twenty rivers representing a broad range of volume discharges and catchment basin population densities are high priorities for monitoring land-based inputs and land-cover/land-use practices in their catchment basins (Table 17). All twenty rivers are part of the Global Terrestrial Network for River Discharge (GTN-R)[233] and should be monitored to provide data needed to compute volume discharge (m^3 day^{-1}) and transports of suspended sediments (often a proxy for inputs of chemical contaminants such as methylmercury and polycyclic aromatic hydrocarbons), dissolved inorganic nutrients (N, P, Si), colored dissolved organic matter (CDOM), particulate organic carbon, and waterborne infectious microbes into coastal receiving waters.

River	LME Receiving Waters	Population Size	Drainage Basin, km²	Discharge, km³/year
1. Ganges *	Bay of Bengal #	472,120,000	1,073,000	240
2. Yangtze * π	East China Sea	433,510,000	1,970,500	560
3. Yellow ǂ	Yellow Sea #	189,000,000	752,000	40
4. Pearl River ǂ	South China Sea #	174,384,000	415,200	150
5. Niger π	Gulf of Guinea #	105,850,000	2,117,700	90
6. Nile π	Mediterranean #	86,430,000	2,881,000	25
7. Danube	Black Sea #	82,000,000	817,000	104
8. Mekong * π	South China Sea #	71,550,000	795,000	250
9. Parana * π	S. Brazil Shelf	51,654,000	2,582,700	280
10. Mississippi * π	Gulf of Mexico #	34,530,000	1,151,000	290
11. Zambezi	Agulhas Current #	30,000,000	1,390,000	54
12. Red π	South China Sea #	28,730,000	169,000	68
13. Vistula	Baltic Sea #	26,247,240	194,400	17
14. Chao Phraya	Gulf of Thailand #	22,456,000	160,400	12
15. Rhine π	North Sea	11,200,000	224,000	35
16. Amazon*	N. Brazil Shelf	10,267,400	7,180,000	2880
17. Yenisey*	Kara Sea	5,005,200	2,580,000	310
18. Lena*	Laptev Sea	4,980,000	2,490,000	270
19. Congo*	Gulf of Guinea #	4,777,500	3,822,000	670
20. Ciliwung	Indonesian Sea #	3,528,000	480	< 1

Table 17. *Rivers of the world ranked by population size of their basins. Thirteen rivers flow into Large Marine Ecosystems with funded (#) programs (Figure 13); nine are in the top 10 rivers in the world based on mean discharge (*); and eight have documented hypoxic zones or areas of interest in their coastal receiving waters (π).*

- Overfishing

The richest fishing grounds in the world are located in LMEs. Of the 64 ecosystems designated as LMEs, sixteen have funded programs.[234] Of these, 8 are ranked very high, 2 high, 4 medium and 2 low in terms of fish catch. These, and fishing hot spots located on Georges Banks and in the Gulf of Alaska, are priority sites for monitoring annual catch statistics (weight, number, length and trophic level) compiled by the FAO (Figure 13).

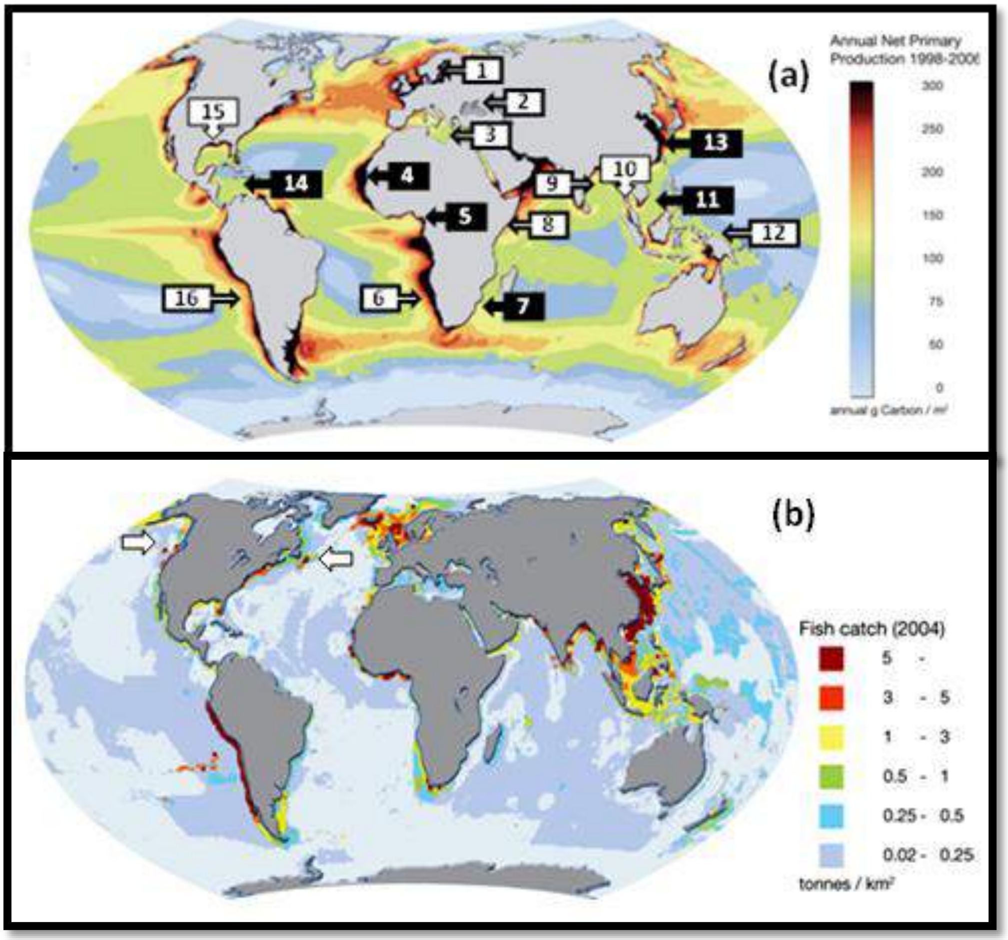

Figure. 13. *(a) Large Marine Ecosystems (LMEs) with programs funded by the Global Environmental Facility are priority sites for monitoring fish catch and catch per unit effort. These are as follows with annual fish catch (VH > 5 tonnes km^{-2}, H = 3-5, M = 1-3, L < 1): 1-Baltic Sea (M), 2-Black Sea (M), 3-Mediterranean Sea (VH), 4-Canary Current (VH)*, 5-Gulf of Guinea (VH)*, 6-Benguela Current (VH), 7-Agulhas Current (L)*, 8-Somali Coastal Current (L), 9-Bay of Bengal (VH), 10-Gulf of Thailand (H), 11-South China Sea (VH)*, 12, Indonesian Sea (M), 13-Yellow Sea (VH)*, 14-Caribbean Sea (M)*, 15- Gulf of Mexico (H), and 16-Humbolt Current (VH). LMEs indicated with white numbers in back squares (*) overlap with species diversity hot spots (Figure 15). These LMEs cover most of the world fisheries hot spots (b) except for those indicated by the arrows in the Gulf of Alaska and the northwest North Atlantic (Georges Banks) which should also be considered priorities for the GCN*.

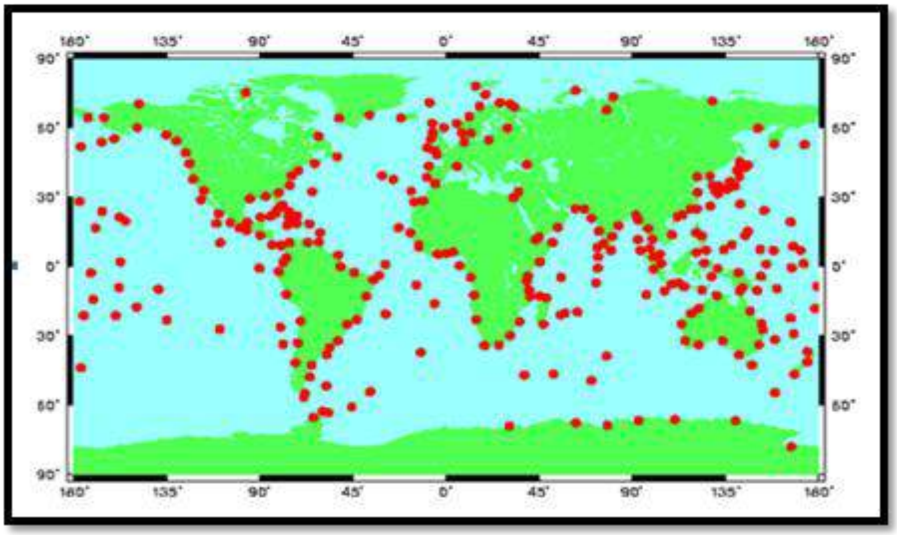

Figure 14. *The core network of GLOSS tide gauges.*

- Sea level rise

High priorities for *in situ* measurements of sea level are the core network of GLOSS sites (Figure 14)[235] and those coastal regions most vulnerable to sea level rise. The latter include Small Island Developing States[236] and the coastal zones of Bangladesh, Belize, China, Djibouti, Egypt, Gambia, Guyana, Indonesia, Japan, Philippines, Suriname, Thailand, United States and Vietnam as well as major port-cities with projected populations of over 2 million vulnerable to flooding (Table 18).[237]

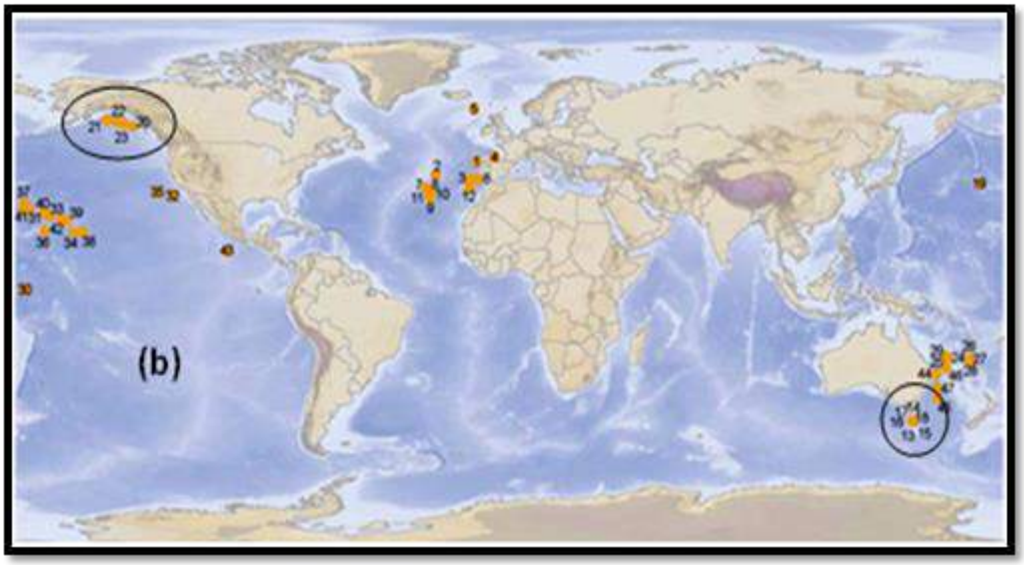

Figure 15. *Biodiversity hot spots associated with coral reef communities: (a) Tropical and subtropical sites of high species diversity based on species richness of fish (1700), warm water corals (804), snails (662) and lobsters (69) and ranked by the number of endemic species with restricted ranges: (1) East China Sea*, (2) Western Australia, (3) Gulf of Guinea*, (4) Great Barrier Reef, (5) Hawaiian Islands, (6) Gulf of California, (7) Lord Howe Island, (8) North Indian Ocean, (9) New Caledonia, (10) Eastern South Africa*, (11) Cape Verde Islands*, (12) West Caribbean*, (13) Red Sea, (14) Philippines*, and (15) South Mascarene Islands (* Sites, black ovals, that overlap with or are encompassed by Large Marine Ecosystems, see Figure 13). Yellow dots show the location of seamounts. (b) Locations of seamounts from where coral and non-coral species data were compiled for the biodiversity analysis. Priority seamounts for monitoring are circled (Gulf of Alaska – Dickens, Giacomini, Pratt and Welker; Southern Ocean – Andy's, Dory Hill, Hill 38, Macca's and Main Pedra).*

- Ocean warming

To assess the impacts of ocean warming on marine ecosystems, high priority sites for monitoring SST are coastal ecosystems with high endemic species diversity (Figure 15), CPR lines at high latitudes (e.g., the Southern Ocean south of Australia and northeast North Atlantic including the North Sea), river gauges near the mouth of major rivers (Table 17), and tide gauges at GLOSS stations.

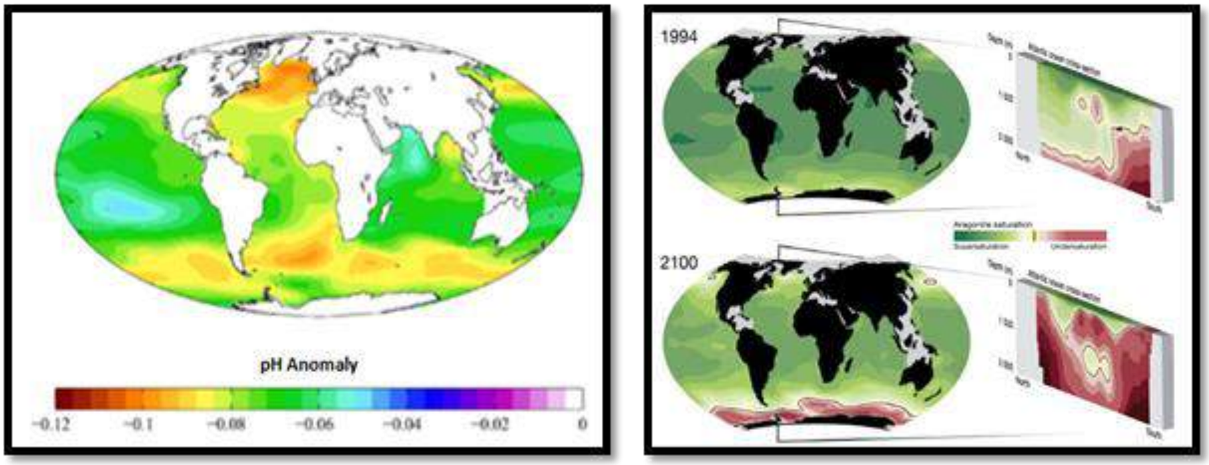

Figure 16. *Change in sea surface pH caused by anthropogenic CO2 between the 1700s and the 1990s and aragonite saturation levels (2100 projected). Projections suggest that Southern Ocean surface waters will begin to become under saturated with respect to aragonite by the year 2050 (Orr et al., 2005). By 2100, this under saturation could extend throughout the entire Southern Ocean and into the subarctic Pacific Ocean. Studies have suggested that conditions detrimental to high-latitude ecosystems could develop within decades, not centuries as suggested previously.*[100]

- Ocean acidification

An ocean carbon observatory network is needed for sustained monitoring key variables (pH, pCO_2, A_T, DIC, temperature, salinity, and aragonite saturation state) needed to predict the effects of ocean acidification on marine ecosystems.[238] Outputs of monitoring are necessary precursors for forecasting the impact of ocean acidification on living marine resources. An observatory network is a prerequisite for further developing and validating models of ocean acidification. Based on pH anomalies and levels of aragonite saturation, high latitudes are expected to experience extremes in ocean acidification (and exert the greatest stress on marine communities), especially in the Southern Ocean where the aragonite saturation depth is expected to shoal most rapidly (Figure 16).[239]

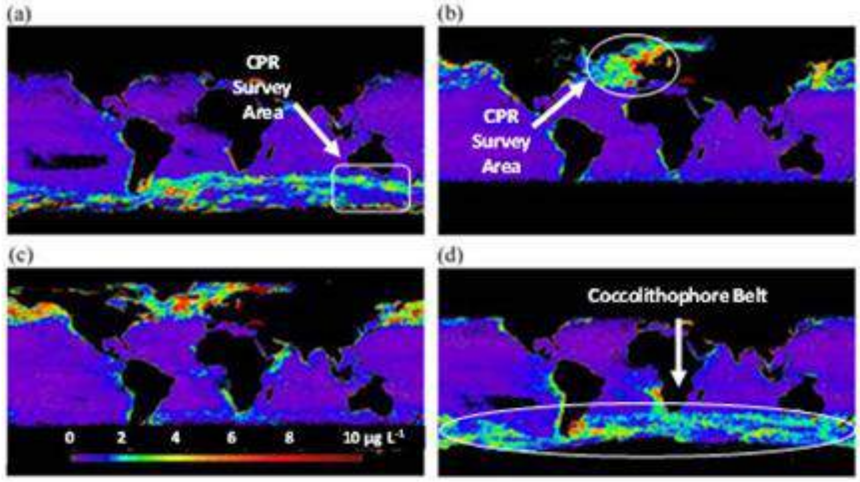

Figure 17. *Suspended particulate inorganic carbon concentrations (an indicator of the abundance of the coccolithophore E. huxleyi) from MODIS/Terra for (a) January–March. (b) April–June. (c) July–September. (d) October–December. CPR surveys south of Australia and in the NE North Atlantic are high priorities for estimating the distribution and* abundance of *Limacina* spp. and E. huxleyi.

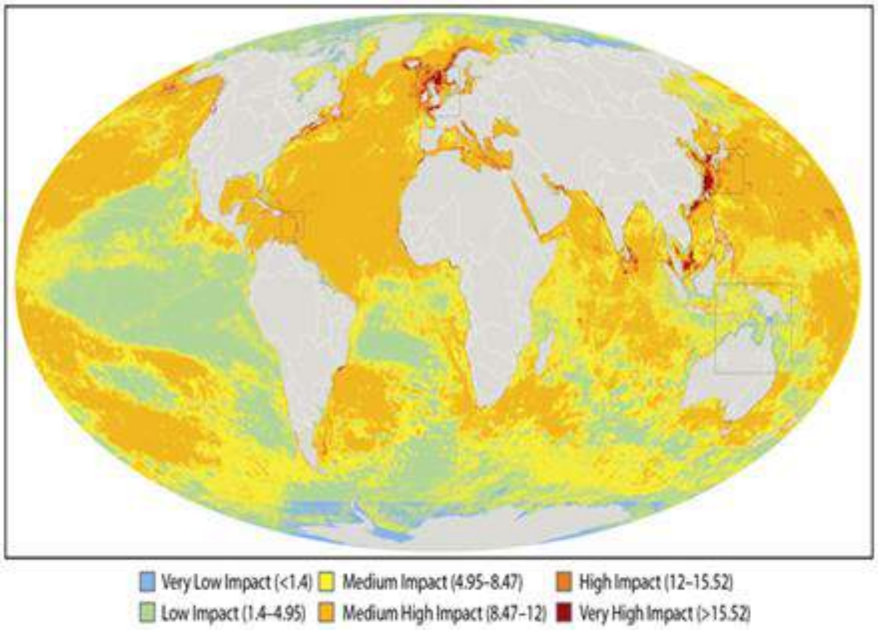

Figure 18 *Global map of cumulative human pressures on marine ecosystem*.

Thus, high priority sites for monitoring ocean acidification (pH, temperature, total alkalinity, and saturation levels of aragonite) are the "Great Southern Coccolithophore Belt" of the Southern Ocean (Figure 17), along CPR survey routes in the Southern Ocean and the northeast North Atlantic Ocean, and over seamounts in the Gulf of Alaska and the Southern Ocean (Figure 15).

- Integrated Indicator of Human Effects

Halpern et al.,[240] developed a standardized, quantitative method, on the basis of expert judgment, to estimate ecosystem-specific differences in the effects of seventeen anthropogenic pressures including fishing (artisanal, pelagic, demersal, bycatch), land-based inputs (organic and inorganic pollution, nutrients), invasive species, oil rigs, coastal population density, commercial shipping, ocean warming, and ocean acidification. The results provided impact weights used to combine multiple drivers into a single comparable estimate of cumulative human impact on 20 ecosystem types (Figure 18). Highest impacted regions are Greenland, North, and Baltic Seas; Gulf of Thailand and Java, Flores, Celebes and South China Seas; and the East China and Yellow Seas. Lowest impacted regions are the Brazil Current; Benguela Current and Gulf of Guinea; the Arafura, Coral and Tasman Seas; and the Antarctic Circumpolar and Falkland Currents.

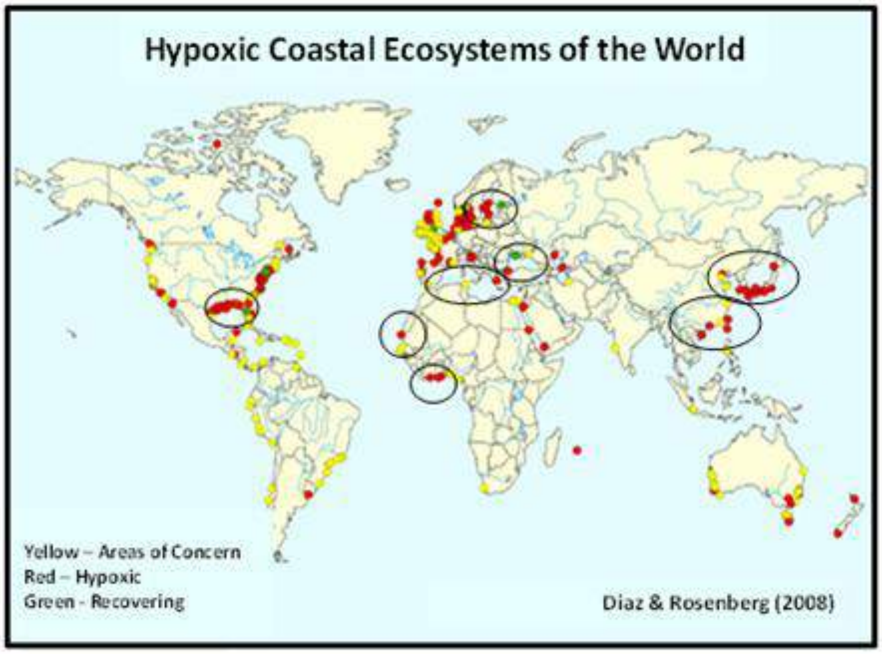

Figure 19. *Sites with depleted bottom water dissolved oxygen levels (red dots < 2 ppm) in 2008. Sites in black ovals are located within Large Marine Ecosystems (Figure 13).*

Ecosystem States

- Indicators of effects of coastal eutrophication (section 3.1)

Accumulations of phytoplankton biomass and bottom water hypoxia are indicators of coastal eutrophication caused by high inputs of nutrients and organic matter during the phytoplankton growth season (from all year in the tropics to seasonal at higher latitudes). Given relationships between nutrient inputs (riverine transport, upwelling and marginal ice zones of the Arctic and Southern Oceans), phytoplankton biomass and the development of bottom water hypoxia, priority monitoring sites are LMEs exposed to major river discharges (Table 16), areas that consistently experience bottom water hypoxia on seasonal time scales or longer (Figure 19), and Eastern Boundary Current LMEs characterized by their upwelling regimes (Canary Current, Gulf of Guinea, Benguela Current, and Humboldt Current).

- Indicators of the effects of exploiting fish stocks (section 3.7)

Monitor harvestable fish stocks in LMEs and fisheries hot spots that are not located in funded LMEs, i.e., the northeast North Atlantic, the North Sea and the Gulf of Alaska (Figure 13) and long term changes in the diversity, distribution and abundance of large marine animals as they move through migratory corridors between spawning and feeding grounds (Figure 20).[241]

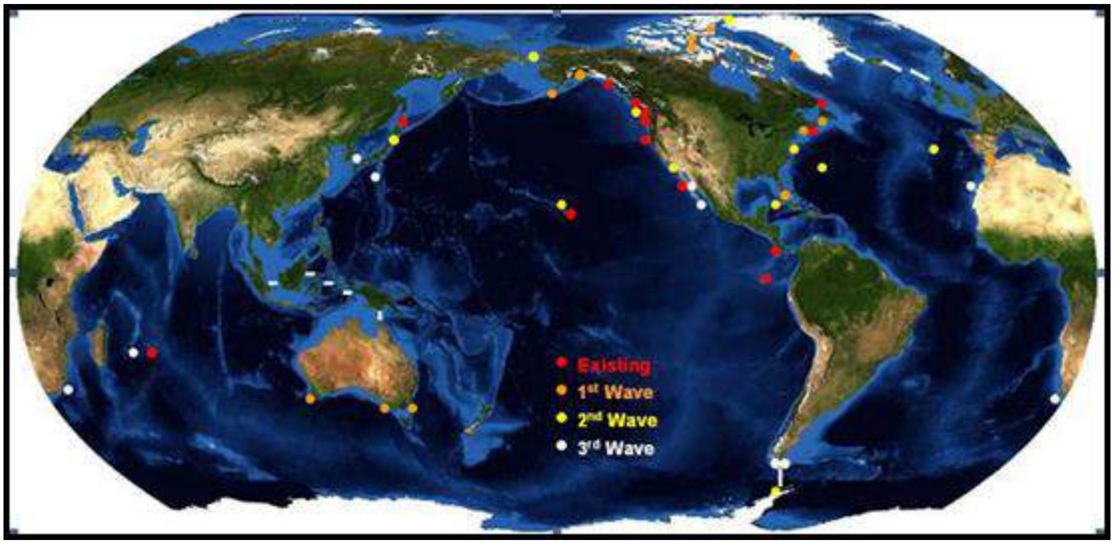

Figure 20. *The Ocean Tracking Network (OTN) is being implemented globally in stages by deploying acoustic curtains across major migratory corridors ("blue highways"). The anticipated global scope of the OTN project, showing existing partner equipment in red, tentatively funded installations for the next three years in orange and yellow and larger scale deployments under consideration in white.*

- Indicators of vulnerability to sea level rise and coastal flooding (section 3.5)

Map the spatial extent and continuity (degree of fragmentation) of ecological buffers (coral reefs, sea grass beds, mangrove forests, salt marshes, sand dunes, and barrier islands) to coastal flooding in river deltas (Table 17), coastlines of major port cities most vulnerable to flooding (Table 18), and low lying islands of Small Island Developing States.

- Indicators of the effects of ocean warming (sections 3.4 and 3.7)

Given the importance of temperature as a parameter of growth for all living organisms and the incidence of microbial pathologies in marine organisms,[242] a cross section of biological indicators is recommended from plankton and pathogens with relatively rapid response times to biologically structured habitats with relatively long response times. Indicators to be monitored include pathologies in coral reefs (bleaching), sea grass beds (wasting disease) and mangroves (fungal infections); the species diversity of the communities of organisms these habitats support; the zoogeography of sentinel species[243] of copepods in the North Atlantic; and the phenology of spring-summer phytoplankton blooms initiated along the ice edge during the spring-summer melt in the Arctic Ocean.

Coral reefs fringe ~ 15% of the world's coast lines and support hundreds of thousands of animal and plant species.[244] Their existence is threatened by ocean warming (e.g., bleaching). Analysis of the distribution of 3,235 species in coral reef communities (corals and reef fish, snails and lobsters) revealed biodiversity "hot spots" characterized by their high diversity of endemic species with restricted ranges that make them vulnerable to extinction.[245] The fifteen highest ranked (based on the number of species with restricted ranges) hot spots are identified here as priorities for *in situ* monitoring (Figure 15). Six of these hot spots are in LMEs (Figure 13) and most are adjacent to terrestrial biodiversity hotspots. The Philippine diversity hot spot and the Indonesian Sea LME are within the "Coral Triangle", a network of coral reefs, mangrove forests, sea grass beds and estuaries that support the highest diversity of species in the world.[246]

CPR surveys[247] in the North Atlantic and North Sea over the last 50 years show a progressive movement in the distributions of warm-water species, temperate species, and subarctic species toward the Arctic Ocean.[248] Over the same period, the abundance ratio of *Calanus helgolandicus* (a warm-temperate species) to *C. finmarchicus* (a cold-temperate species) has increased dramatically in the North Sea.[249] These trends and associated changes in species diversity have important implications for the sustainability of marine fisheries in the North Atlantic and, to the extent that they indicate similar trends in the global ocean, to marine fisheries in general. Data from all surveys should be incorporated into integrated assessments of the marine ecosystems they represent.

The OTN (Figure 20) will enable observations of the migration patterns of iconic megafauna on the scale of ocean basins as they search for food and travel to their nursery grounds. The locations of these feeding and nursery grounds will change as the oceans warm and become more acidic, so the longer term effects of climate change should be reflected in shifting migration patterns. Thus, many of the ocean's large predators are valuable as sensitive indicators of changing conditions in the physical oceans as well as the lower trophic levels.

Warming has been most pronounced across the Arctic Ocean and along the Antarctic Peninsula, with significant decreases in the spatial extent and seasonal duration of sea ice. As the extent and seasonal duration of sea ice decreases, resulting changes in the timing and magnitude of seasonal phytoplankton blooms will impose asynchronies and spatial separations between food requirements of zooplankton and juvenile fish and their food supplies (phytoplankton).[250] Such mismatches are likely cause decreases in reproductive success and recruitment into populations of living marine resources.[251] Phytoplankton blooms in the marginal ice zone (areas in which ice concentration is consistently < 10% over the last 20 days) occur in all seasonally ice-covered areas from spring to late summer and typically peak within 20 days of ice retreat.[252] Using maps of sea-ice concentration estimated from satellite-based remote sensing[253] to guide the timing of operations, conduct ship-based surveys in marginal ice zones of the Barents and Bering Seas during spring-summer to validate satellite based estimates of sea surface chlorophyll-a fields, fill in temporal and spatial gaps in ocean color imagery due to cloud cover, and estimate the volume and depth of buoyant plumes from ice-melt.

- Indicators of the effects of ocean acidification (section 3.6)

Calcareous organisms (e.g., cold water corals and mollusks and planktonic Thecosomata and coccolithophores) are likely to suffer from the effects of ocean acidification (Figure 16), especially if also stressed by ocean warming and land-based inputs of nutrients and sediments. Taxa of sentinel species include Scleractinia (cold water, stony corals), Thecosomata (e.g., *Limacina* spp.), and Coccolithophoridae (e.g., *Emiliania huxleyi*). For planktonic sentinel species, high priority monitoring sites are the "Great Southern Coccolithophore Belt" of the Southern Ocean and CPR survey areas in the Southern Ocean and the NE Atlantic Ocean (Figure 17).[254]

The Census of Marine Life has revealed the vulnerability of habitat-forming stony (scleractinian) corals (and by proxy a diverse assemblage of other species including harvestable fish species) to ocean acidification and trawling on seamounts.[255] Cold water stony coral communities are commonly found on seamounts throughout the world's oceans at temperatures of 4-12°C and within a depth range of 200-1000 m (optimal habitat suitability 250 – 750 m). Seamounts attract prey and provide a wide range of environmental gradients that support high species diversity, an effect that cascades to top predators such as marine mammals.[256] Cold coral communities on seamounts in waters most vulnerable to ocean acidification and for which coral and non-coral species data have been compiled can be used as baseline conditions for assessing effects of aragonite under saturation as indicated by changes in the spatial extent and abundance. Suitable seamount habitats are found in the Southern Ocean and the Gulf of Alaska (Figure 15).

- Indicators of threats to human health (sections 3.2 and 3.3)

High priority sites for monitoring waterborne enteric bacteria are warm (summer in temperate and subpolar latitudes, all year in tropical and subtropical latitudes) coastal waters of recreational beaches, fishing grounds and shellfish beds near large urban areas and rivers that receive large municipal waste discharges and runoff from animal farms (Tables 17 and 18). These are sites where global and regional scale risks of human exposure to infectious microbes are greatest as a consequence of the combination of ocean warming and risk of coastal inundation. Priority sites for toxic phytoplankton events are those that have a history of toxic phytoplankton events near recreational beaches, fishing grounds and shellfish beds. Given the global problem of PSP (Figure 21), sites with a history of PSP should be the initial priority for monitoring.

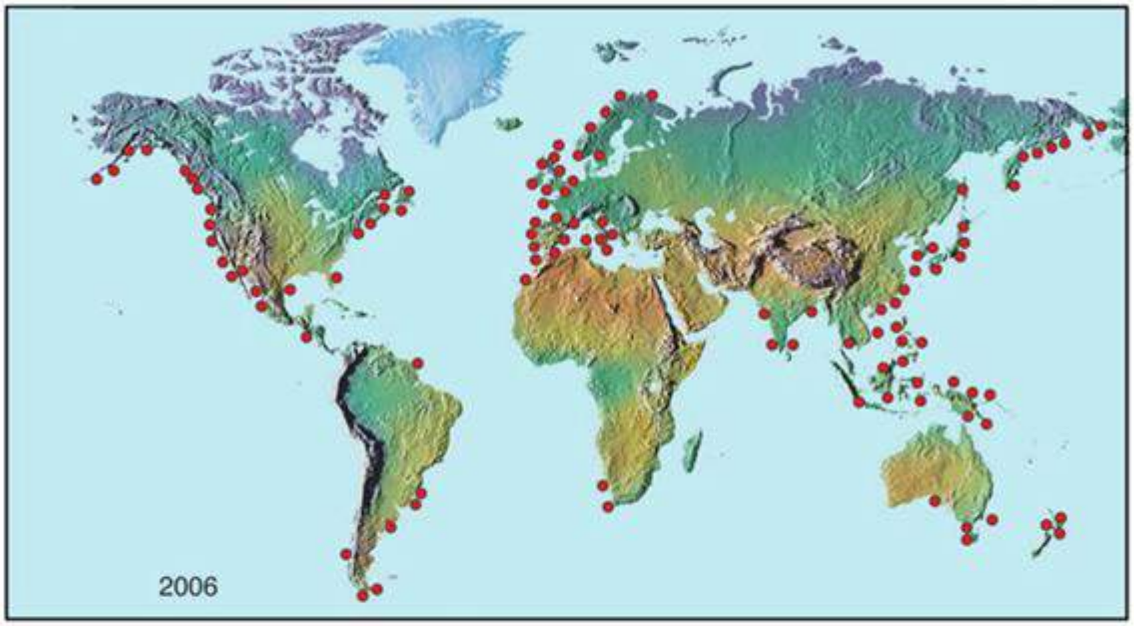

Figure 21. *Global distribution of Paralytic Shellfish Poisoning (PSP) events caused by dinoflagellates (Pyrodinium bahamense var. compressum, Alexandrium tamarense, and Gymnodinium catenatum) in 2006.*

- Indicators of Resilience to Ecosystem Pressures (Ecosystem-level indicator)

Biodiversity underpins the capacity of ecosystems to provide goods and services valued by society. A growing body of scientific evidence indicates that the maintenance of biodiversity and the provision of ecosystem services is critical for sustaining ecosystem health and resilience in the face of multiple ecosystem pressures including modification and loss of habitats, over fishing, land-based inputs of excess nutrients and contaminants, ocean warming and ocean acidification.[257] In this regard, managing for marine biodiversity is likely to become an important parameter of marine spatial planning and for providing early warnings of invasions by non-native species.[258] Thus, status and trends of biodiversity may serve as a "**master indicator**" for informing IEAs and evaluating the efficacy of EBAs.[259]

Key measures of biodiversity are the variety of benthic habitat types within regions (e.g., sea mounts, coral reefs, seagrass beds, mangrove forests and tidal marshes), species richness associated with habitat types, and species richness within pelagic ecosystems.[260] Priority groups for estimating species richness are marine mammals, coastal fishes, sharks, macrozooplankton and corals.[261] High priority sites for monitoring biodiversity are biodiversity hot spots (Figure 22).

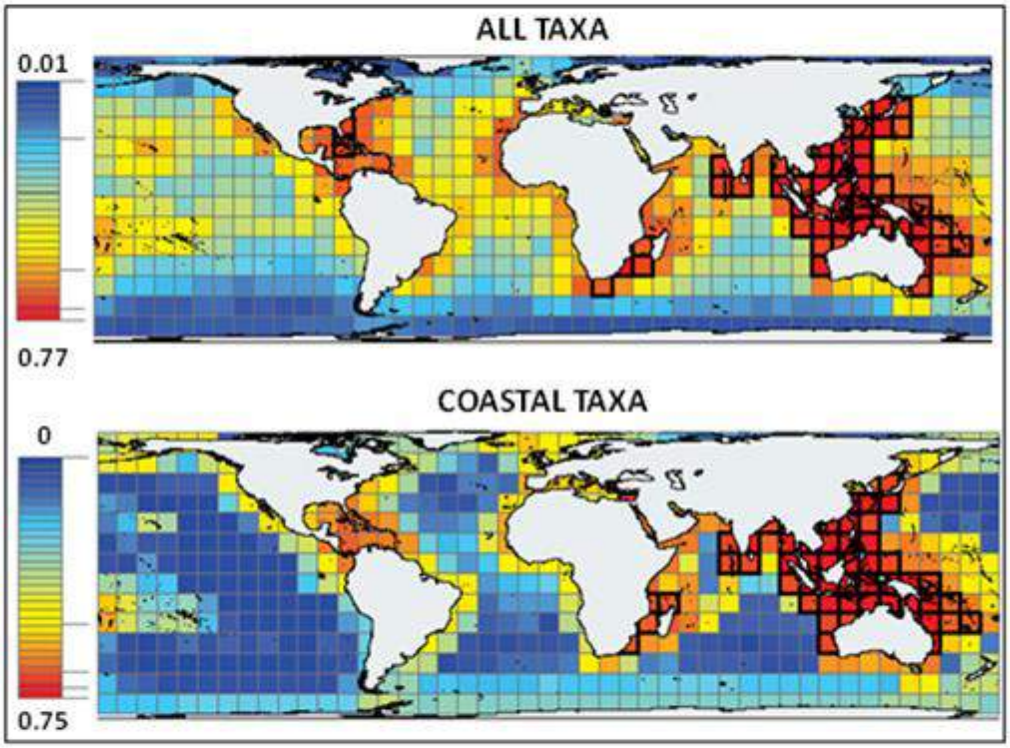

Figure 22. *Distribution of mean species diversity across all taxa (coastal and oceanic) and coastal taxa. By normalizing diversity for each taxon, then averaging across all taxa present in each cell, a synthetic pattern of mean diversity was derived.[1] The highest mean diversity occurred in hotspots around the Philippines, Japan, China, Indonesia, Australia, India and Sri Lanka, South Africa, and the Caribbean and southeast USA. Coastal species groups tended to be disproportionally concentrated in Southeast Asia.*

5.4.2 Spatial Considerations for a Provisional Network of Reference Sites

Given that all marine ecosystems have been perturbed in some way by human activities and climate change, the best that reference (or control) sites can offer is as much contrast with sentinel sites as possible. Marine reserves can provide such a contrast in terms of the exploitation of living marine resources and associated loss of habitats. As of 2010, 5,800 marine protected areas (MPAs) have been identified that cover a little over 1% of the oceans globally. Of these, only a small fraction are marine reserves (also referred to as "no-take zones", "integral reserves", "fully protected areas", and "marine nature reserves") that do not allow removal of living marine resources or the destruction of benthic habitats.[262] There are 124 marine reserves for which peer-reviewed scientific analyses have been made on the effects of no-take zones on the biomass, density, size and diversity of fishes, invertebrates and seaweeds.

Likewise, those marine reserves that experience minimal land-based inputs, warming, acidification and sea level rise can serve as reference sites against sentinel sites for these pressures. In addition to these open water MPAs, Ramsar sites specifically target wetlands of international importance, recognized globally for the conservation and wise use of wetlands. Currently, there are 160 Contracting Parties to the Ramsar Convention.[263] Upon joining, the Party agrees to designate at least one wetland site for inclusion in the List of Wetlands of International Importance (Ramsar Sites). The main objective of this key obligation is "to develop and maintain an international network of wetlands which are important for the conservation of global biological diversity and for sustaining human life through the maintenance of their ecosystem components, processes and benefits..." Ramsar sites most relevant to coastal GOOS are tidal marshes, mangrove forests, seagrass beds and coral reefs located along the coastline.

5.4.3 A Global Network of Sites, Platforms and Sensors

Given the rationale for an ecosystem-based observing system of systems (sections 5.5.1 and 5.5.2), the highest priority for the initial GCN is to target LMEs (Figure 13a), hot spots for species diversity (Figures 16 and 23) and fishing pressure (Figure 13b), and marine reserves. These areas include both sentinel and reference sites and are among the most productive and biologically diverse ecosystems on Earth.

Satellite-based remote sensing and airborne LIDAR surveys (section 5.3.2), combined with GLOSS and the GTN-R (section 5.3.3), provide the operational capability for integrated estimates of shoreline position, near shore bathymetry and topography (erosion, susceptibility to coastal inundation), sea level (coastal inundation), the volume discharge of major rivers (key component of the water cycle and indicators of land-based inputs), and sediment loads (erosion, light penetration, and indicator of chemical contaminants) as well as other physical, biological and biogeochemical assessments worldwide.

As described in section 5.3.4, a mix of platforms (ships and boats, profiling floats, gliders, large pelagic predators, moorings, cabled benthic observatories and piers) will be needed for *in situ* measurements in order for observations (remote and *in situ* sensing) to capture the full spectrum of variability characteristic of coastal ecosystems (Figure 10). These observations are used to both complement and validate satellite-based observations. Coordinated development of several operational and pre-operational programs should be a high priority for implementation. These include the following:

- Use existing fixed platforms and deploy new ones in nearshore coastal waters to extend OceanSites and the proposed network of ocean acidification monitoring sites[264] into targeted coastal ecosystems;
- Extend ship-based, repeat hydrography[265] section into targeted coastal ecosystems;
- Coordinate development of a global network of glider-based cross shelf transects with the development of the OTN, GTOPP and seafloor observatories;
- Develop SOOP (JCOMM) and VOS (WMO) to support more lines and the use of both ferry box and CPR technologies on the same vessels operating in coastal waters; and

- Strategically locate cabled, benthic observatories to support glider operations and OTN acoustic curtains and to provide observations of both sentinel and reference sites.

Existing data providers (section 5.7.2) are the building blocks of the initial network of observations. *In situ* sensing focuses on category 1 variables (dissolved oxygen, nitrate, ammonium, and phosphate; fCO_2, pH, spectral attenuation of downwelling irradiance, chlorophyll-a, spatial extent of coral reefs, seagrass beds, mangrove forests and salt marshes) and passive acoustic recorders (Ecological Acoustic Recorders, EARs). While EARs provide data on biodiversity, this technology is limited to organisms that produce species-specific sounds. Delayed modes of sampling and analyses to monitor biodiversity will be needed. These should target four communities of organisms: (1) planktonic microbes (relatively rapid response), (2) meso- and macro-zooplankton, (3) epiphytes associated with warm water coral reefs, and (4) nearshore benthic communities (relatively slow response). Finally, the initial GCN should include observations of the abundance and distribution of calcareous plankton and coral skeletal density. Technologies and rationale for these are described in section 5.3.3.

5.5 Data Management and Communications

5.5.1 Overview

A revolution will be required in the ways in which data are managed and communicated to guarantee public access and to deliver real-time data and products, when required. This is arguably the greatest challenge to successful implementation of the ecological and biogeochemical aspects of GOOS. Within a few years, the volume of non-physical data on marine ecosystem states will explode. The extent to which the ecological and biogeochemical aspects of GOOS will be operationally useful and scientifically relevant depends on the development of an efficient data management and communications system. As the link between observations and modeling and the primary mechanism for integration, data management and communications (DMAC) is of central importance to the development of an interoperable SoS. DMAC for the coastal GOOS must have the following capabilities: (1) process and archive data on the essential variables according to scientifically sound and well-documented standards and formats; (2) archive and support all relevant data types (in situ measurements, remote sensing and model outputs) in near real-time and delayed mode (post-quality control) as required; and (3) enable access to these data and derived products (e.g., indicators, nowcasts, forecasts, alerts and warnings) by users who have a broad range of capabilities and responsibilities (e.g., from scientists and operational agencies that need raw data to coastal zone, environmental and resource managers who need derived products). In short, the DMAC infrastructure (Figure 23) must evolve to reduce the time required for users to discover, acquire, process and analyze multidisciplinary data of known quality from multiple sources.

These functions will be achieved most effectively by establishing a hierarchical distributed ***network of networks* that evolves incrementally by linking, enhancing and building on existing national and international observing system assets**. For data management, these include the JCOMM Specialized Oceanography Centers (SOCs),[266] the International Oceanographic Data and Information Exchange (IODE) network and the Responsible National Oceanographic Data Centers (NODCs) that populate it, the Global Biodiversity Information Facility (GBIF), the Ocean Biogeographical Information System (OBIS, now under the auspices of IODE),[267] and the Global Runoff Data Center (GRDC).[268]

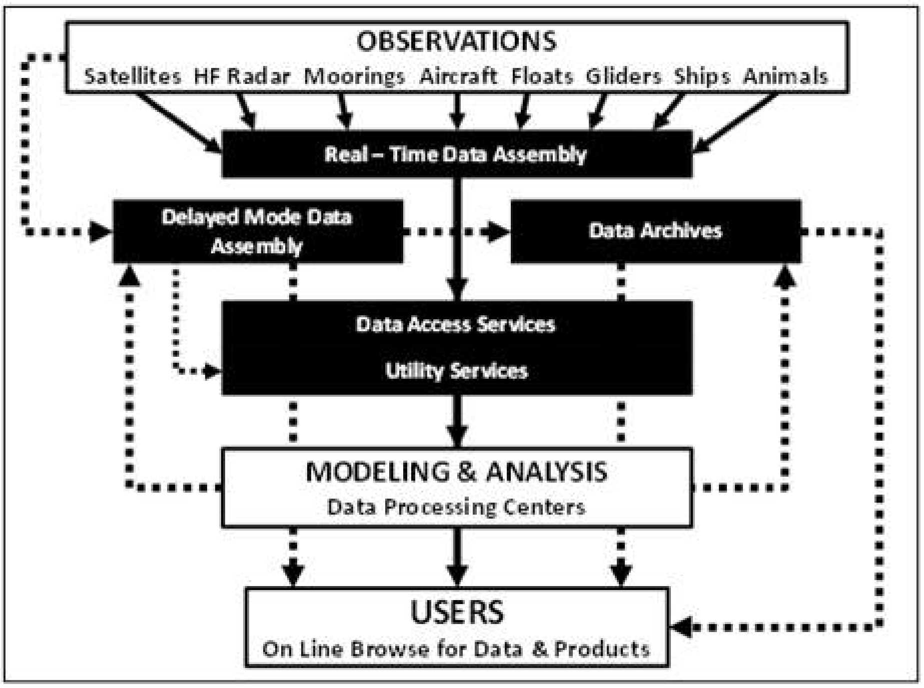

***Figure 23**. The DMAC subsystem (black boxes) links observations and models to create a tightly coupled, "end-to-end" observing system. Data flow from sensors to data assembly centers in both real-time (solid lines) and delayed mode (dotted lines). All data flow through data assembly centers before they are archived. Model generated data are also archived. Users have access to data and products from data assembly centers and archives in real-time and delayed mode. Partitioning of functions does not mean they are performed by different centers or groups, e.g., both real-time and delayed mode data may be assembled at the same center, and data assembly, archiving and processing may take place at the same center.*

Coastal GOOS will be built using a service-oriented architecture (SOA) approach in which existing and new observing systems are 'exposed' via internet-based services that enable a flexible and interoperable data access environment (Figure 24). A priority for establishing GEOSS is to maintain and expand the underpinning observing systems (GCOS, GOOS and GTOS). In this context, **the GEOSS Common Infrastructure** (GCI, GEO Task AR-09-01) [269] provides a framework for growing the data and communications infrastructure for coastal GOOS. Access to a service-based **clearinghouse** (providing information on where data can be found) and associated **registries** (containing information on GEOSS infrastructure, services, standards, capacity building and best practices) are provided via the **GEO web portal**. The GCI also provides a process to register, discover and use numerous services accessible using GEOSS interoperability arrangements. GCI is federated in that data holdings remain with the data providers who can choose either to adopt standard practices and arrangements or contract with another entity to do so on their behalf. Development of the GCI is being facilitated by an

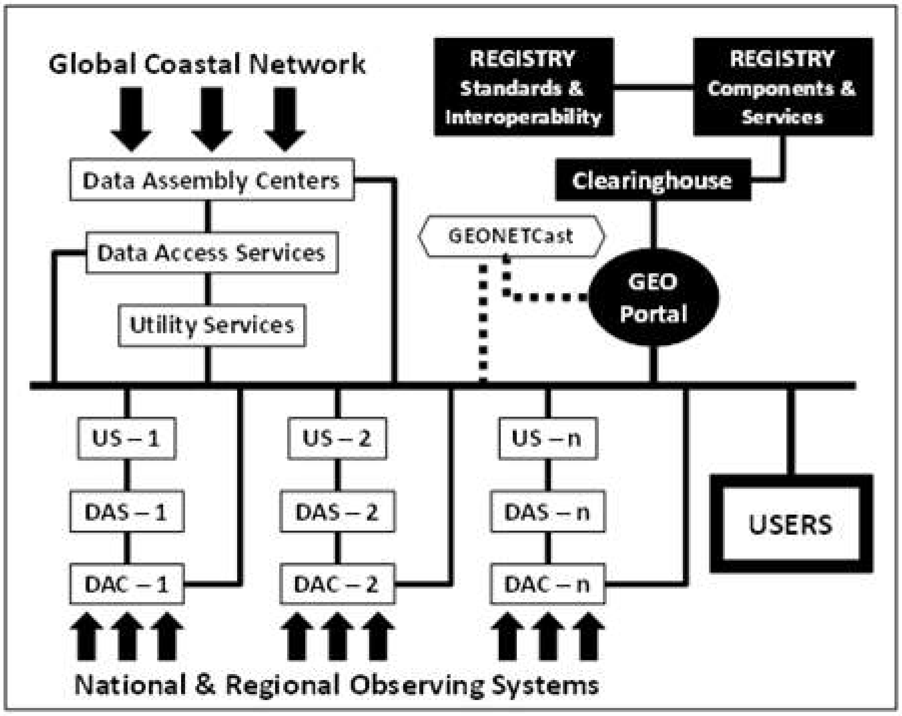

Figure 24. *Service-Oriented Architecture for coastal GOOS (white boxes: US – Utility Services, DAC – Data Access Services, DAC – Data Assembly Centers) with linkages to the GEOSS Common Infrastructure (black compartments). Data dissemination and access are via the internet (thick horizontal line) and satellite-based communications systems (dashed line).*

Architecture Implementation Pilot Project which includes phased development of the clearinghouse and associated registries.[270]

5.5.2 Interoperability

To achieve the societal benefits of GOOS (Table 2), the IOC, WMO and GEO have agreed that there must be full, open and timely (minimum delay) exchange of data, metadata[271] and products among participating organizations and countries; and such exchanges should not exceed the cost of making the information available.[272] Establishing a network of networks that meets these expectations and enables the integration of diverse data from multiple sources requires interoperability within and among networks, i.e., the capacity to exchange, access, and process data from different sources seamlessly (Box 4). This can only be achieved through the use of common standards and protocols for data formats, data representation, metadata (including QA/QC variable-specific protocols based measurement techniques), access services, and utility services.

Box 4

Data Integration Framework (DIF) Pilot Project of the U.S. IOOS Program Office <http://www.ioos.gov/dif/>

In 2007, the IOOS Program Office of the lead federal agency (NOAA) launched a 3 year DIF pilot project to demonstrate the benefits of data integration. Interoperability tests revealed differences in metadata and data formats that prevented direct integration and assimilation of data for the same variable from 3 DACs within NOAA (National Data Buoy Center [NDBC], Center for Operational Oceanographic Products & Services [CO-OPS], and CoastWatch). Using data on 7 essential variables (water temperature, salinity, sea level, currents, waves, sea surface winds and ocean color), the DIF addressed this problem by implementing four user-driven end-to-end systems to demonstrate the value-added of integration (blended data sets) and timely access to data from multiple sources. Priority was placed on the development of common data formats for use by data providers and web services for data access services. The project was conceived as the first step toward full implementation of the data management and communications subsystem of the U.S. Integrated Ocean Observing System. Key legacies of the project are as follows:

<u>Data & Information Exchange</u>

Established the use of a core set of standards and conventions that enable data interoperability (models and observations) among regional ocean observing systems within the U.S. EEZ and national coastal networks.

Increased the volume of data (number of data sets) available via DACs for predictions (harmful algal blooms, coastal inundation and hurricane intensity) and integrated ecosystem assessments.

<u>Data Access Services</u>

Adopted Open Geospatial Consortium (OGC) web services and encoding conventions for geospatial data as follows:

Data Type	Web Service	Encoding
In situ observations (e.g., in situ point or profile data, time series, trajectories	Sensor Observation Service (SOS)	XML – Geography Markup Language (GML) based on Observations & Measurements for data; Sensor Model Language for metadata
Gridded observations (model outputs, level 3 satellite data, HF radar)	Data Access Protocol (DAP), Web Coverage Service (WCS)	Binary – Network Common Data Format with Climate & Forecast Conventions (CF/NetCDF)
Images of data (e.g., maps)	Web Map Service (WMS)	Common image formats (PMG, TIFF, GIF, JPEG)

For *in situ* observations, data on 6 essential variables (temperature, salinity, sea level, currents, waves, and winds) are being served by NDBC, CO-OPS and Regional Associations (operating regional ocean observing systems in the US EEZ) using the SOS. For gridded observations (ocean color), CoastWatch has implemented OPeNDAP (Open-source Project for a Network Data Access Protocol) to serve ocean color and HF radar data.

<u>Processing</u>

The NDBC THREDDS (Thematic Realtime Environmental Distributed Data Services) Data Server supports both OPeNDAP and OGC-Web Coverage Service providing gridded surface currents derived from high frequency radar.

Enhanced SLOSH (Sea, Lake and Overland Surges from Hurricanes) Display Program for integrating water level and wind observations with SLOSH model output.

Assimilating *in situ* current observations to increase the skill of model-based forecasts of HAB trajectories.

5.5.3 Data and Information Exchange

Data assembly centers (DACs) assemble data and provide data and products needed by modeling and data assimilation systems (e.g., nowcasts, forecasts, assessments, scenarios) as well as products directly useable for applications (e.g., SST, wave, current and chlorophyll fields derived from satellite-based observations). Most incoming data from sensors, models and laboratory measurements are in data structures specified by the manufacturers, the telecommunications system, or the provider. Once received by a DAC, the data are converted (if necessary) into formats used for data exchange in "real-time" (up to a few hours old for meteorological data and 30 days for oceanographic data) or a less timely, delayed mode exchange. Data are quality controlled,[273] linked to metadata, made available to users and transmitted to archives via data access and dissemination services.

The GEO portal provides an entry point to the GEOSS Common Infrastructure enabling access to Earth observing data, information and services (decision support tools such as maps and forecasts). The GEO portal allows users to:

- Discover data, information and services available in the GEOSS;
- Access the GEO Clearinghouse to search data catalogues and datasets;
- Visualize geographical information, maps and imagery from various sources (e.g. from different GEO Societal Benefit Areas through the OpenGIS® Web Map Service Interface Standard, WMS services);
- Browse through a comprehensive directory of service providers (e.g., related to GEO Members and Participating Organizations);
- Retrieve Earth observation education, training and capacity building resources and services of many types (e.g., tutorials on Earth observation techniques, data analysis, interpretation, or use); and
- Access information from **GEONETCast**.[274]

The Global Telecommunications System (GTS) (with its emerging WMO Information System[275]) is used for "real-time" exchange of meteorological and physical oceanographic data and has relatively few and well controlled formats (Traditional Alphanumeric Code forms, TACs).[276] TACs are being replaced with Table-Driven Codes (TDCs), e.g., the Binary Universal Form for the Representation of data (BUFR).[277] The BUFR tables were developed for meteorological variables and can be used for physical oceanographic variables. The present structure of the tables is not suitable for chemical and biological data and metadata, most of which are delivered in delayed mode. A number of other widely used and well documented formats are also emerging as good candidates for improving data interoperability.

In delayed mode, there are many formats, and communications are increasingly via the Internet. For these exchanges there is no standard for naming variables and attributes, no universally agreed structures or formats, no real order at all, beyond the broad constraints of standards such as the Hypertext Transfer Protocol (HTTP) and the File Transfer Protocol (FTP). Use of the

Internet is becoming increasingly widespread, but the lack of common standards and protocols makes data exchange challenging since each data provider must document their formats, contents, processing steps, etc., and receivers need to build software that can handle a wide variety formats from different data providers. The challenges associated with naming conventions and the need to reconcile common vocabularies has led to the emergence of projects like the Marine Metadata Interoperability Project[278] to assist data providers in adopting standard ontologies and syntax that can dramatically improve data discovery and interoperability.

5.5.4 Access

Data access services are intended to provide standard methods for serving, browsing and retrieving data from DACs and data archives (e.g., NODCs) via a web-based user interface. Services may be customized for different classes of data (e.g., individual observations, time series, transects and vertical profiles, gridded data, imagery) and for "pulling" data as needed, subscribing to data feeds, and receiving alerts based on specified thresholds. The GEOSS **Standards and Interoperability Registry**[279] enables data exchange by providing information on standards that have been formally adopted for GEOSS or are currently used but not formally adopted including candidates for adoption. All contributors to GOOS are encouraged to list and regularly update standards and protocols currently in use.

Utility services include catalogs that list and describe observing system assets, data sets, models, registries of services, vocabularies,[280] and service gateways[281]; and integration services that merge variable-specific data from multiple providers for "one-stop shopping". This service is provided by the GEOSS **Components and Services Registry**[282] which, in addition to the services given above, provides a process for registering contributions to GEOSS. All contributors to GOOS are encouraged to take advantage of this registration process.

5.5.5 Data Processing

Data come in many versions from raw data to versions of processed data generated by calibrations, quality control, smoothing and filtering, etc., and it is important to distinguish between them. For the purposes of GOOS, there are four levels of data: '0' for raw, full resolution data; '1' for full resolution data that has been time-referenced and annotated with associated information (e.g., calibration coefficients and geospatial referencing parameters computed and appended but not applied to the Level 0 data); '2' for derived variables (e. g., ocean wave height, chlorophyll concentration, sea level at the same resolution and location as level 1 data; '3' for gridded data processed from a single type of sensor (one satellite sensor or one *in situ* network); and '4' for model output or results from analyses of lower level data (i.e., derived data).

Data processing centers provide modeling and data assimilation centers with the real-time and delayed-mode data sets required for validation, estimates of uncertainty, monitoring observing system performance (e.g., continuity of data streams and data quality). Interactions between data assembly, processing and assimilation centers must be sustained to ensure feedback on (1) the quality control performed at the level of data assimilation centers (e.g., comparing observations with a model forecast), (2) the impact of data sets and data products in the assimilation systems, and (3) new requirements.

5.5.6 International Exchange of Data on Ecosystem Pressures and States

Our focus up to this point has been on technical issues of interoperability, data access and data exchange. Implementing the recommendations above will not be possible unless a major hurdle is overcome, i.e., the willingness of nations to allow timely access to data on ecosystem pressures, states and impacts within their respect Economic Exclusion Zones and territorial waters. To address this, the COOP recommended in GOOS 148 that international agreements be executed that would enable timely exchange of data among participating nations. This is a major issue that ultimately must be addressed by the parties to the United Nations Convention on the Law of the Sea (UNCLOS). In this regard, an important precedent has been established by the Benguela Current Commission (Box 5).

Box 5
Benguela Current Commission's Data Policy

The Benguela Current Commission (BCC) is an intergovernmental body established by the Republics of Angola, Namibia and South Africa to manage the Benguela Current Large Marine Ecosystem (BCLME) program. Recognizing that an ecosystem-based approach to managing the BCLME depends on timely exchange of data on the EEZs of all three countries, the BCC has established a program to facilitate access to data and information throughout the region. This includes (1) Appointment of a full time data and information Manager, (2) A meta-database system and (3) Electronically based procedures and protocols for managing data, information and documents.

The BCC oversees the assembly of inter-operable data from national monitoring programs (e.g. Pollution monitoring, top-predator surveys, fisheries assessments) that will enable national data sets to be incorporated into BCLME wide data bases. The BCC secretariat has established a data policy that ensures that all transboundary data generated through its programs remains available (with suitable checks and balances) to the country of origin and the scientists who generate them. These data and metadata are held by the BCC itself and are available to any user, subject to certain terms and conditions.

Data emanating from independent national programs posed more a problem in that domestic legislation placed restrictions and limitation on the communication of data and information across national borders. In addition, data and information considered to be sensitive, of strategic importance may be embargoed indefinitely or for specified periods of time (e.g., survey data used for fisheries quota allocation or data on crude oil extraction and diamond mining concessions). Nevertheless, the three governments have recognized that exchange of data and information is a critical aspect of BCLME management. Two options for facilitating this exist: (1) develop a discrete data and information exchange agreement among the countries which would require domestic ratification by each government or (2) a more progressive option that includes legally permissible exchange of specified data and information among the contracting parties as part of the overall multilateral treaty establishing the Benguela Current Commission. This requires only a clause in the agreement which refers to the BCC data policy that governs the rules, procedures and protocols for the exchange of data and information. At this time (April, 2011), the treaty was in an advanced stage of drafting and is due for signature and ratification by the end of 2011.

5.6 Regional Ocean Observing Systems

5.6.1 Background

As concluded by COOP,[283] regional observing systems are critical building blocks of coastal GOOS for both the GCN and regional observing systems that are explicitly designed to meet national and regional needs. Successful global evolution of the GCN depends on the development of national and regional observing systems that contribute to and benefit from the GCN and are interoperable in terms of the exchange of data and information on the states of their coastal ecosystems. National and regional bodies provide the most effective venues for (1) identifying user groups, (2) specifying data and information requirements that meet their particular needs for data and information on coastal and marine ecosystems, (3) assessing the current state of existing observing systems, (4) implementing an integrated system of systems, (5) refining data-products over time based on user feedback, new knowledge and advances in technology, and (6) reporting on and assessing the value and impact of observing systems for ecosystem-based management in the national and regional setting. Thus, decisions concerning exactly what to measure, the time-space scales of measurement, and the mix of observing techniques are best made by stakeholders in the nations and regions affected.

RCOOSs are in various stages of development globally in terms of their readiness level, regional coverage and scope (number of phenomena of interest addressed). As articulated in "An Integrated Framework for Sustained Ocean Observing", readiness levels fall into one of 3 categories: concept, pilot and mature.[284] The concept phase includes research projects where ideas are articulated, tested and peer reviewed. The pilot phase includes pilot projects where aspects of the system are tested and made ready for implementation as a mature contribution to GOOS. At maturity, the new capability becomes a sustained contribution to GOOS. For most of the developing world and emerging economies, sustained ocean observing is in the concept phase at best. This creates an enormous challenge to global implementation given that the majority of sentinel and reference sites lie in their EEZs and territorial waters (compare Figure 2 with Figures in sections 5.4.1 and 5.4.2). Among the more mature regional systems that can be used as models for design and implementation of RCOOSs are observing systems for the Baltic Sea,[285] the Mediterranean Sea,[286] and coastal waters of Australia[287] and the United States.[288]

5.6.2 Procedures for Design, Implementation and Evolution

Procedures for developing an RCOOS must enable the evolution of ocean observing systems that are interoperable on a global scale and, by definition, complex. This is a process driven by both the users and providers of data and services, i.e., the national and regional stakeholders. Users (decision makers from private and public sectors and scientists) must be at the table to specify their data and information needs. Data providers (from both operational and research communities) must be at the table to establish what is doable now and what the priorities for research and pilot projects should be to improve capacity to provide needed data and information to support timely decisions. The iterative cycle of steps to achieve this goal (Figure 25) is based on a systems engineering approach[289] and on "best practices" learned from implementing regional systems that are most mature. The procedure takes into account the need to design, implement and evolve systems over time as scientific understanding of relationships between pressures, states and impacts improves; capacity increases (from interoperability among nations and regions to infrastructure readiness and modeling capabilities); more stakeholders become involved; and priorities change.

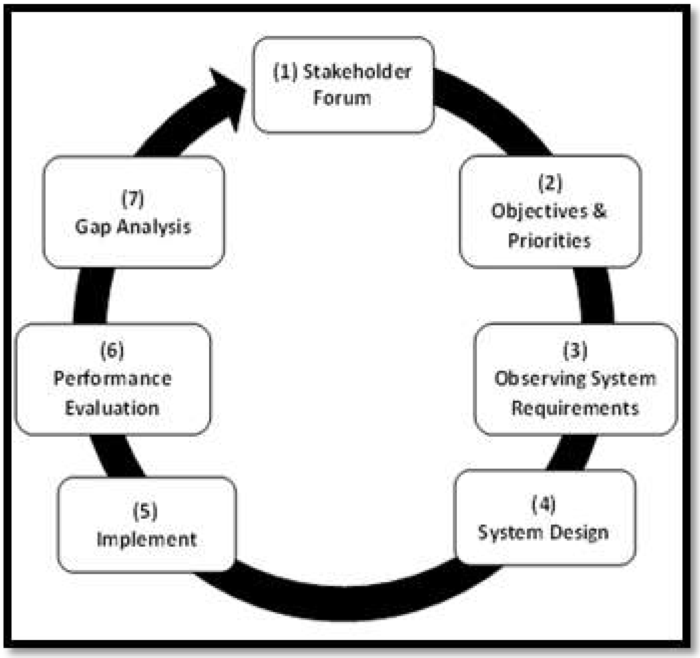

Figure 25. *Bottom-up, sustained and iterative life cycle for designing, implementing, evaluating, and improving an RCOOS over time.*

(2) Once the target ecosystems have been identified and priority PoIs agreed to, determine objectives of the observing system and identify priority pressures, states and impacts to be monitored and modeled. Objectives are guided by data, products and services specified by the users and informed by maps of the region (dominant features such as coral reefs, mangrove forests, water masses, coastal upwelling, fronts, seamounts, and submarine canyons; surface chlorophyll concentrations; spawning, nursery and feeding grounds of exploitable fish populations); an inventory of ecosystem goods and services currently used (fishing grounds, aquaculture sites, point source discharges, shipping lanes, recreational areas, etc.); and maps of land-cover and use in catchment basins draining into coastal ecosystems. These provide a framework for specifying data and information needed for IEAs and marine spatial planning.

This stage concludes with the signing of a Memorandum of Agreement (MOA) by the stakeholders defining user expectations in terms of the provision of data and information and the roles and responsibilities of all stakeholders in the design, implementation, sustained operation, capacity building and funding of the observing system; and service level agreements that ensure the provision of the required data and information.[291] MOAs and service level agreements should be "living" documents in that they are revised and updated with each iteration of the life cycle. Outcomes include an initial set of partners with well defined roles and objectives, a common language, agreed upon priorities, an inventory of current capacity, an empowered user community, and commitments by data and service providers to follow through on each stage of the life cycle.

(3) Given the results of stages (1) and (2), requirements for the sustained provision of data and information can now be determined, i.e., requirements for models, data management and observations. Requirements for observations should be guided by data requirements for models[292] and include the variables to be observed,[293] time and space scales of resolution, precision and accuracy, data delivery times (real time telemetry or delayed mode; if delayed mode, the acceptable lag time between in situ changes and their detection), platforms and sensors (remote sensing and *in situ* measurements) to be used, and locations to be sampled for *in situ* measurements.

In addition to observations of ecosystems, requirements for observations of external pressures on ecosystems and impacts of changes in ecosystems states must be determined. This should be done in the context of GEOSS since pressures occur on larger scales than targeted ecosystems within the region, and it would be prudent to engage representatives from the operators of adjacent RCOOS and basin scale observing systems. Observing system requirements set forth the sections above may be used to help guide this stage of the process.

(4) Given, objectives, priorities, and requirements, design the initial SoS and prepare a phased implementation plan (with milestones and cost estimates) with existing programs as the building blocks. The implementation plan should include procedures for coordinating and collaborating among programs; procedures for establishing common standards and protocols for measurements, data transmission, DMAC and modeling; and a business plan for acquiring and allocating the resources needed for integration and sustained operations of the SoS.

This is where what is "doable" in terms of existing resources and capabilities comes into play. On the technical front, existing observing, data management and modeling capabilities must be integrated vertically within participating organizations and horizontally among them. On the administrative front, the SoS life cycle must be managed in such a way that integration is achieved without compromising the ability of existing systems to perform their original missions and functions while enabling interoperability among them. Thus, establishing a hierarchical governance structure that harmonizes top-down (e.g., an Executive Council) bottom-up (Stakeholder Forum) responsibilities and authority is critical to successful integration of existing capabilities and implementation of the life cycle.

(5) All data providers (observations, models and data archives) collaborate to initiate phased implementation of the plans formulated in (4). Since data management and communications (section 5.4) are critical to linking observations and models and to the development of an integrated system, establishing this link in the observations to products chain should be the highest initial priority. Administratively and technically, this stage will be the most demanding in terms of the coordination, collaboration and training needed to make the implementation plan a reality.

(6) Sustained evolution of an RCOOS requires a systematic and rigorous process for periodic performance evaluations that ensure adherence to GOOS design principles. Performance metrics fall into two broad categories: (i) system performance and (ii) user satisfaction. System performance includes measures of data quality, continuity of data streams, data flow from measurements to models, model skill, and the diversity of user groups. User satisfaction is measured in terms of user "pull" (demand) and the timely provision of data and information that enable timely and informed assessments and decisions. Data providers, users of RCOOS data and information (clients), and funding bodies must be involved in specifying performance criteria. Where possible, existing national and international measures should be adopted to assess individual components of the system (e.g., Box6) and the achievement of objectives (e.g., long-term predictions of sea level rise) and societal goals.

Box 6: Performance Metrics

Recommended by the IPCC for Sea Level Observations

Metric 1 – Complete the installation of real-time, remote reporting tide gauges and co-located permanent Global Positioning System (GPS) receivers at 62 stations for long-term trends, and 30 stations for altimeter drift calibration, as part of the international Global Sea Level Observing System.

Metric 2 – Establish the permanent infrastructure necessary to process and analyze satellite altimetry, tide gauge, and GPS data for the routine provision of annual sea level change reports with (1) estimates of monthly mean sea level for the past 100 years with 95% confidence; (2) variations in relative annual mean sea level for the entire record for each instrument; and (3) estimates of absolute global sea level change accurate to 1 mm per year.

(7) A gap analysis (assess current technical expertise and infrastructure assets for end-to-end systems, management capabilities and licenses against the requirements and objectives) is performed to set the stage for recommendations to the Stakeholder Forum on the way forward in terms improving performance to provide the data and information needed to achieve the objectives and inform ecosystem-based approaches to managing anthropogenic pressures and adapting to the impacts of climate change.

Ultimately the system must be cost-effective and designed to evolve over time as capacity is built, stakeholder numbers increase, new knowledge and technologies become available, and priorities for observing system data and information change or expand. Thus, periodic assessment by the stakeholders must result in satisfied users and the sustained evolution of more effective infrastructure and efficient operations from observation and data management to models and services.

5.7 International Partnerships and Collaborations

Given that implementing coastal GOOS globally begins by integrating data from existing monitoring assets to increase the value of ocean observing, a critical step in the implementation process is the establishment of sustained collaborations with programs that share common objectives for EBAs and will benefit from the development of coastal GOOS, those providing data and information needed for IEAs (data providers); and global networks that can facilitate implementation of coastal GOOS. IOC regional sub-commissions, committees and offices should play an important role in developing and sustaining collaborations beginning with those described below.[294]

5.7.1 Major Interdisciplinary Groups and Programs with Common Objectives for EBAs

Major programs with common objectives requiring interdisciplinary observations and modeling include the GEO Biodiversity Observation Network,[295] Regional Seas Conventions,[296] Marine Protected Area management programs,[297] and Large Marine Ecosystem programs.[298]

- The goals of the Group on Earth Observations Biodiversity Observation Network (GEO BON) and of coastal GOOS are very similar and achieving them will benefit from formal collaboration. GEO BON is the biodiversity arm of GEOSS. Some 100 governmental and non-governmental organizations are collaborating through GEO BON to make their biodiversity data, information and forecasts more readily accessible to policymakers, managers, experts and other users. It has been recognized by the Parties to the Convention on Biological Diversity as well as by the member states of the Group on Earth Observations.

GEO BON is a "network of networks" composed of two types of constituent networks: Regional BONs and Topical BONs. Regional BONs are autonomous networks that form (largely spontaneously) to serve the biodiversity observation needs of a group of neighboring countries. Topical BONs are global in geographical scope and focused on a particular aspect of biodiversity (e.g., one taxonomic group, trophic level, or type of data). The goal of this network of networks is to develop a coordinated, global system for gathering and sharing information on biodiversity, providing tools for data integration and analysis, and contributing to more effective environmental management and human well-being.

GEO BON is intended to facilitate linkages among the many countries, organizations and individuals contributing to the collection, management, sharing and analysis of observations on the status and trends of the world's biodiversity. It will also identify gaps in and between existing biodiversity observation systems and promote mechanisms to fill them. The scope of GEO BON includes primary observations and observation-based inferences on changes in ecosystem biodiversity, structure, function, and services in terrestrial, freshwater, coastal and open ocean marine domains.

The GEO BON Steering Committee consists of biodiversity information users and providers. The Steering Committee meets as needed, and consults electronically between meetings. It reports to the Group on Earth Observations (GEO) plenary. The coordination actions of GEO BON are conducted by working groups, established by the Steering Committee, with a defined purpose and for a limited period. The members of the working groups are experts, appointed on a voluntary basis and in their own capacities, selected to provide the necessary skills, experience and connections to achieve the task. There are eight working groups: (1) Genetics / Phylogenetic Diversity, (2) Terrestrial Species Monitoring, (3) Terrestrial Ecosystem Change, (4) Freshwater

Ecosystem Change, (5) Marine Ecosystem Change, (6) Ecosystem Services, (7) *In situ* / Remote-Sensing Integration Through Modeling, and (8) Data Integration and Interoperability.

Priorities for the Marine WG are as follows:

- Facilitate the mobilization and accessibility of online biodiversity data;
- Facilitate consensus on data collection protocols, data quality control and coordination of development of interoperability among monitoring programs;
- Facilitate data rescue activities (recovering data in paper publications or other forms) to make them available for analysis;
- Facilitate the global monitoring of ecosystems using a combination of remote sensing and *in situ* approaches;
- Coordinate the efforts of individual institutes, countries and large programs to perform *in situ* measurements in a sustainable way;
- Stimulate/Coordinate all activities to define a marine ecosystem classification and visualization thereof;
- Help to provide *in situ* data to develop process models and forecasting related to biodiversity;
- Stimulate long term observations for monitoring human-induced changes of critical ecosystem parameters linked to biodiversity change such as pH, T, nutrients, oxygen, chlorophyll, and currents;
- Facilitate research to characterize the state of ecosystems by metagenomic tools;
- Identify gaps in monitoring of crucial ecosystems by a detailed inventory of ongoing and past monitoring activities;
- Stimulate the embedding of biological and sequence data in a contextual and metadata context;
- Stimulate capacity building through major international programs related to POGO, the NIPPON Foundation, SCOR, IOC and others.

The starting point for organizing a partnership for coastal ocean observations will be the networks of marine laboratories including the European Network of Marine Research Institutes and Stations (MARS), the North American Association of Marine Laboratories (NAML) and the Canadian Healthy Oceans Network (CHONE). These and other regional networks are joining together to establish the World Association of Marine Stations (WAMS) under the auspices of the IOC (see section 5.7.3).

The Marine WG will request assistance from the National and Regional Implementation Committees of the Census of Marine Life to achieve an up-to-date inventory of existing networks and to identify the individual scientists who are willing and able to support the development of BONs. In addition to WAMS, key partners will include the Partnership for the Observation of the Ocean (POGO), the Sir Alister Hardy Foundation for Ocean Science (SAHFOS), the Global Ocean Biodiversity Initiative (GOBI),[299] and Bird Life International.

- GEO Coastal Zone Community of Practice (CZCP)[300]

The CZCP supports the operational goal of providing data and information needed to inform management decisions across the land-sea interface. To this end, the CZCP engages stakeholders in the development of those elements of the GOOS and GTOS that are required to provide and integrate data on terrestrial, freshwater, marine and atmospheric systems that converge in the coastal zone. Specific objectives of the CZCP are to (1) engage data providers and users in the specification of requirements for *in situ* and remote observations; (2) evaluate current and projected observation capabilities against these requirements, and identify gaps, redundancies and activities that need to be strengthened; (3) promote the development of workshops and "proof of concept" pilot projects; and (4) promote development and strengthening of networks of institutions globally, regionally, and across Communities of Practice that contribute to and benefit from GEOSS to achieve the mutual goals of GOOS and GTOS. High and immediate priorities for GEOSS are improved forecasts of sea-level rise and associated increases in coastal inundation that may be exacerbated by increases in the frequency of extreme weather and the loss of ecological buffers to coastal inundation.

- The Regional Seas Program, launched in 1974 by UNEP, is among the longest running initiatives aimed at marine environmental protection on a regional, multinational (trans-boundary) scale. It is intended to engage neighboring countries in comprehensive actions to protect their shared marine environment. Beginning with an initial focus of action plans on protecting the marine environment from pollution, their objectives have expanded over the years to include integrated coastal management and the development of appropriate response to the impacts of climate change. Thirteen Regional Seas Programs are recognized by UNEP,[301] but only those with legally binding conventions that ensure cooperation among governments have enjoyed success. Examples of the latter are the Barcelona Convention for the Mediterranean Sea (established in 1976), the Oslo and Paris Convention for the NE North Atlantic Ocean (OSPAR, established in 1992), and the Helsinki Convention for the Baltic Sea area (HELCOM, established in 1992).

- The Large Marine Ecosystem (LME) Program was implemented to develop EBAs and build capacity in developing countries. Two features of LMEs are particularly relevant to coastal GOOS. First, spatial boundaries were not based on political or economic criteria. Using ecological criteria (bathymetry, hydrography, productivity, and trophic relationships), 64 LMEs have been delineated around the coastal margins of the Atlantic, Pacific and Indian Oceans. Second, sets of indicators, many of which have been identified for coastal GOOS (Table 16), are used to assess the success or failure of actions to recover depleted fish stocks, restore degraded habitats, and reduce and control coastal pollution and nutrient enrichment (Table 19). The LME concept for ecosystem-based approaches to managing fisheries and ecosystem health are being applied to 16 of the designated LMEs (Figure 13) through funding from the Global Environment Facility (GEF), the World Bank, participating countries, and other donors.

Category	Indicator
Productivity	Primary productivity, Chlorophyll-a, SST, Zooplankton
Fisheries	Catch (landings & value) & Effort Catch from trawling and dredging Status of stocks Marine trophic & fishing in balance indices Primary production required
Ecosystem health	Harmful algal blooms (HABs) & hypoxic zones Freshwater discharge & sediment loads Sea level rise Concentrations of dissolved inorganic nitrate & total phosphorus Mercury & other contaminants (oil, litter, etc) Acidification Reefs & deltas at risk indices Extent of mangrove, saltmarsh & seagrass habitats Marine Protected Area coverage (%)
Socio-economics	Marine-based income (by livelihood or economic sector) Industrial fisheries vs Small scale (employment, landings) Recreational fisheries, Forage fisheries & use Fishing subsidies Human development index & component indicators Population in coastal zone and distribution by elevation Fishery and aquaculture index Marine activity index Agriculture (fertilizer application, t/km2/yr) Economic losses from disasters (e.g., coastal flooding, HABs, oil spills)

Table 19. *Indicators identified for Large Marine Ecosystems*.

- Regional networks of MPAs began with the 1971 Ramsar Convention, the first global intergovernmental treaty for the environment.[302] The keystone of the Convention is the establishment of a network of protected areas (Ramsar Sites) under the "List of Wetlands of International Importance" to conserve and sustainably used wetland goods and services. Marine and coastal wetlands, which account for ~ 20% of the nearly 2,000 Ramsar sites, encompass a broad range of habitats including permanent shallow marine waters; marine subtidal aquatic beds (e.g., kelp beds, sea-grass beds, tropical marine meadows); coral reefs; rocky marine shores; sand, shingle or pebble shores (e.g., sand dunes, sand bars, spits and sandy islets); estuaries and deltas; intertidal mud, sand or salt flats; intertidal marshes; intertidal forested wetlands (e.g., mangrove forests); coastal brackish/saline lagoons; and brackish to saline lagoons. The global network of Wetlands International provides rapid access to specialists on wetland conservation throughout the world. These are supported by 13 regional and project offices on five continents.

In 2002, the World Summit on Sustainable Development called for the establishment by 2012 of marine protected areas consistent with international laws and based on scientific information, including representative networks. The 2003 Durban Action Plan called for regional action and targets to establish a network of protected areas for 20 to 30% of the world's oceans by the goal date of 2012.[303] The World Commission on Protected Areas (WCPA), in partnership with the

Global Marine and Protected Area Program of the International Union for the Conservation of Nature (IUCN), is leading the effort to establish the global network. MPAs are important tools for EBAs (ecosystem-based assessments) in managing marine resources and, therefore, share requirements in common with GOOS for monitoring and modeling. Coordinating and integrating data collection and analysis, and coordinated implementation of MPA-monitoring programs with coastal GOOS will allow more cost-effective and timely detection of changes in ecosystem states and more effective management responses to impacts.

5.7.2 Data Providers

Satellite Remote Sensing

The primary providers for satellite ocean remote sensing data are the (multi) national space agencies, including:

- Canadian Space Agency (CSA)
- Centre National d'Études Spatiales (CNES)
- Chinese Meteorological Administration (CMA)
- European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)
- European Space Agency (ESA)
- Indian Space Research Organisation (ISRO)
- Japan Aerospace Exploration Agency (JAXA)
- Korea Aerospace Research Institute (KARI)
- National Aeronautics and Space Administration (NASA)
- National Oceanic and Atmospheric Administration (NOAA)

These and other agencies are members of the Committee on Earth Observation Satellites (CEOS). Extensive details on satellite missions, instruments and measurements, along with other related information, are available in the extensive data bases that CEOS maintains.[304] In support of GEO objectives, and to coordinate and facilitate activities across its member agencies, CEOS has implemented virtual, space-based Constellations for a number of parameters. These include the Ocean Surface Topography, Ocean Surface Vector Wind, and the Ocean Color Radiometry Constellations for the oceans.

The space agencies have a number of programs and activities specifically dedicated to facilitating the acquisition, processing and distribution of space-based coastal and ecosystem observations and supporting associated applications and services. These include ESA's CoastColour and MarCoast Projects, and NOAA's CoastWatch and Coral Reef Watch Programs.[305] Likewise, there are various international agency and institutional partnerships that provide coastal and ecosystem space-based observations and applications, including GHRSST and ChloroGIN (section 5.3.2).

Finally, there are extensive regional and local providers of satellite data, including academic and research institutions, federal, state and municipal agencies, non-governmental organizations, and commercial firms. These entities acquire their data from space agencies or commercial satellite providers (e.g., DigitalGlobe, GeoEye, Spot Image) and derive and distribute user-friendly and regionally-tailored data in support of specific end-user needs, typically with customized algorithms, formats, and derived products and information. Many of these efforts are directly related to GOOS, with satellite data and derived products distributed by regional coastal ocean observing systems, such as from the North-East Asian Regional GOOS (NEAR-GOOS) or the U.S. Integrated Ocean Observing System (IOOS®).[306]

<u>*In Situ* Data</u>

Data centers and *in situ* programs directly relevant to developing the GCN include the IODE,[307] FAO, [308] the GTN-R,[309] GLOSS,[310] ChloroGIN,[311] International network of Coral Reef Ecosystem Observing Systems (I-CREOS)[312] and GCRMN,[313] the global Seagrass Network (SeagrassNet),[314] Natural Geography In Shore Areas (NaGISA) Project,[315] the CPR Survey,[316] the OTN and GTOPP.

- International Oceanographic Data and Information Exchange Program (IODE)

The IODE program was established in 1961 by the IOC to enhance marine research and sustainable use of the marine resources by facilitating the exchange of oceanographic data and information among member states and by meeting the needs of users for data and information products. The IOC Committee on IODE held its Twenty-first Session (IODE-XXI) in 2011. Outcomes include (1) adoption of OBIS by IODE and establishment of an IOC Project Office for IODE/OBIS; (2) the continuation of the IOC Project Office for IODE in Oostende, Belgium; (3) a statement on the IODE role in the ICSU World Data System; (4) expansion of OceanTeacher to include a wider range of IOC disciplines as well as the recommended development of a 5-year training plan; (5) the planned revision of the IOC Strategic Plan for Oceanographic Data and Information Exchange (2012-2015).[317]

- Food and Agriculture Organization (FAO) of the United Nations

The FAO collects, compiles, analyzes and disseminates data and information in fisheries and aquaculture. The Organization has collaborated with the Coordinating Working Party on Fisheries Statistics[318] to develop standard concepts, definitions, classification, and methods for the collection and archival of fishery statistics. The compilation of accurate, relevant and timely data in standard formats facilitates monitoring, comparisons and analyses of status and trends that are essential for sustainable fisheries and aquaculture. Its databases are open to the public. To this end the FAO seeks to support and strengthen national capacity to collect, analyze and use accurate, reliable and timely data.

- The Global Terrestrial Network for River Discharge (GTN-R)

The GTN-R was established in 1988 by the Global Runoff Data Center (GRDC)[319] to improve access to near real-time river discharge data from selected gauging stations globally. The network of gauges monitors most of the freshwater flow into the oceans (380 discharge stations). The volume transport of freshwater into the oceans is an “essential variable for the GCOS, and the GTN-R is supported by an action item in the Second Report on the Adequacy of the Global Climate Observing System for Climate.[320] The GRDC, an international data center operating under the auspices of the WMO, has established standard data and metadata formats and data transfer protocols for exchanging hydrological data and information based on relevant ISO standards.

- Global Sea Level Observing System (GLOSS)

GLOSS is an international program (operating under the auspices of JCOMM) to establish global and regional networks of tide gauges. There are four components: (1) a core network of 290 coastal sea level stations that are roughly evenly distributed globally (Figure 14); (2) the long term trends network (some, but not all, are a part of the core network) for monitoring long term trends and accelerations in global sea level (to be equipped with GPS for measuring vertical land movements); (3) the altimeter calibration set on islands; and (4) the ocean circulation set with gauge pairs at straits and polar regions.

- Chlorophyll Globally Integrated Network (ChloroGIN)

ChloroGIN is a GEO and GOOS demonstration, capacity building project that enables members to measure SST and chlorophyll-a concentrations to calibrate and validate satellite-based remote sensing to inform ecosystem-based management of fisheries. The network of members includes laboratories and agencies in Argentina, Australia, Brazil, Canada, Chile, China, European Commission, India, Mexico, Namibia, Peru, Philippines, South Africa, Sri Lanka, Switzerland, Tanzania, Thailand, United States, Venezuela and Vietnam. All members of ChloroGIN have communication links to three centers (Plymouth Marine Laboratory, UK; European Commission Joint Research Centre, Italy; and Bedford Institute of Oceanography, Canada) that enable integration of data from in situ and remote sensing.

- An International network of Coral Reef Ecosystem Observing Systems (I-CREOS)

I-CREOS has been proposed to organize and build on existing coral reef observation systems being developed around the globe. This effort builds on the Global Coral Reef Monitoring Network. The GCRMN was established in 1997 in response to global scale degradation of coral reefs in the tropics from East Africa and Southeast Asia to the Caribbean. It is sponsored by the IOC, UNEP and IUCN. Goals are to (1) improve the conservation, management and sustainable use of coral reefs and related coastal ecosystems by providing data and information on the trends in biophysical status and social, cultural and economic values of these ecosystems; and (2) provide individuals, organizations and governments with the capacity to assess the resources of coral reefs and related ecosystems and collaborate within a global network to document and disseminate data and information on their status and trends. The collection of data and information on reef status and trends began in 1997. Regional nodes have been created within participating countries to coordinate training, monitoring, and data management in regions based on the Regional Seas Programs: Middle East, western Indian Ocean and east Africa, south Asia, east Asia, the Pacific, and the Caribbean and tropical Americas. Additional observing systems that are the building blocks of I-CREOS include NOAA's Coral Reef Ecosystem Integrated Observing System[321] and the Great Barrier Reef Ocean Observing System.[322]

- SeagrassNet

Established during the 3rd International Seagrass Biology Workshop in 1998 (Manila, Philippines) SeaGrass Net functions as the primary mechanism for serving the data and information needed by the World Seagrass Association (WSA) to promote research and provide advice to management agencies and the public on the protection and restoration of sea grass communities. Objectives are: to (1) develop an observing system to assess the status (areal extent and health) of seagrass ecosystems worldwide; (2) facilitate data and information exchange among scientists; (3) develop models to predict the effects of global climate change and human activities on seagrass ecosystems; and (4) enhance training and education and disseminate information on seagrass beds, their importance as essential fish habitat, their ecological significance, and their contribution to the well-being of human coastal populations.

- The Natural Geography In Shore Areas (NaGISA) Project

The goal of NaGISA is to establish a network of well-distributed standard transects from the high intertidal to a depth of 20 m worldwide (from pole to pole and around the equator. The NaGISA protocol is simple, cost-effective and intentionally low-tech.[323] Each transect or set of transects (sites) has been adopted by local communities, citizen scientists, universities or high school schools for monitoring.[324] Some of these groups have committed to repeated sampling for up to 50 years. Administrative Centers (University of Kyoto, University of Alaska-Fairbanks, University of Pisa, Simon Bolivar University, and Central University of Venezuela) organize NaGISA regionally with assistance from national organizations (e.g., University of Baja California, Phuket Marine Biology Center, and the University of Cape Town).

- The Global Alliance of Continuous Plankton Recorder (CPR) Surveys

Operating under the auspices of the Sir Alister Hardy Foundation for Ocean Science (SAHFOS), the CPR program has been using ships of opportunity to monitor plankton populations and phytoplankton biomass since 1931 in the NW North Atlantic (initially focused on the North Sea) and more recently in the Southern Ocean, Australian coastal waters, and coastal waters of the NW North Atlantic, and the North Pacific. Monitoring plankton diversity, variability and trends over large areas of oceanic and coastal water with the CPR is efficient and cost effective and is a powerful, proven tool for detecting and predicting oceanic impacts of global warming. SAHFOS is working with JCOMM to establish a global CPR survey as part of SOOP and the VOS program. The goal is to build regional surveys with common standards for sampling, analysis, data processing and sample storage that generate compatible and freely exchangeable data. It is envisaged that the resulting global network of CPR routes will complement the emerging GTN.

The Global Alliance of CPR Surveys (GACS) was formed in 2011. The general aim of GACS is to understand changes in plankton biodiversity at ocean basin scales through a global alliance of CPR surveys. Specific aims are under development but current specific aims include developing a global CPR database, producing a regular ecological status report for global plankton biodiversity, and providing an interface for plankton biodiversity with other global ocean observation programs.

- The Ocean Tracking Network (OTN) and the Global Tagging of Pelagic Predators (GTOPP)

The OTN and GTOPP are GOOS pilot projects. Together, they will provide information on ocean food webs crucial to inform EBAs. OTN is developing a global infrastructure to collect comprehensive data on the movements of marine animals (e.g., salmon, tuna, whales, sharks, penguins, crabs, seals) and the environmental conditions they experience as they search for food and migrate to spawning and feeding grounds. The animals are tagged with small electronic transmitters that can operate for up to 20 years. Acoustic receivers (~ the size of kitchen food processors) are being deployed on the sea floor ~ 800 m apart (“acoustic curtains) in 14 ocean regions off all seven continents (Figure 12). The receiver’s record coded acoustically transmitted data specific to each tagged animal that passes within 0.5 km of a receiver. These records are then used to determine migratory patterns and mortality rates.

GTOPP expands the value of the acoustic network by equipping larger pelagic predators with sensors that measure temperature, salinity, depth, geographic position, and other properties such as chlorophyll-a. This provides data on marine ecosystems from the animal’s perspective. By combining data from a diverse number of highly migratory species, and overlaying them with oceanographic data, it is possible to identify critical habitats and detect changes in marine ecosystem states. The objective is to understand the factors that influence animal behavior in the ocean and provide the data and information needed to sustain their populations. Once established, the network of acoustic curtains and tagged animals will monitor the distribution, abundance, migratory behavior, and environmental experience of a diversity of pelagic animals. The latter will help to address the problem and undersampling and enable climate scientists to detect and predict changes in the ocean-climate system more effectively.

5.7.3 Global Networks for Facilitating Coastal GOOS Implementation and Evolution

By its nature, the *in situ* elements of coastal GOOS will be implemented and operated as a distributed system of systems, and networks of coastal marine and oceanographic institutions will play an important role in this process. In addition to the networks described above, these include the following:

- GOOS Regional Alliances (GRAs)[325]

The IOC has recognized twelve GRAs that, in principle, are overseeing the implementation and evolution of Regional Coastal Ocean Observing Systems. However, levels of government commitments and readiness vary enormously from region to region in terms of their ability to benefit from and contribute to building GOOS. The heart of the problem is funding levels for GRAs to build capacity[326] which ranges from relatively mature in some developed countries to nonexistent in many developing countries. This having been said, a fully functional network of GRAs offers the most effective mechanism for implementing coastal GOOS on a global scale.

- The Partnership for Observation of the Global Oceans (POGO)[327]

POGO promotes GOOS and its potential to both benefit from and contribute to the development of coastal GOOS is enormous. Among initiatives that POGO has implemented are the Centre of Excellence in Ocean Observations and the Visiting Fellowship Program. Both are intended to help build marine scientific capacity and technological expertise in developing countries. Recently (March 2011), POGO strongly endorsed the following: (1) Establish a globally-coordinated network of time series observation stations in the oceans to monitor a rapidly changing Earth System through OceanSITES; (2) Monitor changes in ocean acidification at the global scale; (3) Implement a sustained deep ocean observation system to study heat storage, deep-sea biogeochemistry and ecosystem function and other properties that are poorly known; (4) Improve baseline data and sustained observations, especially in vulnerable areas such as the polar oceans and semi-enclosed basins, to facilitate rapid response and mitigation in the event of natural or man-made disasters; (5) Establish Oceans United[328] as a global forum for dialogue within the marine scientific community, and with international agencies responsible for marine stewardship; and development of communications plans to "engage citizens of the world in the importance of marine research for the well-being of society."

- Nippon Foundation-POGO Alumni Network for Oceans (NANO)

Establishing an integrated ocean observing system is a high priority for the Nippon Foundation (NF) and the Partnership for Observation of the Global Oceans (POGO). To this end, the NF-POGO partnership has (1) initiated a Visiting Professorship Program (established in 2005 to allow distinguished professors from renowned oceanographic institutes to teach young scientists in developing countries and promote collaborations and networking among institutions of developing and developed countries,[329] (2) established a Centre of Excellence (CofE) in Observational Oceanography which gives scholars from developing countries an opportunity to receive training from world-class scientists for ten months at the Bermuda Institute of Ocean Sciences,[330] and (3) created NANO. The latter is a global network of past and present NF-POGO scholars held together by a common interest in and commitment to ocean science; and by the common will to communicate the results of their work for the public good. NANO is organized around four regions: Asia, Latin America, Africa, and Europe. The vision for the Network is "Integrated Observations of a Changing Ocean".

- The World Association of Marine Stations (WAMS)

WAMS is a “network of networks” created in 2010 to engage national and regional networks in facilitating more effective and efficient use of their collective infrastructure and scientific expertise. The purpose is to inform and serve public and private institutions responsible for ensuring the sustainability of healthy marine ecosystems and the goods and services they support. “Activities will include research, training, and education…in response to the needs of the user community.” Existing and planned ocean observatories could be connected directly to these coastal marine stations. WAMS will collaborate closely with POGO and the marine component of the GEO Biodiversity Observation Network (GEOBON). It can provide critical support to global programs including GOOS, LMEs, OBIS and IGBP. This cooperation could be implemented quickly and cost-effectively given the resources of the marine stations and their parent organizations.

Together with representatives from IOC and UNESCO’s Man and the Biosphere (MAB) program, the first phase in the development of WAMS will be implemented by a steering group of representatives from national and regional networks of marine stations: the European Marine Network of Marine Institutes and Stations (MARS), the U.S. National Association of Marine Laboratories (NAML), the Association of Marine Laboratories of the Caribbean (AMLC), the Japanese Association for Marine Biology (JAMBIO), the Pacific Institutes of Marine Science (PIMS), the Partnership for Observation of the Global Ocean (POGO), the Australian Tropical Marine Network (TMN), and GOOS–Africa (representing African marine laboratories).

- IOC-IODE Ocean Data and Information Networks

The IODE has initiated Ocean Data and Information Networks ODINs in Africa, Latin America, the Caribbean, the Black Sea region, and the WESTPAC region. Of these, the most advanced is ODINAFRICA.[331] The project brings together more than 40 marine related institutions from twenty five countries in Africa. With the support of the Intergovernmental Oceanographic Commission of UNESCO and the Government of Flanders (Kingdom of Belgium), the network has strived to ensure that data and information on oceans and coasts generated by national, regional and global programs are readily available to a wide range of users in easily understandable formats. The ODINs can contribute to building regional data and communication system for regional GOOS programs.

- Everyone's Gliding Observatories (EGO)[332]

The EGO initiative facilitates collaboration among teams of oceanographers working on the development and use of gliders for ocean observations. EGO consists of scientific teams from Australia, Canada, France, Germany, Italy, Norway, Spain, United Kingdom and the United States. Experiments with international fleets of gliders have been carried out, and annual EGO Workshops (including "Glider Schools") are organized to present and discuss advances in technology and ocean science enabled by gliders.

- Regional Marine Instrument Centers (RMICs)

IOC Resolution EC-XLIII.5 calls for the establishment of IOC-WMO Regional Marine Instrument Centers (RMICs). The primary functions of RMICs are to (1) assist Members of WMO and Member States of the IOC ("the members) to calibrate meteorological and oceanographic *in situ* sensors deployed to measure essential geophysical variables; and (2) improve adherence and traceability of ocean observations and associated metadata to high level standards for instruments and methods of observation on a regional basis. RMICs must (1) assist members in their region to calibrate their national meteorological standards and related oceanographic monitoring instruments; (2) participate in, or organize, JCOMM and/or regional instrument inter-comparisons, following relevant JCOMM recommendations; (3) make a positive contribution to members regarding the quality of measurements; (4) advise members on enquiries regarding instrument performance, maintenance and the availability of relevant guidance materials; (5) participate, or assist, in the organization of regional workshops on meteorological and related oceanographic instruments and measurements; (6) cooperate with other RMICs in the standardization of meteorological and related oceanographic measurements and sensors; and (7) regularly inform members and report, on an annual basis, to the JCOMM Management Committee on the services offered to Member States and the activities carried out. JCOMM in turn should keep the IOC and WMO governing bodies informed of the status and activities of the RMICs, and propose changes, as required.

The IOC Executive Secretary is to work with the Secretary-General of WMO and with IOC Member States toward a global coverage of a RMIC network, with particular emphasis to meet the needs of developing and least developed countries. Two RMICs have been designated to date: (1) National Center of Ocean Standards and Metrology (NCOSM), Tianjin, China for the Asia-Pacific Region and (2) National Data Buoy Center (NDBC), Mississippi, USA North and Central America.

5.7.4 Improving and Expanding Operational Capabilities through Research

Developing operational capabilities is critically dependent on synergies between research, operational communities and the users of marine ecosystem goods and services. Research programs important for coastal GOOS and an emerging alliance of marine industries are highlighted below.

- The Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) Project[333]

IMBER aims to understand and predict how the ocean responds to accelerating global change and the consequent effects on the Earth system and human society. The precursor to IMBER (GLOBEC, Global Ocean Ecosystem Dynamics) was completed at the end of 2009, and some of its ongoing regional programs are being incorporated into IMBER. For example, CLIOTOP (CLimate Impact on Oceanic TOp Predators) emerged during the last 5 years of GLOBEC and is now part of IMBER. The goal is to organize global program to elucidate mechanisms by which climate variability and fishing alter the structure and function of pelagic ecosystems and their top predators. This will be achieved through comparative analyses marine ecosystems in the Atlantic, Indian and Pacific Oceans. The vision is the provision of reliable predictions of changes in top predator populations caused by fishing and climate effects (e.g., land-based inputs of freshwater, sediments and nutrients; ocean warming and acidification).[334]

- The International Long Term Ecological Research Program (ILTER)[335]

ILTER is global 'network of networks' has research sites in a broad spectrum of ecosystems (including many coastal marine and estuarine ecosystems) worldwide. Most ILTER members are national or regional networks of scientists with expertise in the collection, management and analysis of long-term environmental data. Together they are responsible for creating and maintaining a large number of unique long-term datasets. The broad goal is to help understand environmental change from local to global scales through comparative ecosystem analyses. Primary objectives are to (1) Foster collaboration and coordination among ecological researchers and research networks at local, regional and global scales; (2) Improve comparability of long-term ecological data from sites around the world, and facilitate exchange and preservation of this data; (3) Deliver scientific information to scientists, policymakers, and the public to meet the needs of decision-makers at multiple levels; and (4) Facilitate education of the next generation of scientists doing long-term research. Core research areas are primary production and biogeochemistry, population dynamics of key species, and patterns of disturbance.

- The European Marine Ecosystem Observatory (EMECO) [336]

EMECO is an informal European network for integration of monitoring, modeling and research. The partners are building a sustained and integrated end-to-end system to provide IEAs that meet the challenges posed by the European Marine Strategy Framework Directive.

- U.S. Ocean Observatories Initiative (OOI) [337]

OOI has been implemented to build an *in situ* infrastructure for sustained ocean observations in the form of an interactive, globally distributed and integrated system consisting of permanent networks of platforms and sensors (e.g., from cabled observatories to gliders and moorings) that will support long-term time series observations for detecting and studying short-lived episodic events and for resolving, quantifying, and explaining longer-term changes in the oceans. The program is organized around global, regional and coastal scale nodes. The global component includes a network of globally deployed moored instruments designed to support research on the ocean's role in, and response to, climate change; regional observatories provide long-term and adaptive access to measurements of geological and oceanographic phenomena along a single tectonic plate, using electro-optical cable technology to distribute high levels of power and two-way communication bandwidth to the installed sensors; and the coastal scale nodes are consist of two arrays (the Endurance Array in the Northeast Pacific and the Pioneer Array in the Northwest Atlantic) both of which are intended to provide long term time series observations of coastal ocean circulation, material mass balance (e.g., nutrient and carbon fluxes across the continental shelves between land and ocean), ecosystem stability and change, coastal morphology, beach erosion, and other anthropogenic dimensions of land-sea interaction. The regional and coastal nodes support both moored instruments and AUVs.

- The Integrated Marine Observing System (IMOS) of Australia[338]

IMOS-Australia has taken an approach similar to that of the OOI. Five major research themes are addressed: multi-decadal ocean change, climate variability, major boundary currents, continental shelf processes and biological responses. IMOS is designed to be a fully-integrated, national system, observing at ocean-basin and regional scales, and covering physical and biological variables. This is achieved through the operation of a matrix of nodes and facilities. The science nodes act as a focal point for the scientific community and stakeholders to influence the design of the observing system by developing the science plans. There is a Blue Water-Climate Node, and Regional Nodes in Western Australia, Queensland, New South Wales, Southern Australia and Tasmania. IMOS Facilities (mooring networks, gliders, profiling floats, HF radar, CPR surveys, data management and communications, etc.) are being established to support ocean research and long term observations conducted via the Nodes.

- The U.S. Alliance for Coastal Technologies (ACT)[339]

ACT works to (1) identify technology needs and novel technologies; (2) document technology performance and potential; (3) maintain dialogue among technology users, developers, and providers; (4) provide ocean observing systems with information needed to deploy reliable and cost-effective sensor networks; and (5) transition emerging technologies to operational use rapidly and effectively. The Alliance serves as a third-party test bed for evaluating coastal technologies, as an information clearinghouse for coastal technologies, and as a forum for capacity building.

- The World Ocean Council (WOC)[340]

The WOC brings together a wide range of ocean industries (e.g., shipping, oil and gas, fisheries, aquaculture, tourism, renewable energy, ports, dredging, cables and pipelines, and maritime legal, financial and insurance communities) that can increase the "pull" needed to improve and expand operational capabilities. This international coalition aims to achieve a number of objectives that can and should be informed by data and information generated by GOOS including the following: (1) Coordinate collaborative efforts to develop science-based solutions for managing specific industry impacts to the marine environment; (2) Develop collective cross-sectoral industry support for improved ocean science to guide safe and environmentally responsible industry operations; (3) Coordinate constructive ocean industry engagement with other ocean stakeholders to develop business understanding of and contribution to solutions that industry will support (e.g., industry input to multi-stakeholder negotiations on high seas marine protected areas, involvement in the annual UN Law of the Sea meetings); (4) Assist ocean industries to improve environmental performance through best practices and stewardship; and (5) Facilitate interaction among sectors to reduce ocean use conflicts.

6 BUILDING A SYSTEM OF SYSTEMS

6.1 Introduction

Through UNCLOS most coastal nations have agreed to be responsible for maintaining healthy marine ecosystems and sustaining their biodiversity and living marine resources within their respective Exclusive Economic Zones and territorial waters.[341] As discussed in Chapters 4 and 5, pressures on marine and estuarine ecosystems and the impacts of ecosystem state changes exhibit broad spectra of time-space variability that do not recognize national jurisdictions. In addition, coastal waters of IOC member states have many pressures, state changes and impacts in common, and detecting and predicting them requires observations that go beyond national jurisdictions (including the high seas).

Concerns over changes occurring in marine ecosystems led the UN General Assembly to call for a *Regular Process* of assessing ecosystem states by region globally.[342] Such assessments and ecosystem-based approaches to marine spatial planning, environmental protection, resource management and coastal zone management, require implementing, sustaining and evolving a global network of interoperable coastal ocean observing systems (Chapters 2 and 3). Developing the network requires collaboration among nations to build capacity and exchange data, knowledge and technologies. Capacity building and technology transfer are critical to implementing coastal observing systems globally. Exchanging data and information on coastal marine ecosystems is critical to anticipating the effects of larger scale pressures on ecosystem states and the impacts of changes in states. The challenge facing IOC member states is how best to facilitate and accelerate global implementation and sustained evolution of the network.

Currently, there are major differences among nations and regions in their technical capabilities to implement the observing system infrastructure described in Chapter 5. These differences are not surprising given the number and distribution of coastal nations with low GDP per capita (Chapter 1, Figure 2). The current state of coastal ocean observing systems reflects a history of relatively low levels of international coordination and support. Clearly, without a concerted effort by the international community of nations to build capacity in developing countries and emerging economies, these inequalities can be expected to persist and may even grow. The persistence of large gaps in a global network of coastal observing systems creates unacceptable risks to nations in regions where gaps occur as well as to the global community of nations as a whole.

It is in the interests of the global community to develop and implement initiatives to address these deficiencies in order to achieve a comprehensive and effective global network of ocean observations, data management and modeling. This will not be easy. Chapter 1 reviews the challenges that have impeded attempts by the international community to address these needs. Four are addressed here, i.e., the need for (1) multi-scale, multidisciplinary observations in four dimensions, (2) operational ecosystem models and measurements of essential chemical and biological variables, (3) international agreement on standards and protocols for quality control and interoperability of biological and chemical data, and (4) global coordination and collaboration among all IOC member states.

The review of current technical capabilities in Chapter 5 shows that, while additional research and development are clearly needed, existing capabilities can in principle support an effective and sophisticated integrated system of systems (challenges 1 and 2). The immediate challenges are (3) and (4). Here we propose a number of practical and effective initiatives that the international community can undertake to accelerate the implementation of a global network of coastal ocean observing systems.

6.2 A Framework for International Action to Accelerate Coastal GOOS Implementation

Delivering on this vision will require strong collaboration, cooperation and communication among coastal nations and regional bodies as well as among diverse scientific, operational and user communities. Adequate progress is unlikely to be achieved by any one program or approach. Four complementary approaches to accelerating the delivery of Coastal GOOS are as follows:

- Invest in DMAC to Improve Access to Existing Data;
- Support National and International Programs Targeting Priority Infrastructure;
- Support Capacity Building Programs to Fill Priority Spatial and Temporal Gaps in the GCN; and
- Facilitate Regional Implementation of a Pilot Project in a Priority “Super Site” to demonstrate the value added of an end-to-end SoS (e.g., multiple applications of data and

information needed to guide EBAs derived from a common set of observations and models).

These approaches should be seen as complementary and are not mutually exclusive. Investment in DMAC to make existing data available will be cost-effective in itself and will be required to underpin the other approaches. Investment in pilot projects that target priority phenomena of interest and indicators will continue to play an important role in advancing operational capabilities and establishing global communities of practice. Regional implementation and capacity building are complementary activities that will accelerate development of end-to-end integrated systems. The former offers the most direct route to an integrated system of systems, but roll-out of these pilot projects is likely to be limited to a small number of regions due to funding constraints. If the development of each regional observing system takes 5 – 10 years, it will require several decades to achieve full global coverage. Capacity building to fill gaps in a minimal GCN offers a rapid route to a GCN for global assessment, but without establishing regional systems to meet regionally specific needs.

6.2.1 Invest in DMAC to Improve Access to Existing Data

While current investments in coastal ocean observations are substantial (especially in Australia, Europe, Japan, and North America), access to coastal ocean data (near real-time and archived) is often difficult to impossible on regional to global scales. Nationally, local data are often proprietary, accessible only to the funder and collecting organization; data from compliance monitoring (e.g., point source discharges, shellfish beds, aquaculture sites) are often lost or not available in archives once compliance is demonstrated; and data generated by volunteer observers are often not archived for access by groups other than those for which the observations were made originally. Globally, there are a number of international programs designed to acquire and distribute international data sets that target particular phenomena of interest or ecosystem states (see sections 5.7.2 and 5.7.3). **These should be linked and expanded into a global network as outlined in section 5.5.**

Given the existence of relevant data, an investment in a nested network of national, regional and global DMAC systems should prove to be cost-effective. Integration of the data sets produced by the existing international programs should be most straightforward, as these data sets are generally already well-managed and publicly accessible. In addition to building technical capacity in DMAC, international initiatives will need to address legal and political impediments to sharing data through mechanisms such as UNCLOS.

As demonstrated by the implementation strategies of EUROGOOS,[343] IMOS-Australia,[344] NEAR-GOOS (Box 7), IOOS-USA (Box 4), and ODIN programs (section 5.7.3), there are two primary drivers that enable establishing an integrated DMAC system. The first is technical and focuses on (1) the formulation and adoption of common standards and protocols for data formats, data representation, metadata (including QA/QC variable-specific protocols based measurement techniques), access services, and utility services (section 5.5) and (2) near real-time data telemetry (from both *in situ* and remote sensors) and data communications systems for streaming data into web-based data assembly centers (section 5.5, Figures 25 and 26). The programs listed above have already made substantial investments in formulating common standards and protocols (e.g., Boxes 4 and 7) and establishing the required data communication and processing infrastructure. Thus, there is an opportunity for developing counties to take advantage of these advances, minimize costs, and avoid “reinventing the wheel,” as has occurred for example through the broad adoption of mobile telephone and web-based services for business and banking.

The second driver is adoption of the principle of a “public data commons.” This has been something of a revolution for the research community where exclusive access to data for a limited period has been seen as a “right” of those collecting data. However, increasingly public funding of research comes with the condition that data streams from observations and models be made broadly available as soon as is feasible. Most of the observations and modeling of marine and estuarine ecosystems are funded by public monies, and there is a strong argument that these data should be subject to the same conditions. Adoption of modern information technologies and common standards and protocols, and adoption of the principle of a public data commons, could revolutionize access to existing observations nationally and globally. These should be priority goals for GOOS.

Box 7

NEAR-GOOS & DMAC[345]

The North East Asian Regional GOOS (NEAR-GOOS) program is being implemented by WESTPAC[346] as a partnership among the Peoples Republic of China, Japan, the Republic of Korea and the Russian Federation. The highest immediate priority is to facilitate data sharing among the partners via the internet to support daily mapping of environmental conditions in the marginal seas bordered by the partnering countries.

As a first step, two types of operationally linked databases were established: (1) Real-Time Databases (RTDB) that receive and distribute data through the WMO Global Telecommunications System (GTS) and (2) Delayed-Mode Databases (DMDB) which archive the data. It was envisaged that whole datasets from the RTDBs would be binned and periodically transferred to the DMDBs to form a permanent archive.

Data types were confined to physical data (temperature, salinity, current and surface waves), and it was intended to include *in situ* data from moored surface buoys, drifting buoys, towers, coastal stations, research vessels and volunteer observing ships. Also, satellite remote sensed data from geostationary, polar-orbiting satellites and earth-observation satellites were intended for inclusion as this became possible.

In practice it proved appropriate and necessary for each partner to establish (or identify) their own RTDB and DMDB within a national agency with each being responsible for periodically transmitting its data holdings to a corresponding NEAR-GOOS Regional RTDB (RRTDB) or NEAR-GOOS Regional DMDB (RDMDB). To satisfy national requirements for autonomy, national data centers functioned independently and provided data to the RDMDB at their discretion. By the completion of phase 1 each country had consolidated their RTDBs and DMDBs; a regional database system was created as a contribution to GOOS; a policy of free and open data exchange was agreed to; and a data management training program for regional participants was initiated. Major problems remained, including the following: no agreement on what data should be shared; data is submitted at the discretion of each partner; unacceptable delays in data exchange among the partners; the lack common standards and protocols for data management and communication; and specific applications have not been identified that would be improved through data integration, and benefits remain to be seen.

Today the RRTDB is operated by the Japan Meteorological Agency (JMA) for the exchange of oceanographic data among the participating institutions in the NEAR-GOOS. The database contains data collected at JMA from national RTDBs or directly from data providers. Once data has resided in the RRTDB for 30 days, they are transferred to the RDMDB operated by the Japan Oceanographic Data Center. JMA data products include SST fields from merged data streams from in situ and satellite-based observations (global, western North Pacific Ocean, and the seas around Japan), subsurface temperature fields for the seas around Japan, Pacific sea surface heights, and sea ice conditions in the north-east Asian marginal seas.[347]

6.2.2 Support International Programs Targeting Priority Infrastructure

Successful expansion of GOOS to incorporate biological and chemical observations required for EBAs depends on sustained national support of regional "pioneer" ocean observing and predictions systems in, for example, Australia (Integrated Marine Observing System), Europe (EuroGOOS and Global Monitoring for Environment and Security) , and the United States (Integrated Ocean Observing System). Priority infrastructure includes data management and communications systems, remote and in situ observations, and modeling and analysis as described in Chapter 5. Many existing international programs and initiatives described in Chapter 5 are establishing the infrastructure needed to support coastal GOOS priorities for sensors (sections 5.3.2 and 5.3.3) and platforms (section 5.3.4). Most of these programs build on strong scientific and technical communities of practice that provide natural forums for international programs and provide cross-cuts through local and regional observing systems.

Those focused on platforms provide the equivalent of the observing facilities identified and supported in national programs such as IMOS-Australia, i.e., Argo floats, ships of opportunity, national mooring network, gliders, HF radar, animal tagging and tracking, satellite remote sensing, and marine information and ocean data services.[348] Global expansion of such an approach is needed to implement coastal GOOS via existing interdisciplinary programs that have objectives in common with coastal GOOS (section 5.7.1) and global networks (section 5.7.3).

6.2.3 Support Capacity Building Programs to Fill Priority Spatial and Temporal Gaps in the GCN

Section 5.4 provides a justification and initial design for a GCN of Sentinel and Reference Sites. Such a network, when combined with satellite and ocean climate data and data-products, would provide the minimum diversity of measurements and volume of data required for monitoring and assessing global trends in pressures on coastal ecosystem state and state changes. If the global community chose to make the completion of the GCN a high priority, it could review existing and planned programs, identify spatial gaps, and allocate resources to fill those gaps. **The GEO Coastal Zone Community of Practice (section 5.7.1) could oversee the gap analysis**.

Given that many of the gaps are in the EEZs of developing countries, this approach will play an important role in building capacity and will require training to build the workforce and establishment of local infrastructure to fill the gap. Where possible, this could be done through local marine institutions drawing on international partnerships such as WAMS and POGO. Local site support centres could also become local centres for access to the broader data and information accessible through the GCN and coastal GOOS. One might also expect these sites to serve as nuclei for the development of expanded national and regional coastal observing systems.

Depending on available resources, filling gaps may be a phased process beginning with single moorings with monthly visits and expanding over time to include repeat glider transects and mooring networks. The chosen level of investment would depend both on the justification (importance of the gap) and the local capacity to operate and maintain the infrastructure. For example, those nations and regions with limited resources and observing system capabilities may initiate the life cycle (Figure 25) by identifying high priority PoIs that can be addressed using satellite-based remote sensing. Here the priority would be to collaborate with data providers for remote sensing (section 5.7.2), regional networks of marine laboratories (section 5.7.3), the JCOMM Satellite Requirements Task Team, and GHRSST, IOCCG et al. to establish access to satellite data and products that are relevant to their region. The process can be guided by pilot projects such as ChloroGIN, by operational programs such as GLOSS and GTN-R, and by existing volunteer observing programs such as GCRMN and SeaGrassNet. Where Regional Seas Conventions and/or Large Marine Ecosystem programs are active, the first step may be to collaborate with their governing bodies to facilitate their engagement in building coastal GOOS for mutual benefit.

6.2.4 Facilitate Regional Implementation of a Pilot Project in a Priority "Super Site" to Demonstrate the Value Added of a SoS

The IOC provides an important forum for facilitating national commitments, establishing institutional mechanisms for designing and implementing GOOS (e.g., the GOOS Steering Committee, IOC Regional Subsidiary Bodies, and GRAs), and investing in capacity building needed to establish GOOS. However, this has not been sufficient to overcome the challenges described in section 1.2, and it has become clear that these commitments, institutional mechanisms and investments must be complemented by other mechanisms. As Claustre et al. pointed out,[349] international partnerships among research and operational organizations (e.g., POGO, WAMS, and WMO) will provide an opportunity for valuable shared learning by all participants and could be focused initially on priority "super sites" of global significance.

Beyond general guidelines provided in this report, how can the international community provide practical support for implementing integrated and sustained coastal observing systems, especially in regions populated by developing nations? Any such independent initiative should address at least four essential requirements:

- Support the regional community of data providers and users in translating strategic design plans into a cost-effective, feasible, end-to-end observing system of systems that meets local needs;
- Collaborate to establish the required workforce, infrastructure and services for observations, DMAC and modeling and analysis;
- Ensure that local capacity is established to operate, maintain and improve the observing system over time; and
- Attract sufficient long-term funding to sustain and evolve the SoS over time based on user demand for data and information from observations and modeling.

These requirements could be addressed by partnership programs between developed and developing countries that allow participants to share expertise and experience in the design of observing systems and in the deployment and operation of observing platforms and sensors, the DMAC system, and modeling and analysis.

One way to address these requirements is to fund pilot RCOOSs as partnership programs between developed and developing countries. This would allow participants to pool expertise and experience in the design, deployment and operation of observing system infrastructure and in the process train a regional workforce needed for long-term operation, maintenance and improvements. Recognizing the cost and complexity of a global SoS for marine and estuarine ecosystems, a phased, cost-effective plan for building an integrated GCN should include an approach that targets regions characterized by their high productivity and diversity and by resident species-populations and communities of animals and plants that are most likely to provide early warnings of changes in states caused by pressures associated with population growth and distribution, natural hazards and climate change (Table 20). Hypoxia hot spots were identified from Figure 19, toxic harmful algal events from Figure 21, fishing hotspots from Figure 13, hotspots for coastal flooding and human health risks from Table 18, ocean acidification from Figures 17 and 18, temperature and biodiversity from Figure 22, and human impacts from Figure 18.

Region	Hypoxia	Toxic HABs	Fishing Pressure	Health & Flood	Ocean Acid	T°C & Diversity	Human Impact	TOTAL
NORTH ATLANTIC OCEAN								
(1) South/MAB	X	X		X				3
(2) GoM-SL/Lab Sea		X	X					2
(3) G/N/B Seas, BB*ϕ	X	X	X		X		X	5
(4) Canary Currentϕ			X			X		2
(5) Med Sea*ϕε		X		X				2
(6) GoM*/Caribbeanϕϕ ε	X			X				2
SOUTH ATLANTIC OCEAN								
(7) BrC*								0
(8) BeC/GoG**ϕϕ			X	XX				3
INDIAN OCEAN								
(9) AC*ϕ ε						X		1
(10) AS				X				1
(11) BB/AS*ϕ			X	5X		X		7
(12) WAC/TS ε						X		1
SOUTH PACIFIC OCEAN								
(13) A/C/T Seas ε						3X		3
(14) PCϕ			X					1
NORTH PACIFIC OCEAN								
(15) IA-SC Sea****ϕϕϕ εs	X	X	X	5X		X	X	10
(16) EC/Y Seas**ϕ	X	X	X	3X		X	X	8
(17) Seas of J/O		X		X				2
(18) BSea/GoA			X		X	X		3
(19) CC/GC	X	X						2
SOUTHERN OCEAN								
(20) ACP/FC					X			1

Table 20. *Multiple pressures on coastal marine and estuarine ecosystems parsed into 20 regions globally [(1) Western boundary: South & Mid-Atlantic Bights/Long Island Sound; (2) Gulfs of Maine & St. Lawrence/Labrador Sea; (3) Eastern boundary: Greenland-North-Baltic Seas/Bay of Biscay; (4) Eastern boundary: Canary Current; (5) Mediterranean Sea; (6) Gulf of Mexico/Caribbean Sea; (7) Western boundary: Brazil Current; (8) Eastern boundary: Benguela Current/Gulf of Guinea; (9) Western boundary: Agulhas Current; (10) Arabian Sea; (11) Bay of Bengal/Andaman Sea; (12) Eastern boundary: West Australian Current/Timor Sea; (13) Arafura/Coral/Tasman Seas; (14) Eastern boundary: Peru Current; (15) Indonesian Archipelago-South China Sea (Gulf of Thailand and Java, Banda, Celebes, Sulu, and South China Seas); (16) East China/Yellow Seas; (17) Seas of Japan/Okhotsk; (18) Bering Sea/Gulf of Alaska; (19) California Current/Gulf of California; (20) Antarctic Circumpolar Current/Falkland Current] (* Rivers with population densities in their coastal flood plains from Table 17, ϕ LME in the region from Figure 13, and ε regions with marine reserves).*

Country	A	B	Total
Indonesia	10	4	14
Malaysia	2	6	8
Philippines	5	17	22
Thailand	4	6	10
Vietnam	1	6	7
Cambodia	2	2	4

Table 21. *Number of priority MPAs of global-regional (A) and national (B) significance.*[1] *The MPAs are protected areas with substantial open water area. RAMSAR sites with little open water are not included.*

Three regions are subjected to the greatest number of pressures and have multiple sites (3-5) that have high risks of flooding and exposure to waterborne pathogens:

(1) Bay of Bengal-Andaman Sea region;
(2) Indonesian Archipelago-South China Sea (Gulf of Thailand-Java-Banda-Celebes-Sulu-South China Seas) region; and
(3) East China-Yellow Seas region.

Of these the Indonesian Archipelago-South China Sea region is unique in that it has the highest species diversity of any region globally and has sentinel sites for human pressures (Table 21) and state changes for all of the phenomena of interest. The Philippines, Indonesia and Malaysia derive 60-70% of their animal protein from marine fisheries.[350] This region also includes the "Coral Triangle," an area recognized as the global epicenter of marine biodiversity[351] and a global priority for conservation.[352] In addition, the region has three GEF funded LMEs (South China Sea, Indonesian Sea, and Gulf of Thailand, Figure 13a).

Thus, **as a demonstration (pilot) project, a regional version of the GCN as described in section 5.4.3 is recommended for development in the Indonesian Archipelago-South China Sea region.** This regional "super site" could take the form of an international data assimilation demonstration project (modeled after an IMBER-GODAE hybrid) with the goal of providing data and data-products required to inform adaptive, ecosystem-based approaches to marine spatial planning, environmental conservation and coastal zone management for the region as a whole. Through an international coalition of data providers (scientists and technicians) and users (managers, conservation groups, shipping and tourist industries, and fishers) from developed (e.g., Taiwan, Australia and New Zealand), emerging economies (e.g., China) and developing nations (e.g., Philippines, Vietnam, Cambodia, Thailand, Malaysia, Indonesia, East Timor), this could become the prototype for both building an integrated SoS and for regional capacity building, i.e., phased implementation of the system achieves the goal through capacity building (see section 6.2.4 below).

Networks in the region that can facilitate implementation of such a demonstration project include the following:

- Ocean Data and Information Network for the Western Pacific (ODINWESTPAC) Pilot Project[353] initiated to provide an effective capacity building framework for DMAC; to promote regional sharing of marine data, information and products; to develop cooperation with other ODINs and international and regional projects and programs; and to provide data and information services for WESTPAC member states and other users. Member states include Australia, China, Fiji, Indonesia, Malaysia, New Zealand, Philippines, Russia, Samoa, Singapore, Solomon Islands, Thailand, Tonga, UK, USA, and Vietnam.

- The Southeast Region GOOS (SEAGOOS) Committee has been established to promote regional operational oceanography in the wider Southeast Asian Basin through GOOS by establishing SEAGOOS; draft a SEAGOOS strategy document that incorporates the economic, social and environmental protection needs of the region with a clear approach to detailed planning and implementation of SEAGOOS; publicize and disseminate SEAGOOS plans and information to regional governments and the general public; recommend scientific and technical activities to support SEAGOOS implementation by coordinating new pilot projects and providing linkages to existing projects; produce guiding documents for the near real time data collection and exchange in the Wider Southeast Asian Region; advise and consider sources of funding for pilot project development with various funding agencies and in consultation with pilot project leaders; identify the SEAGOOS capacity building needs of participating countries and international or regional organizations that can contribute to SEAGOOS; liaise with national SEAGOOS committees, NEAR-GOOS, GOOS Project Office and other GOOS-related bodies as appropriate.[354]

- The Global Environmental Facility is funding several projects in this region including the following:
    - "Reversing Environmental Degradation Trends in the South China Sea and Gulf of Thailand"[355] is being implemented by UNEP in partnership with seven states bordering the South China Sea (Cambodia, China, Indonesia, Malaysia, Philippines, Thailand, and Vietnam). Goals of the projects are to facilitate collaboration among all stakeholders for addressing environmental problems of the South China Sea-Gulf of Thailand and to enhance the capacity of participating governments to integrate environmental considerations into national development planning. Priority areas of concern are the loss and degradation of coastal habitats, over-exploitation of fisheries in the Gulf of Thailand, and land-based pollution. Of these, habitat degradation and loss is the largest and focuses on mangrove forests, salt marshes, coral reefs, and seagrass beds.

- West Pacific East Asia Oceanic Fisheries Management (WPEA OFM) Project[356] is a collaboration with the Western and Central Pacific Fisheries Commission (WCPFC) to ensure, through effective management, the long term conservation and sustainable use of highly migratory fish stocks in accordance with the 1982 United Nations Convention on the Law of the Sea and the UN Fish Stocks Agreement.
- Arafura and Timor Seas Ecosystem Action (ATSEA) Program[357] has the goal of sustaining the use of the living coastal and marine resources (including fisheries and biodiversity) and improved sustainable socio-economic conditions and opportunities for coastal peoples. The program is in support of the Arafura and Timor Seas Expert Forum (ATSEF) which was established to assist the stakeholders who depend upon the Arafura and Timor Seas in achieving the goals of sustainable development to support their livelihood.
- Sulu-Celebes Seas Sustainable Fisheries Management (SCS SFM) Project[358] works with Conservation International to update the transboundary diagnostic analysis (TDA) of the Sulu-Celebes (Sulawesi) Seas Large Marine Ecosystem (SCS LME).
- Large Marine Ecosystem programs in the Gulf of Thailand, South China Sea and the Indonesian Sea (Figure 13 and section 5.7.1).

- The East and Southeast Asia Biodiversity Information Initiative (ESABII) was established to contribute to the implementation of the Strategic Plan for the Convention on Biological Diversity (CBD). This will be achieved through the development of biodiversity information systems and taxonomic capacity building in East and Southeast Asia. Members include countries (Brunei Darussalam, Cambodia, China, Indonesia, Japan, Lao People's Democratic Republic, Malaysia, Mongolia, Myanmar, Philippines, Republic of Korea, Singapore, Thailand and Viet Nam), organizations (Secretariat of the CBD, the Association of Southeast Asian Nations (ASEAN) Centre for Biodiversity, and the Global Biodiversity Information Facility), and networks (Natural Geography In Shore Areas, the Asia-Pacific Biodiversity Observation Network, and BioNET-International).[359]

- The Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security of Conservation International (CI) is a government partnership (Philippines, Indonesia, Papua New Guinea, Malaysia, East Timor, Solomon Islands) dedicated to promoting healthy oceans by helping people manage their marine resources through creating and strengthening Marine Protected Areas (MPAs), promoting Seascape management at a large scale, improving fisheries, adapting to climate change and recovering threatened species.[360] CI has targeted the area as a priority for marine conservation activities. Through two Seascapes (Sulu Sulawesi and Bird's Head), CI and its partners are working to improve the stewardship of marine wildlife and to reinforce and enhance the legal and policy authorities for marine conservation in the Seascapes. In addition to its Seascape approach, CI's work in the Coral Triangle centers around developing marine protected areas, sea turtle and shark conservation, helping species and communities prepare for and adapt to climate change, supporting the Global Marine Species Assessment, and improving fisheries management.

- Pacific Institutes of Marine Science (PIMS) is a non-profit organization and a member of WAMS. Its objectives are to promote joint research program and exchange graduate students, post doctoral fellows, and faculty. PIMS' objectives include increasing research and education on marine and coastal resources, facilitating the wise use and conservation of marine and coastal resources, and encouraging collaboration on initiatives in related areas, and to stimulate cooperation among member institutions.[361]

6.3 Priorities for Research and Development

6.3.1 Modeling

GODAE OceanView

The GODAE OceanView Work Plan (section 5.2.1) identifies seven application areas to be addressed that are important to the development of operational capabilities of GOOS as a whole:

- The use of data assimilation to provide integrated descriptions of the global ocean state (reanalysis) and to characterize and detect climate change in the ocean;
- The application of ocean prediction techniques to the prediction of climate change (so-called decadal prediction);
- The assessment and characterization of specific sources of uncertainty in down-scaling of climate and climate-change scenario simulations and predictions in studies of the impact of climate change in coastal regions (e.g. sea level rise and coastal flooding, ocean warming and acidification);
- The development of improved atmospheric and climate forecasts (near coasts, tropical cyclones, monsoons, seasonal);
- Real-time forecasting in near-shore coastal waters (e.g., current and wave fields, biogeochemical cycles) and coupling between open ocean and coastal waters;
- Ecosystem modeling to inform ecosystem based management of living marine resources (coupled physical-trophic dynamics); and
- Marine environment monitoring in support of ocean policies.

To the extent that these objectives are achieved, GODAE OceanView will make a major contribution to implementing coastal GOOS. Of particular relevance to the development of coastal GOOS as an integral contribution to GOOS as a whole will be the extension of eddy-resolving data-assimilating ocean models inshore, across the shelf, and into bays and estuaries, exploiting advances in model nesting and variable resolution and adaptive grids. We can also expect to see "improved integration of wave models into coastal coupled atmospheric-hydrodynamic models, and improved sediment model predictions of turbidity and coastal geomorphology." PICO strongly endorse these objectives and urges the OceanView task teams to implement the recommendation herein as appropriate.

Receiving Water Quality Models (RWQMs)

While RWQMs have been widely applied (section 5.2.2), many implementations have been used tactically to support "one-off" environmental impact assessments and then abandoned. A limited number of coastal water bodies have been the subject of long-term modeling efforts.[362]

In comparison with operational ocean forecasting models, metrics and performance criteria for coastal model evaluation and inter-comparison are not well established. This is an area that is receiving increasing attention. But even where quantitative performance criteria are adopted, model calibration and parameter estimation is still largely a process of heuristic tuning, and there is a serious risk of over tuning given the large number of parameters and relatively sparse observations. There are no objective criteria for the adequacy of observations to support model development, and in the absence of formal data assimilation techniques, it is not possible to use OSEs or OSSEs for observing system evaluation and design.

This heuristic approach to model error partly reflects the fact that RWQMs are typically used to generate "what-if" scenarios of the long-term implications of implementing different management strategies rather than providing nowcasts and forecasts that are used operationally guide management decisions. In this sense, they have been more like coupled climate models, than to data-assimilating, ocean forecasting models. The success of GODAE has enabled and inspired a current move to develop operational, near real-time coastal models to provide a number of potential uses and benefits:

- Maritime operators and environmental managers have uses for more accurate nowcasts and short-term forecasts in coastal waters.
- The establishment of data-assimilating models would encourage and require agreement on standard metrics for model-data comparison, and performance measures for model skill.
- Data-assimilating model nowcasts can potentially provide more accurate assessments of system status by dynamically interpolating among sparse observations.
- Data-assimilating models would allow development of OSEs and OSSEs to provide badly needed objective advice and guidance into the design of coastal observing systems.
- Long hindcasts from data assimilating models can be expected to dramatically improve our understanding of coastal physical and ecosystem processes, as it has done for ocean circulation and ecosystems.

- Establishment of ongoing operational models would avoid the waste of the recurrent implementation of new models to meet tactical needs, and likely prove more cost-effective over time.

Just as for climate modeling, coastal modelers need to improve and understand errors in long-term model scenarios, not just nowcasts and short-term forecasts. This requires methods for data assimilation or model data fusion that do not simply nudge or adjust the current model state to agree better (in a dynamically consistent sense) with observations, but simultaneously to adjust model parameters to provide more consistent scenarios. This is an active research area.[363]

It's unclear whether the long-term outcome for inshore coastal modeling will involve ongoing operational models in all estuaries, or even all large priority estuaries. It may be that most estuaries will still be served on an "as needed" basis by relocatable models, although there is an increasing trend to incorporate multiple estuary models as part of regional operational models through variable grids.[364] In any case, development of the tools implied above (agreed performance and skill metrics, data-assimilation and automated calibration, use of OSSEs to support observing system design) would radically improve relocatable coastal modeling capability.

Fisheries and Ecosystem Models

Extending fisheries models to address interactions among multiple species and to support ecosystem based approaches to fisheries management has received considerable attention over the last decade. International collaboration in this area has been supported by GLOBEC and now IMBER. The questions and applications driving the development of multi-species and ecosystem models for fisheries can be consolidated under the following broad categories: [365]

- What are the impacts of harvesting a particular target stock on other parts of the ecosystem, including bycatch, trophic interactions, and habitat modification? Do these effects feed back to change the conclusions about sustainable fish yields obtained from single-species models?
- What are the impacts of changes in abundance and distribution of other biological components of the ecosystem on sustainable fishery yields, and/or on prospects for recovery of depleted stocks? This question has arisen particularly with respect to the effects of the recovery of marine mammal populations from previous exploitation.
- Where multiple interacting stocks are harvested, how do trophic interactions affect yields, and how should effort and catches be distributed across species?
- What are the bottom-up effects of changes in the physico-chemical environment on ecosystem structure in general and fishery yields in particular. These changes can include not only climate variability and change, but also potentially impacts of coastal pollution, ocean fertilization and acidification.

Models needed to address these questions fall into the following categories in order of increasing scope and complexity:

- Extensions of single-species assessment models, to take a small number of other interactions into account;
- Dynamic multi-species models or "minimum realistic models" include a limited number of other species or functional groups which interact strongly with the target species, typically direct prey or predators, or key habitats;
- Dynamic system models represent the interaction between bottom-up (physico-chemical) and top-down (biological) forces operating in an ecosystem, and typically take a more comprehensive approach to the representation of food web structures;
- Whole of ecosystem models, which attempt to represent all trophic levels in the ecosystem, but in some cases also represent physio-chemical drivers and the socioeconomic dynamics of the fleets exploiting the resource.

Data requirements are particularly high for multi-species virtual population analyses (MSVPA), which are arguably the most ambitious assessment models currently in use. These diagnostic models use both catch-at-age data and diet (usually stomach content) data to estimate fishing and predation mortalities of multiple interacting populations, in some cases in a spatially-resolved context. Obtaining the required stomach content data is particularly difficult and expensive, and suitable data are available for only a few regions, such as the North Sea, the Gulf of Alaska and Georges Bank.

Key trends and future opportunities in ecosystem modeling for fisheries include the following:

- Improvements in coupling physico-chemical or biogeochemical models to trophic dynamic and whole ecosystem models;
- Improved spatial resolution in ecosystem models;
- Coupling of multiple ecosystem models to form "meta-ecosystem" models;
- Development of hybrid agent-based and bulk dynamical models;
- Increasing use of ecosystem models as operating models (while noting the limitations of data availability); and
- Development of socio-ecological models that can be used for cost-benefit analyses of implementing ocean policies and for assessing the efficacy of management in terms of both socioeconomic and ecological indicators.

<u>Convergence, Integration, and Synergy for Operational Marine Ecological Modeling</u>

Based on the above review and the summary of current modeling capabilities in section 5.2, there is a clear need for (1) more rigorous and quantitative metrics for model error and skill; (2) the development of quantitative and objective statistical procedures for model calibration, parameter estimation, and data assimilation; (3) using OSSEs to help inform observing system design; and (4) integrating physical, biogeochemical and ecosystem models to inform EBAs.

Metrics for model error and skill are most advanced for physical ocean models and fisheries stock assessment models. Dynamical models of biogeochemical cycles, trophic dynamics (phytoplankton to large predators), and ecosystems are high priorities for R&C and pilot projects. It is important to note that, if it is not to be *ad hoc*, the comparison of model state with observations requires a formal probabilistic treatment of observation error as well as process model error. This requires the careful analysis and modeling of observation methods and processes. In many cases, mismatches in scale and even in type between observed and modeled variables make a much larger contribution than instrument or analytical errors. It is also important to note that measures of model performance and skill are not context free, and generally relate to particular products and applications.

Through projects such as GODAE, and drawing the long history developing data assimilation techniques for numerical weather prediction, procedures for model calibration, parameter and state estimation have developed rapidly for ocean circulation models in the last decade. Most of these techniques are computationally demanding, and it is only in the last decade that computing power has advanced to the point where they can be widely applied to highly-resolved numerical models, e.g., eddy-resolving ocean circulation models. We can expect to see rapid progress in the development of data assimilation techniques for coastal circulation models and perhaps to biogeochemical models. Nonetheless, there is an important distinction between the use of these techniques for improving state estimation (the principal use in ocean forecasting) and their use for model calibration and improvement. The latter is essential for applications which depend on long-term predictions and scenarios, as opposed to analyses and short-term forecasts where errors are dominated by errors in initial conditions. The fisheries techniques have been developed to address both, and there is a need to extend these methods or develop new approaches for computationally expensive physical and biogeochemical models.

These techniques are subject to the curse of dimensionality, and it’s unclear how far they can be extended to whole ecosystem models, with very high levels of structural uncertainty and large numbers of uncertain parameters. At present, most ecosystem modelers do not recommend their use for quantitative forecasting, but rather as a basis for qualitative scenarios or as operating models in OMP/MSE frameworks. The benefits of these techniques are not only more accurate products, and more objective and realistic assessments of model error, but potentially very large increases in efficiency and effective capacity, if heuristic model tuning techniques, requiring large investments of time from “experts”, can be replaced by more automated procedures.

As noted in section 5.2.3, there is an interesting parallel between OSSEs and the OMP/MSE frameworks used in fisheries. The OMP/MSE approaches evaluate the benefits of different adaptive management strategies or procedures and, consequently, attach a benefit to monitoring programs that are essential for adaptive strategies. In general, OMP/MSE goes further than OSSEs, by estimating benefits in terms of the expected performance against management objectives. One can think of OSSEs as a special case of OMP/MSE, with "management objectives" confined to model skill. In both cases, the benefits of improving observations need to be weighed against the costs.

There is a well-recognized risk of circular reasoning in that OSSEs and OMP/MSE draw conclusions about observing system design based on theoretical model predictions. There are two arguments for doing this. One is that, if the observations are to be interpolated and interpreted through assimilation into a model, it's appropriate to assess their value in the context of the model. The other more general argument is, in effect, a "bootstrapping" argument. Given accurate observations of all variables at all time and space scales, one could carry out observing system design empirically, based on the data. But in most cases it is neither feasible nor affordable to collect dense sets of observations on the full spectrum of properties and processes that constitute marine ecosystems, i.e., the available observations tend to be sparse in space and time and represent only a subset of variables. Realistic models, such as high-resolution circulation models, provide information about spatial and temporal autocorrelations and cross-correlations that are not available in sparse observations. It's these correlation structures that are exploited to identify efficient sparse observing designs.

The emerging convergence of modeling disciplines to develop integrated whole ecosystem models can be seen as a logical consequence of the move to adopt EBAs for environmental and natural resource management. Users are less inclined to manage individual phenomena and system components in isolation, and are more concerned about interactions among drivers and pressures through biophysical and socioeconomic systems. This partly reflects growing awareness of the importance of interactions, and partly the fact that the growing intensity of human uses and pressures means that interactions are more frequent and more significant when they do occur. The trend also reflects growing capability and skill within the component disciplines. As data-assimilating circulation models or coupled climate models provide hindcasts of ocean and coastal states with unprecedented resolution and accuracy, and more realistic scenarios for future states, it makes sense to incorporate this knowledge into fisheries models and RWQMs.

That said, the challenges involved in integrating information and processes at widely differing spatial scales, and different levels of uncertainty, should not be underestimated. Leaders in this field have described the development of ecosystem models as being in its formative years. These models are still the subject of active research and development, and are not regarded as operational. They have been successfully used as operating models within an MSE framework. As concepts and software platforms mature, one can expect wider and more cost-effective implementation, and Ecopath with Ecosim has already made substantial steps in that direction.

The lack of adequate observations and of clear specifications of the data requirements represents a significant barrier to their operational implementation.

6.3.2 Remote Sensing

In addition to data continuity concerns (section 5.3.2); a major challenge for satellite-based observations of coastal ecosystems is detecting and adequately resolving changes in pressures, states and impacts. Most current satellite sensors were deployed primarily for observing and characterizing global and basin-scale ocean processes and phenomena, and do not entirely capture the spatio-temporal variability that characterizes coastal marine and estuarine ecosystems. Coastal ecosystems require geophysical and biological/biogeochemical observations with greater resolution than existing satellite-based sensors can provide.[366] In particular, improved resolution (spatial, temporal and/or spectral), broader coverage and increased accuracy are needed for OCR[367], sea surface height[368] and ocean surface vector winds[369] in support of coastal applications. These and other needs will hopefully be addressed by the next generation of satellite sensors/missions to be implemented in the coming decade and beyond.[370]

- Increased temporal resolution (e.g., hourly or better observations of targeted marine ecosystems) and spatial resolution (~ 100 m compared to typical current capability of ~ 1,000 m) of ocean color radiometry (OCR) observations are needed to monitor phytoplankton biomass/productivity and dynamic processes in coastal marine ecosystems. OCR sensors on geostationary platforms that can be positioned over specific regions and marine ecosystems will address the need for increased frequency of observations.[371] A constellation of geostationary ocean color imagers providing synoptic coverage across the ocean basins would significantly improve our ability to detect climate-driven changes in phytoplankton biomass and productivity that impact the carrying capacity of marine ecosystems for living marine resources and carbon sequestration in the ocean. Spectral coverage and resolution for OCR should span the ultraviolet (UV) through the shortwave infrared (SWIR), with a greater number (>10) of spectral bands, to ensure there is enough spectral information to accurately discriminate in water constituents and characterize aquatic processes and phenomena in dynamic, optically-complex coastal waters.
- Improved aerosol characterizations and atmospheric corrections for ocean color radiometry represent a significant knowledge challenge[372], likewise the ability to differentiate and quantify phytoplankton floristic and functional groups which will be facilitated by hyperspectral space-based sensors. Continued efforts are needed to develop new and improved algorithms, as well as remotely sensed proxies (e.g., extracted from water-leaving radiance spectra) for essential variables that cannot be measured directly (e.g., chemical contaminant and pathogen concentrations).
- Proposed swath altimeter missions (e.g., SWOT from NASA and CNES) would allow for higher spatial resolution and broader coverage for improved estimates of water level (sea

level and volume of water in land-based freshwater systems) as well as improved information on bathymetry, tidal variations, circulation features (e.g., eddies and fronts) and currents in coastal and estuarine ecosystems.[373] Estimates of river discharge are likewise of great interest and need, and could result from proposed swath altimeter missions such as SWOT. These measurements are all likewise of interest to the preceding food security and exposure to waterborne contaminants applications.

- Wind fields from scatterometry need greater resolution (goals of 1-5 km, 1-3 hours), coverage (to within 1 km of the coastline), and accuracy (± 2 kt) under both rainy and high wind conditions to support operational needs and to improve the skill of forecasts that depend on coupled ocean-atmosphere models.[374]
- Other space-based knowledge challenges continue to exist[375], including routine and synoptic observations of ocean surface currents in the coastal zone.

6.3.3 *In Situ* Sensing

As discussed in 5.3.3, *in situ* sensors for near-real time monitoring of biological and chemical variables fall into three categories: (1) operationally mature, (2) pre-operational and (3) emerging technologies. Major aspects of marine biogeochemistry (carbon, nitrogen, and phosphorus cycles), lower trophic levels (phytoplankton and zooplankton), and biologically structured shallow water and tidal habitats are monitored using category 1 sensors. Thus, a priority for improving operational capabilities is sustained monitoring of large pelagic predators. As summarized below, the first priority is to begin the process of transitioning pre-operational projects into operational contributions to GOOS for this purpose. The second priority is to improve operational capabilities in general by transitioning key emerging technologies into a pre-operational mode.

Priority 1

Two acoustic based systems for tracking the movements of pelagic animals, estimating their abundance and mortality rates, and monitoring upper ocean marine ecosystems are being implemented globally: the OTN and GTOPP.

OTN is an international collaboration that is building on technologies developed by the Pacific Ocean Shelf Tracking (POST) project[376] to implement a global network of acoustic curtains for tracking the movements of relatively small fish (implanted with individual-specific acoustic tags) over continental shelves. GTOPP program builds on technologies developed by the TOPP project[377] and is also an international collaboration, but with a focus on tracking the movements of highly migratory, apex predators and large organisms (e.g., sharks, tuna, swordfish, squid, turtles, seals, whales, albatross and sooty shearwaters) and using them as sensor platforms. Many of these animals also undergo extensive diel vertical migrations and thereby provide data on the vertical distributions of essential variables (e.g., temperature, salinity, ambient light, dissolved oxygen, pH, fCO_2, and chlorophyll-a).[378] By tracking the movements of several species of large

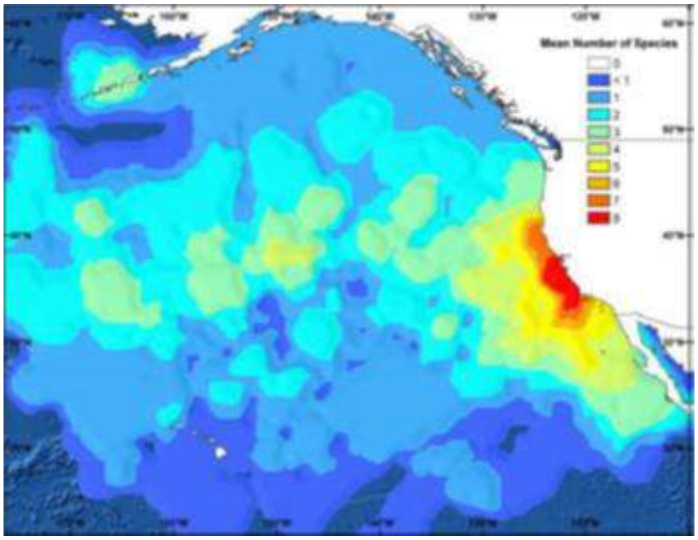

Figure 26. *Patterns of marine biodiversity can be identified using the methods developed by TOPP. The red patch off the west coast of North America is a "hot spot" of biodiversity in terms of the number of pelagic predators that congregate there to feed.*

pelagic animals, data are provided on their environmental experience, encounters with other tagged animals, and "hot spots" where organisms aggregate to feed (Figure 26).

The OTN and GTOPP programs complement and enable each other. TOPP technology uses large animals and depends on satellites for tracking and transmitting data while POST technology uses smaller animals and depends on benthic acoustic receivers for acquiring data with data transmission via fiber optic cable and satellites. With the implementation of OTN, the larger GTOPP animals can also transmit data to data assembly centers via benthic receivers. The Ocean Tracking Network (OTN) integrates both the POST and TOPP technologies to record the passage of tagged animals and record oceanographic data from depths to 500 m hundreds of kilometers offshore. Together, the OTN and GTOPP will enable estimates of abundance and mortality rates of pelagic animals from 20 gram fish to 20 tonne whales (three trophic levels from apex predators down) and semi-continuous monitoring of the movements pelagic animals, the environmental experience of larger animals, and encounters between large predators and small fish (e.g., prey). Currently, these data are recovered in delayed mode, but near real-time data telemetry is in development.

Priority 2

Clearly, many of the building blocks of an integrated global ocean observing exist, and there is a continuing need for low costs sensors that are small and capable of long, autonomous measurements (stable with low power requirement). In addition to the need for research to develop more sensitive nutrient sensors and fish tags that can download data to acoustic curtain receivers as discussed above, five *in situ* sensor system currently in development need to be transitioned to pre-operational status: aragonite saturation state, toxic phytoplankton and waterborne pathogens (bacteria and viruses), abundance and distribution of zooplankton, and species diversity of communities associated with coral reefs.

- **Aragonite Saturation State** (Ω_{arag})

Ω_{arag} is a function of temperature, salinity, pressure, and the concentrations of Ca^{2+} and CO_3^{2-}. Since [Ca^{2+}] changes in sea water are relatively small, changes in Ω_{arag} are directly related to changes in [CO_3^{2-}] which can be estimated from measurements of dissolved inorganic carbon and A_T. Both can be measured in the laboratory using coulometric and potentiometric techniques,[379] but proven *in situ* sensor technologies have yet to be developed. Prototype sensors for DIC[380] and A_T [381] have been built and are the most promising near-term prospects for full CO_2 system characterization. However, they all require moving parts in the form of pumps and valves. In the meantime, a multiple linear regression model for robust estimates of Ω_{arag} from observations of temperature and oxygen (R^2 = 0.987, RMS error 0.053) has been developed using data collected in the Pacific Northwest region.[382]

- **Toxic Phytoplankton and Waterborne Pathogens**

Both optical and molecular techniques have been developed to estimate the abundance of toxic phytoplankton species and waterborne pathogens. The former include measurements of both inherent (e.g., absorption and fluorescence spectra) and apparent (ocean color, distribution of light in the ocean) optical properties of microbes. The latter includes immunoassay, molecular probes, polymerase chain reaction (PCR), quantitative PCR (Q-PCR), nucleic acid sequence based amplification (NASBA), and microarrays. Operational *in situ* sensors for infectious microbes (and their indicators, e.g., enterococci) and non-pigmented phytoplankton rely on molecular techniques while those for pigmented, toxic phytoplankton may use either or both.

The most advanced optical biosensor for detecting and quantifying the abundance of toxic phytoplankton is the Optical Phytoplankton Discriminator[383] (OPD) or “brevebuster” which has been developed to discriminate *K. brevis* from other particles based on its inherent optical properties. This instrument has been successfully deployed on moorings and autonomous underwater vehicles to monitor and map blooms in the Gulf of Mexico, and can be customized to detect other species with unique pigment signatures.

In situ biosensors that have the potential to detect and monitor the concentration of both infectious microbes and toxic phytoplankton depend on the development of automated sampling systems that capture, concentrate and detect molecular targets specific to the targeted species or strain. Three instruments are currently available for this purpose: the Imaging Flow Cytobot,[384] the Autonomous Microbial Genosensor[385] (AMG) and the Environmental Sample Processor[386] (ESP). The AMG is a microbe detection buoy that transmits data on species-specific cell concentrations in near real-time. It utilizes a syringe pump for sampling, filtration-extraction columns to concentrate and extract RNA, and NASBA (an RNA-based amplification technique) with resulting increase in fluorescence used to estimate the abundance of *K. brevis* in the sample. Like the OPD, the AMG can be customized to detect other species or strains.

The Imaging FlowCytobot enumerates and discriminates of different types of individual phytoplankton cells based on size (flow cytometry) and shape (photo-imaging). The instrument has been field tested on ships, moorings and profiling platforms in the Gulfs of Maine and Mexico where it has detected cells of *Karenia brevis* and *Dinophysis cf. ovum*. The latter led to the closure of shellfish beds before humans were exposed.[387]

The ESP is generally deployed on moorings at fixed locations for time series measurements (e.g. 30 d) or from ships for small to mesoscale surveys. The instrument automatically collects discrete water samples sequentially through time, concentrates microorganisms, and uses molecular probe technologies (sandwich hybridization assays and enzyme-linked immunosorbent assays) to measure the concentration of microbial species and strains. The molecular probes can be multiplexed for simultaneous detection of multiple target species of phytoplankton, toxins and bacteria simultaneously. The ESP also supports sensors for measuring oceanographic variables (e.g. temperature, salinity, and chlorophyll-a) and is able to archive samples for subsequent laboratory analyses.

- **Meso- and Micro-zooplankton (including micro-nekton)**

Optical imaging and acoustic systems are developing that will provide observations needed to estimate the time-space distribution and abundance of mid-trophic level organisms in near real-time.

Automated plankton recognition systems have developed to achieve two objectives:[388] (1) reduce the time required to analyze samples collected with traditional nets, and (2) identify and enumerate plankton in near real-time using images of organisms collected *in situ* by video plankton recorders. A number of possible systems now exist,[389] but most of them still need considerable re-engineering to be suitable for long term systematic unattended observing systems. The current state of optical plankton imaging and analysis systems can be summarized as follows:

  - Most planktonic organisms < 20 μm (most phytoplankton and many microzooplankton) are not amenable to automatic recognition;
  - Analysis and software systems for plankton identification are less mature than the imaging hardware;
  - Biofouling can degrade performance on long term deployments;
  - Coastal regions present a particular challenge to discriminate the target particles against a high background of non-target particles;
  - Offshore regions present the challenge of observing a large enough volume (and broad

depth of focus) in environments with a low density of particles; and
- New low-power, broad size-range digital holographic systems integrated into profiling floats show potential for remote sensing of plankton taxa over large areas of the ocean.

Active acoustic observations are essential for detecting and predicting changes in the distribution and abundance of mid-trophic organisms (mesozooplankton, macrozooplankton, and micronekton) upon which top predators depend and for parameterizing, validating, and constraining numerical models of trophic dynamics required to inform EBAs to sustaining living marine resources. Development of multi-frequency systems to obtain backscattered energy from different size classes of organisms has been rapid in the last decade. Advanced sonars can see shrimp 3km down and wave-guide acoustics can count fish within a 100km circle.[390] Automated acoustic surveys using hydrophone arrays and AUVs have the potential to provide simultaneous two- or three-dimensional observations of organisms from zooplankton to large predators over a broad range of scales. Hydroacoustics enable the direct observation of ecological relationships and can provide quantitative estimates of forage biomass. A major initiative has been proposed to do just this, i.e., establish a network of automated acoustic recorders using a variety of platforms from moorings to ships.[391] The goals of the Mid-Trophic Automatic Acoustic Sampler (MAAS) initiative is to establish a network of platforms equipped with multi-frequency acoustics that will provide data for identification and quantification of mid-trophic animals globally and to develop routines and protocols for assimilating these data into an existing and future model frameworks and thus demonstrate.

Given the spatial extent of open-ocean pelagic ecosystems and the extensive travels of many top predators, an approach that combines Lagrangian and Eularian techniques will be needed, e.g., digital holographic recorders on profiling floats and a network of automated acoustic monitoring stations (autonomous calibrated echo sounders with automatic data analysis and processing). An effort that aims to incorporate both approaches is the Climate Impact on Top Predators (CLIOTOP) initiative. The broad goal of CLIOTOP is to conduct a comparative ecosystem analysis on a global scale to determine the effects of climate variability and fishing on the structure and function of open ocean pelagic ecosystems and their top predator species by elucidating the key processes involved in open ocean ecosystem functioning, including the dynamics of mid-trophic level animals.[392]

- **Species Diversity** (Near-real time and delayed mode)

Coral Reef Communities

In addition to deploying Autonomous Reef Monitoring Structures (ARMS) as described in section 5.3.3 (delayed mode monitoring), passive acoustic recorders (Ecological Acoustic Recorders, EARs) have been used for near-real time monitoring of warm water coral reefs with the acoustic spectra providing data on the species diversity of reefs and activities of sound-producing organisms and humans.[393] The acoustic signatures tend to follow well-defined, temporal patterns that are correlated with diel cycles, changes in day length, and seasons. Thus, the ambient sound field also reflects abiotic factors experienced by the coral reef community.

Near-Shore Benthic Communities

The Natural Geography of Inshore Areas (NaGISA) project is being established to observe changes in the species diversity of benthic communities from the high intertidal to 20 m from pole to pole and around the equators (section 5.3.3). This should be promoted as a GOOS pilot project.

DNA Bar Coding

The development of massively parallel DNA sequencing technology has enabled scientists to begin building a library of species-specific "bar codes" that can be used to rapidly identify strains and species of viruses, bacteria, phytoplankton and zooplankton (section 5.3.3). Continuing these efforts and developing platforms (section 5.3.4) for their application to near-real time detection, is a high priority for coastal GOOS.

6.4 Next Steps

6.4.1 Implementation

Coastal GOOS will be implemented by nations, by GRAs and by other international bodies supported by nations. **Needed are mechanisms to ensure the development of a network of national and regional observing systems that are locally relevant and globally coordinated**. Such mechanisms must (1) promote the development of regional coastal ocean observing systems and services worldwide; (2) promote the development of a GCN through coordinated regional development (as described in section 6.2); (3) engage groups that use, depend on, manage or study marine systems (see section 5.7) in the design, operation and improvement of a coastal GOOS that meets their data and information needs on local to global scales; and (4) effectively interface with the existing planning, oversight and implementation bodies of GEOSS, GOOS, GCOS and GTOS.

In 2006 a Joint JCOMM-GSSC-GRA *ad hoc* Task Team (TT)[394] was tasked with proposing mechanisms for establishing coastal GOOS based on the COOP Implementation Strategy.[395] The following TT recommendations recognize the significance of land-based sources of water, sediments, nutrients and chemical contaminants as pressures on coastal marine and estuarine ecosystems and reflect recent changes in the governance of GOOS:[396]

- The GOOS Regional Council (GRC) should be strengthened and institutionalized to ensure the implementation of a GCN that meets the needs of GRAs as a whole and is interoperable on a global scale (for both coastal and global modules). GRC members should be appointed by the GRAs, and a Chairperson should be elected by the membership. The GRC should function under the auspices of the GSC.

- Establish a Joint (GOOS/GTOS) Panel for Integrated Coastal Observations (JPICO) for technical guidance as recommended by the IGOS Coastal Theme. J-PICO should report to the GSC and the GTOS Steering Committee and provide scientific and technical guidance to GRAs and JCOMM through the GSC.

- Within the framework of the UN Convention on the Law of the Sea, agreements will be needed among countries to enable the timely exchange of data on the state of coastal waters relevant to achieving the six societal goals of coastal GOOS. This will be a challenge and should be a high priority for the IOC Assembly, especially for essential variables identified by the Panel for Integrated Coastal Observations.

- Capacity building is particularly important for implementing the coastal module globally. There is an immediate need to establish mechanisms by which GRAs determine priorities for capacity building in their respective regions and for IOC-IODE-JCOMM-GEO capacity building efforts to be coordinated to address these priorities. This should involve implementing capacity building efforts as part of ongoing programs (e.g., GLOSS capacity building) and GOOS pilot projects (e.g., ChloroGIN) based on guidance from the GRC to the GSC and the IOC Capacity Building Committee.

With these recommendations in mind, **high priority should be given to establishing Regional Stakeholder Forums and putting in motion RCOOS life cycles** (section 5.6.2, Figure 25) to implement the priorities set forth in 6.2. The effectiveness of this approach depends on the developing the capability to (1) monitor and predict the propagation of ecological variability across global-regional-local scales and (2) conduct comparative analyses of marine ecosystems globally. Thus, the operational goal must be the establishment of interoperable networks of ocean observing and prediction systems that encompass local, regional and global scales. Achieving this goal will require substantial investments by developed countries in coastal observing and prediction systems beyond their own EEZs, i.e., internationally coordinated investments in sustained capacity building through partnerships between developed countries, emerging economies and developing countries as recommended in section 6.2. Without such investments, the development of the coastal module of GOOS will be highly patchy and based on the resources of a few wealthy nations. Some regions will have highly advanced and mature networks of sensors, platforms and models while other will have next to nothing. In the absence of timely and regular global assessments of ecosystem health and their capacity to provide goods and services, implementation of EBAs to managing, mitigating and adapting to changes in our environment will be incomplete if not impossible.

6.4.2 Coordination

JCOMM is the coordination mechanisms for implementing the open ocean-climate observing systems of GOOS and GCOS.[397] The Commission coordinates and develops and recommends standards and procedures for a fully integrated marine observing, data management and services system that uses state-of-the-art technologies and capabilities, is responsive to the evolving needs of all users of marine data and products, and includes an outreach program to enhance the national capacity of all maritime countries. No such mechanism is in place for coordinating the global establishment of coastal networks of observations, data management, and analysis that includes the full spectrum of required geophysical, biophysical, chemical and biological variables.

Although the Joint JCOMM-GSSC-GRA TT also recommended that JCOMM coordinate the integration of all of the essential variables to be measured as part of the GCN (as their data streams become pre-operational and bodies have been established to sustain them), JCOMM does not have the resources or expertise to take on most essential chemical, biological and biophysical variables (Table 14). The way forward for coastal GOOS should either involve resourcing an expanded JCOMM or, as recommended in the COOP Implementation Strategy, resourcing the GRC to oversee an equivalent of JCOMM for the non-geophysical variables.

6.5 Capital, Operations and Maintenance Costs

PICO was not adequately resourced in terms of funding, time or the spectrum of experts needed to formulate realistic estimates of the cost of implementing coastal GOOS in terms of observations and data telemetry, data management and communications, and modelling and analysis. **This important task should be funded under the auspices of the GEO Coastal Zone Community of Practice (section 5.7.1) in coordination with the GOOS Steering Committee.**

6.6 Next Steps

Successful implementation of the priorities above as an integral part of GOOS and GEOSS depends on developing international partnerships and collaborations as described in section 5.7, , in active coordination with sustained coastal observing system efforts within and across the GRAs.

Successful implementation also depends on more effective collaboration with the OOPC as well as on effectively engaging stakeholders (data providers and users) across the land-sea interface in the process. The CZCP was established by GEO to do the latter. Thus, we recommend that the CZCP be charged and jointly resourced by the IOC, GEO member countries, and GEO Participating Organizations to oversee both the gap and cost analyses described above.

Finally, we also endorse the recommendation of the Joint JCOMM-IOC-GRA *ad hoc* Task Team[398] that an expert panel such as the proposed Joint Panel for Integrated Coastal Observations (J-PICO), or alternatively the CZCP, be tasked and resourced to provide sustained scientific and technical guidance and ensure the coordinated evolution of ocean and terrestrial observing systems across the land-sea interface. Should the CZCP be given this important responsibility, this would have the added benefit of establishing an important and direct link between IOC-GOOS and GEO-GEOSS (and the GEO Ocean Monitoring Task advocated by POGO and Oceans United).

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ANNEX I

A sample (1960 – 2008) of the many global, regional and national ocean policies and related conventions, action plans, agreements and laws requiring the sustained (continuous) provision of data and information on marine ecosystems to achieve their goals and objectives.

Global	• Stockholm Declaration on the Human Environment • Ramsar Convention; • Convention on the Law of the Sea & the 2009 UN session on Oceans and Law of the Sea; Agreement on the Conservation & Management of Straddling & Highly Migratory Fish Stocks • Convention on Biological Diversity & the Jakarta Mandate on the Conservation & Sustainable Use of Biological Diversity, Convention on International Trade in Endangered Species, Convention for the Conservation of Migratory Species, Reykjavik Declaration, Code of Conduct for Responsible Fisheries; • Framework Convention on Climate Change; • Global Program of Action for the Protection of the Marine Environment from Land Based Sources; • UNCED Agenda 21, Program of Action for Sustainable Development; • Implementation Plan of the World Summit on Sustainable Development; • International Convention for the Prevention of Pollution From Ships
Africa	• Convention for Co-operation in the Protection and Development of the Marine and Coastal Environment of the West and Central African Region (Abidjan Convention); • The Nairobi Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region; • Southern African Development Community Protocol of Fisheries; • The Benguela Current Commission Interim Agreement (on Marine Ecosystem Based Co-operative Management)
Europe	• Marine Strategy Framework Directive & Integrated Maritime Policy; • OSPAR Convention, HELCOM Baltic Sea Action Plan; • EU Maritime Policy, European Common Fisheries Policy; • EU Sustainable Development Strategy; • 'Habitats Directive', Urban Waste Water Directive & Nitrate Directive.
Japan	• Water Quality Conservation Law, Basic Law for Environmental Control, Water Pollution Control Law, Special Law for the Conservation of the Environment of the Seto Inland Sea; • Basic Act on Ocean Policy.
United States	• National Policy for the Stewardship of the Ocean, Our Coasts, and the Great Lakes (Executive Order 13547) • An Ocean Blueprint for the 21st Century; • Clean Water Act, Fishery Conservation & Management Act, Coastal Zone Management Act, Endangered Species Act, Oceans and Human Health Act.

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ANNEX III
ACRONYMS

ACT	Alliance for Coastal Technologies
ADCIRC	Advanced Circulation Model
AIMS	Adaptive and Integrated nutrient Monitoring System
ALOS	Advanced Land Observing Satellite
AMEMR	Advances in Marine Ecosystem Modeling Research
AMG	Autonomous Microbial Genosensor
AMLC	Association of Marine Laboratories of the Caribbean
AMR	Advanced Microwave Radiometer
AMSR	Advanced Microwave Scanning Radiometer
AoA	Assessment of [marine ecosystem] Assessments
ARMS	Autonomous Reef Monitoring Structures
ASCAT	Advanced Scatterometer
ASEAN	Association of Southeast Asian Nations
ATSEA	Arafura and Timor Seas Ecosystem Action
ATSEF	Arafura and Timor Seas Expert Forum
AUV	Autonomous Underwater Vehicle
AVHRR	Advanced Very High Resolution Radiometer
BOD	Biological Oxygen Demand
BURF	Binary Universal Form for the Representation of data
CBD	Convention on Biological Diversity
CDOM	Colored Dissolved Organic Matter

CEOS	Committee on Earth Observation Satellites
CFU	Colony Forming Units
ChloroGIN	Chlorophyll Globally Integrated Network
CHONE	Canadian Healthy Oceans Network
CLIOTOP	CLimate Impact on Oceanic TOp Predators
CLIVAR	Climate Variability and Predictability
CMA	Chinese Meteorological Administration
CNES	Centre National d'Études Spatiales
CoML	Census of Marine Life
COOP	Coastal Ocean Observations Panel
CPR	Continuous Plankton Recorder
CSA	Canadian Space Agency
CTD	Conductivity-Temperature-Depth instrument
CZCP	GEO Coastal Zone Community of Practice
CZCS	Coastal Zone Color Scanner
DAC	Data Assembly Center
DHI	Danish Hydraulic Institute
DIC	Dissolved Inorganic Carbon
DIF	Data Integration Framework
DMAC	Data Management and Communications
DONET	Dense Oceanfloor Network system for Earthquakes and Tsunamis
DPSIR	Driver-Pressure-State-Impact-Response framework
EBA	Ecosystem-Based Approach

EDAS	Enhanced Data Acquisition System
EEZ	Exclusive Economic Zone
EGO	Everyone's Gliding Observatories
ELISA	Enzyme Labelled Immune-Sorbent Assay
EMECO	European Marine Ecosystem Observatory
EMSO	European Multidisciplinary Seafloor Observatory
ESA	European Space Agency
ESABII	East and Southeast Asia Biodiversity Information Initiative
ESONET-NoE	European Seas Observatory NETwork-Network of Excellence, ESONET-NoE
ESP	Environmental Sample Processor
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EUROGOOS	European GOOS
EwE	Ecopath with Ecosim
FAO	Food and Agriculture Organization
FISH	Fluorescence In Situ Hybridization
FTP	File Transfer Protocol
GADGET	Globally applicable Area Disaggregated General Ecosystem Toolbox
GBIF	Global Biodiversity Information Facility
GEF	Global Environmental Facility
GEO	Group on Earth Observations; Geostationary Earth Orbit
GEO BON	Group on Earth Observations Biodiversity Observation Network
GEOSS	Global Earth Observing System of Systems
GCI	GEOSS Common Infrastructure

GCN	Global Coastal Network
GCOS	Global Climate Observing System
GCRMN	Global Coral Reef Monitoring Network
GHRSST	Group for High-Resolution Sea Surface Temperature
GLOBEC	Global Ocean Ecosystem Dynamics
GLOSS	Global Sea Level Observing System
GOBI	Global Ocean Biodiversity Initiative
GOCI	Geostationary Ocean Color Imager
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GRA	GOOS Regional Alliance
GRC	GOOS Regional Council
GRDC	Global Runoff Data Center
GTOPP	Global Tagging of Pelagic Predators
GTN-R	Global Terrestrial Network for River Discharge
GTOS	Global Terrestrial Observing System
GTS	Global Telecommunications System
HAB	Harmful Algal Bloom
HICO	Hyperspectral Imager for the Coastal Ocean
HPLC	High Pressure Liquid Chromatography
HTTP	Hypertext Transfer Protocol
HyCOM	Hybrid Coordinate Ocean Model
HyspIRI	Hyperspectral InfraRed Imager

IASSOO	International Association of Sub-Sea Observatory Operators
I-CREOS	International network of Coral Reef Ecosystem Observing Systems
ICSU	International Council for Science
IEA	Integrated Ecosystem Assessment
IGOS	Integrated Global Observing System
IKONOS	Derived its name from the Greek term *eikōn* for image.
ILTER	International Long Term Ecological Research Program
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IMOS	Integrated Marine Observing System (Australia)
IOC	Intergovernmental Oceanographic Commission
IOCCG	International Ocean Colour Coordinating Group
IODE	International Oceanographic Data and Information Exchange
IOOS®	Integrated Ocean Observing System (United States)
IPCC	Intergovernmental Panel on Climate Change
ISFET	Ion-Sensitive Field-Effect Transistor
ISO	International Organization for Standardization
ISRO	Indian Space Research Organization
JAMBIO	Japanese Association for Marine Biology
JAXA	Japan Aerospace Exploration Agency
JCOMM	Joint Commission for Oceanography and Marine Meteorology
JGOFS	Joint Global Ocean Flux Study
J-PICO	Joint (GOOS/GTOS) Panel for Integrated Coastal Observations
KARI	Korea Aerospace Research Institute

LEO	Low Earth Orbit
LIDAR	Light Detection And Ranging
LME	Large Marine Ecosystem
LMR	Living Marine Resource
LOICZ	Land-Ocean Interactions in the Coastal Zone
MAAS	Mid-Trophic Automatic Acoustic Sampling
MACHO	Marine Cable Hosted Observatory
MARS	European Network of Marine Research Institutes and Stations
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Marine Protected Area
MSE	Management Strategy Evaluation
NaGISA	Natural Geography of InShore Areas
NAML	North American Association of Marine Laboratories
NANO	Nippon Foundation-POGO Alumni Network for Oceans
NASA	National [US] Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NCOSM	National [China] Center of Ocean Standards and Metrology
NDBC	National [US] Data Buoy Center
NDIR	Non-Dispersive Infrared Detection
NEAR-GOOS	North-East Asian Regional GOOS
NEPTUNE	North East Pacific Time-series Underwater Networked
NGO	Non-Governmental Organization

NOAA	National (US) Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NSP	Neurotoxic Shellfish Poisoning
NWP	Numerical Weather Prediction
OBIS	Ocean Biogeographical Information System
OCR	Ocean color radiometry
ODIN	Ocean Data and Information Network
OECD	Organization for Economic Cooperation and Development
OFS	Operational Forecasting System
OMP	Operational Management Procedures (OMP)
OOI	Ocean Observatories Initiative
OOPC	Ocean Observations Panel for Climate
OPD	Optical Phytoplankton Discriminator
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiments
OSVW	Ocean Surface Vector Winds
OTN	Ocean Tracking Network
PICO	Panel for Integrated Coastal Observations
PIMS	Pacific Institutes of Marine Science
POC	Particulate Organic Carbon
POGO	Partnership for Observation of the Global Ocean
PoI	Phenomenon of Interest
PSP	Paralytic Shellfish Poisoning

QA/QC	Quality Assurance and Quality Control
Q-PCR	Quantitative Polymerase Chain Reaction
RCOOS	Regional Coastal Ocean Observing System
RMIC	Regional Marine Instrument Center
ROMS	Regional Ocean Modeling System
RWQM	Receiving Water Quality Model
SAFARI	Societal Applications in Fisheries and Aquaculture using Remotely-Sensed Imagery
SAHFOS	Sir Alister Hardy Foundation for Ocean Science
SAR	Synthetic Aperture Radar
SEAGOOS	Southeast Region GOOS
SEAPODYM	Spatial Ecosystem and Population Dynamics Model
SEAS	Spectrophotometric Elemental Analysis System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SMOS	Soil Moisture and Ocean Salinity
SOC	Specialized Oceanography Center
SOOP	Ships Of Opportunity Program
SoS	System of Systems
SPOT	Système Probatoire d'Observation de la Terre
SSR	Sea Surface Roughness
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TACs	Traditional Alphanumeric Code forms
TDA	Transboundary Diagnostic Analysis

TDCs	Table-Driven Codes (TDCs)
TMN	Australian Tropical Marine Network
VOS	Volunteer Observing Ship
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United National Environmental Program
USGS	United State Geological Survey
VOS	Volunteer Observing Ship
VPA	Virtual Population Analysis
WAMS	World Association of Marine Stations
WESTPAC	IOC Sub-Commission for the Western Pacific
WMO	World Meteorological Organization
WMS	OpenGIS® Web Map Service Interface Standard
WOC	World Ocean Council
WOCE	World Ocean Circulation Experiment
WPEA OFM	West Pacific East Asia Oceanic Fisheries Management
WQM	Water Quality Monitor

NOTES

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[9] *EBAs are stakeholder-driven, integrated processes that strive to balance diverse societal objectives by taking into account the knowledge and uncertainties of the biotic (including humans) and abiotic components of ecosystems and their interactions. The goal of EBA is to maintain healthy ecological and socioeconomic systems. Key objectives are to (1) sustain the structure, function and biodiversity of ecosystems and account for interactions among (2) organisms (including humans) and their environment (ecosystem dynamics); (3) atmospheric, terrestrial and marine systems (pressures); and (4) ecological and socioeconomic systems (impacts of state changes and human responses to them). EBA differs from current approaches that focus on a single species or sector in that it considers the cumulative interactions among different sectors and has explicit geospatial boundaries (Garcia, S.M. and Cochrane, K.L. 2005. Ecosystem approach to fisheries: a review of implementation guidelines. ICES J. Mar. Res. 62, 311-318; McLeod, K. L., J. Lubchenco, S. R. Palumbi, and A. A. Rosenberg. 2005. Scientific Consensus Statement on Marine Ecosystem-Based Management, COMPASS http://www.compassonline.org/science/EBM_CMSP/EBMconsensus).*

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[12] *"Operational" refers to models and observations that routinely and continuously provide quality controlled data and information in forms and at rates needed and used by environmental policy makers and decision makers who depend on, manage or study marine and estuarine environments and the organisms that inhabit them. Thus, a system is operational when processing is done in a routine and regular, is based on a pre-determined systematic approach, and monitors performance constantly. In this context, regular re-analyses, organized analyses, and assessments of climate data may be considered operational.*

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[14] *de Young, B., M. Barange, G. Beaugrand, R. Harris, R.I. Perry, M. Scheffer and F. Werner. 2008. Regime shifts in marine ecosystems: detection, prediction and management. Trends in Ecology and Evolution, 23: 402-409.*

[15] *An ecosystem is a geographically specified dynamic system of organisms (including humans) interactive with each other and their abiotic environment. Coastal ecosystems come in many sizes and shapes from small estuaries and bays (< 10 km^2) to coastal seas, Marine Protected Areas and Large Marine Ecosystems (1 – 5 x 10^5 km^2). Thus, small marine ecosystems (e.g., mesoscale eddies, tidal wetlands, rocky intertidal zones, kelp forests, seagrass beds, and coral reefs) are often embedded in larger ones, and, while some marine species spend their entire life cycle within a single ecosystem (e.g., many small reef fish), most have larval or juvenile stages that are transported across ecosystems within a large ecosystem and some migrate across large ecosystems as adults (e.g., large pelagic fish, sea turtles, and marine mammals) just as migrating birds move across tundra, forest and prairie ecosystems.*

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[21] ***UNESCO.*** *2005. An Implementation Strategy for the Coastal Module of the Global Ocean Observing System. GOOS Report No. 148, pp 141.*

[22] *The design and implementation of national and regional ocean observing systems is the responsibility of nations and regional, multinational organizations.*

[23] *A provisional set of essential (common) was identified by the Coastal Ocean Observations Panel (UNESCO. 2003. The Integrated Strategic Design Plan for the Coastal Ocean Observations Module of the Global Ocean Observing System. GOOS Report No. 125, 190 pp.) using a systematic procedure based on the needs of users, data requirements of models, and a consensus-based review derived from the expertise and experience of a broad range of scientists. The recommended essential variables are updated in Chapter 5. The essential variables for coastal GOOS must be supplemented by variables measured by other global observing systems. These include open ocean boundary conditions and basin scale pressures, meteorological variables (air temperature, vector winds, humidity, wet and dry precipitation, and incident solar radiation), and surface and ground water transports of water, nutrients, sediments and contaminants.*

[24] ***UNESCO****. 2009. Progress Report on the Implementation of the Global Observing system for Climate in Support of the UNFCCC 2004-2008. GOOS Report No. 173, pp. 98 (http://gcos.wmo.int);* ***GOSIC*** *(2009) Overview of the growth of GOOS observation programs (www.gosic.org/goos/GOOS-observational-programs.htm).*

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[26] ***Maier****, M.W. 1998. Architecting principles for system of systems. Systems Engineering, 1 (4): 267-284; http://www.infoed.com/Open/PAPERS/systems.htm*

[27] ***United Nations.*** *2002. Global Challenge, Global Opportunity: Trends in Sustainable Development, pp 21 (http://www.un.org/jsummit/html/documents/summit_docs/criticaltrends_1408.pdf).*

[28] *There is no commonly agreed regional division of the world's oceans; several divisions exist for different purposes, often not covering the whole ocean area. The Group of Experts therefore agreed on a list of 21 regions solely for the purpose of reviewing assessments at the regional level. The AoA regions are a practical compromise among the many regionalization systems that have been proposed, and are based on both bio-geographic factors and existing assessment mechanisms. They are delineated to avoid unnecessary overlaps while ensuring global*

coverage, including high seas areas. No precise boundaries are established between them. The AoA regions take into account: (1) Existing regional mechanisms that have permanent, government recognized structures (e.g., Regional Seas conventions, regional fisheries bodies, Food and Agriculture Organization [FAO] statistical areas, and Large Marine Ecosystem [LME] programs): (2) Ecologically sensible delineations conducive to an ecosystem approach (e.g., an LME or sets of linked LMEs) and the work on marine eco-regions of the world and Global Open Ocean and Deep Sea bioregionalization; (3) Ready accommodation of past or existing monitoring and assessment programs; (4) An administratively manageable number of regional units; and (5) The need to ensure coverage of areas within and beyond national jurisdiction, including all ocean basins. In this context, a spectrum of spatial scales is used in the AoA (UNEP and IOC-UNESCO. 2009. An Assessment of Assessments, Findings of the Group of Experts. Start-up Phase of a Regular Process for Global Reporting and Assessment of the State of the Marine Environment including Socio-economic Aspects:

- *Global: All the world's oceans;*
- *Regional: Any existing regional division, including AoA regions;*
- *Supra-regional: Any geographical unit extending beyond a region but not global;*
- *Sub-regional: Sub-division of a regional unit into smaller units, e.g., a large marine ecosystem comprising part of an AoA region;*
- *National: Ocean areas under coastal states' jurisdiction;*
- *Sub-national: Any sub-division of areas within national jurisdiction (e.g., a Marine Protected Area or MPA).*

[29] *www.un.org/Depts/los/global_reporting/global_reporting.htm*

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[36] *For example, the Alliance for Coastal Technologies (ACT) (http://www.act-us.info/).*

[37] *Seitzinger, S. P., J. A. Harrison, E. Dumont, A. H. W. Beusen, and A. F. Bouwman. 2005. Sources and delivery of carbon, nitrogen, and phosphorus to the coastal zone: An overview of Global Nutrient Export from Watersheds (NEWS) models and their application. Global Biogeochem. Cycles 19: GB4S01.*

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[40] *Common Implementation Strategy for the Water Framework Directive. 2009. Guidance Document No. 23 Guidance Document on Eutrophication Assessment in the Context of European Water Polices. ISBN 978-92-79-12987-2*

[41] *http://www.loicz.org/imperia/md/content/loicz/print/rsreports/14report.pdf*
[42] *http://ccma.nos.noaa.gov/stressors/pollution/eutrophication/est_update.aspx*

[43] *http://lwa.gov.au/programs/national-land-and-water-resources-audit*

[44] *http://www.wri.org/map/coastal-eutrophic-and-hypoxic-areas-europe*

[45] *Light attenuation and reflectance in case 2 waters is dominated by particulate matter other than phytoplankton (e.g., suspended sediments, detritus, bacteria) in contrast with case 1 waters where phytoplankton account for most light attenuation and reflectance.*

[46] *The half-life of infectious microbes is longer in warm than cold waters.*

[47] *The discharge of untreated sewage is a major source of waterborne pathogens. Over 80% of sewage discharges into the ocean are untreated in East Asia, South and Central America and West and Central Africa.*

[48] *Only ~ 40% of the global coastline (~ 620,000 km of coastline) is habitable. Thus, as the number of people living within 100 km of the coast increases, their population density will increase as will the number of temporary beach and shellfish bed closures.*

[49] *WHO. 2003. Guidelines for safe recreational water environments: Coastal and fresh waters, vol. 1, Geneva, World Health Organization.*

[50] *Log [Grastrointestinal illness/1000 swimmers] = 0.0456 [mean enterococcus CFU/100 ml] + 0.677,* $r^2 = 0.56$

[51] *Half-life is a function of the duration of viability and rates of growth and mortality.*

[52] *In addition to microorganisms introduced to recreational waters through human or animal faecal contamination, many pathogenic microorganisms are free-living in such areas or, once introduced, are capable of increasing more rapidly than Enterococcus (e.g., Vibrio spp. are natural inhabitants of marine aquatic environments in both temperate and tropical regions, and their occurrence is not correlated with the occurrence of Enterococcus.).*

[53] *e.g., Wisconsin Beach Health: http://www.wibeaches.us*

[54] *NowCast (www.ohionowcast.info/index.asp), Project SAFE (www.glsc.usgs.gov/projectSAFE.php), and SwimCast (http://www.lakecountyil.gov/Health/want/Pages/SwimCast.aspx)*

[55] *www.epa.gov/waterscience/beaches/sanitarysurvey/*

[56] *www.mbari.org/microbial/esp*

[57] *www.marine.usf.edu/microbiology/genosensor.shtml*

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[61] *Hoagland P. and S. Scatasta. 2006. The economic effects of harmful algal blooms. In E Graneli and J Turner, eds., Ecology of Harmful Algae. Ecology Studies Series. Dordrecht, The Netherlands: Springer-Verlag, Chap. 29.*

[62] *Paralytic shellfish poisoning (PSP) – Alexandrium spp., Pyrodinium bahamense var. compressum, and Gymnodinium catenatum; diarrhetic shellfish poinsoning (DSP) – Dinophysis spp. and Prorocentrum spp.; neurotoxic shellfish poisoning (NSP) – Karenia brevis; amnesic shellfish poisoning (ASP) – Pseudo-nitzschia spp.; Azaspiracid shellfish poinsoning (AZP) – Protoperidinium cassipes; ciguatera fish poisoning (CFP) – Gambierdiscus toxicus; Respiratory problems, skin irritation and neurological effects – Karenia brevis, Pfiesteria piscicida, and Nodularia spumigena; and Hepatotoxicity – Microcystis aeruginosa and Nodularia spumigena.*

[63] *Malone, T.C., 2008. Ecosystem Dynamics, Harmful Algal Blooms and Operational Oceanography. In M. Babin, C. Roesler, and J. Cullen (eds.), Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms. Monographs on Oceanographic Methodology, UNESCO, pp. 527-559.*

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[65] *Alliance for Coastal Technologies Workshop on HAB Biosensors (http://www.act-us.info/Download/Workshops/2002/CBL_HAB)*

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[82] *Millennium Assessment, 2005*

[83] *Marine spatial planning is about managing ocean uses to minimize conflicts and maximize synergies. Most scientific attention in MSP focuses on the data needed to characterize ocean uses and impacts. A major bottleneck to progress is often the lack of rigorous, explicit and practical approaches for making science based decisions about tradeoffs among diverse human uses in both data poor and data rich settings.*

[84] *http://www.gcrmn.org/*

[85] *http://www.seagrassnet.org/*

[86] *http://ecoforecast.coral.noaa.gov/*

[87] *http://coralreefwatch.noaa.gov/satellite/index.html*

[88] *http://www.Ramsar.org/*

[89] *Danielsen, F.. M. K. Sørensen, M.F. Olwig, V. Selvam, F. Parish, N.D. Burgess, T. Hiraishi, V.M. Karunagaran, M.S. Rasmussen, L.B. Hansen, A. Quarto, and N. Suryadiputra. 2005. The Asian tsunami: A protective role for coastal vegetation. Science, 310: 643.*

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[91] *The Human Development Index (HDI) is a componsite, dimensionless index of human achievements as indicated by human life spans, education, and income (http://hdr.undp.org/en/reports/).*

[92] *http://www.centre-cired.fr/IMG/pdf/OECD_Cities_Coastal_Flooding.pdf*

[93] *Risk = (Probability of a flooding event) x (Value of loss) x (Vulnerability to flooding).*

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[95] *(Calderia and Wickett, 2003, 2005)*

[96] *e.g., Kleypas et al., 2006; Cao and Caldeira, 2008; Fabry et al., 2009; Gledhill et al., 2009;*

[97] *e.g., Orr et al., 2005; Fabry et al., 2009; Kleypas and Yates, 2009*

[98] *Cooley et al., 2009; Cooley and Doney, 2009*

[99] *(Doney et al., 2009)*

[100] *E.g., the European Project on Ocean Acidification (EPOCA), the German project Biological Impacts of Ocean ACIDification (BIOACID), the United Kingdom Ocean Acidification Research Program, the IMBER/SOLAS Ocean Acidification Working Group, and the NOAA Ocean and Great Lakes Acidification Research Plan amongst others; Feely, R. and others. 2010. "An International Observational Network for Ocean Acidification" in Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.29*

[101] *Byrne, R. and others. 2010. "Sensors and Systems for In Situ Observations of Marine Carbon Dioxide System Variables" in Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.13*

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[269] *GEO 2009-2010 WP (www.earthobservations.org/documents/work%20plan/geo_wp0911_rev2_091210.pdf);*

The GEOSS Common Infrastructure (www.earthobservations.org/gci_gci.shtml)

[270] *http://www.ogcnetwork.net/AIpilot*

[271] *Sensors, data and service level metadata.*

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[273] *Quality control and assessment uses knowledge of oceanography and marine ecosystem and of the place and data are collected. The degree of scrutiny is generally higher for delayed mode data than for "real-time data. Real-time data are typically checked using less rigorous automated procedures because of the large volume of data and the need for rapid dissemination. As long as the number and type of errors that pass through the procedures do not adversely affect the results, this is acceptable. Controlling the quality of delayed mode data is typically the responsibility of the data provider. Because of the accepted constraints of moving data in real-time, users accept that not all errors will be caught. For delayed mode data, quality control often requires a broader set of corroborating evidence and general acceptance of standard quality control procedures is often more difficult.*

[274] *GEONETCast is a near-real time, global network of satellite-based data telemetry systems designed to distribute remotely sensed (from space-based, airborne, and land-based platforms) and in situ data, metadata and products to diverse communities. It is currently being developed under the auspices of the GEO Architecture and Data Committee.*

[275] *The Global Telecommunications System (GTS) is a near-real time global satellite telecommunications network that telemeters data to and among official WMO data centers over secured channels for forecast operations under the international World Weather Watch.*

[276] *www.obsmar-mexfra.org/FOO_ConsultDraft_v7_15May2011.pdf*

[277] *www.wmo.ch/web/www/WMOCodes.html*

[278] *http://marinemetadata.org/*

[279] *http://seabass.ieee.org/groups/geoss/*

[280] *Vocabularies include terms for names of sensors, platforms, models, variables, units of measure, coordinate reference systems, species of organisms, etc.*

[281] *Application servers that enable data flow between sensors and the Internet (conversion services for interoperability).*

[282] *http://www.earthobservations.org/gci_cr.shtml*

[283] *An Implementation Strategy for the Coastal Module of the Global Ocean Observing System (Chapters 3 and 7, Annex III), GOOS Report No. 125.*

[284] *http://www.oceanobs09.net/wg/IFSOO-TT_teleconference_25MAR_report.doc*

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[290] A community of practice (CoP) is a group of people who have common interests and/or goals. A CoP can evolve naturally because of the members' common interest, or it can be created specifically with the goal of gaining knowledge related to their respective fields of expertise. It is through the process of sharing information and experiences with the group that the members learn from each other, have an opportunity to develop themselves personally and professionally, and achieve common goals. An important function of communities of practice is to increase the performance of organizations by reducing the learning curve of the group as a whole, responding more rapidly and effectively to stakeholder needs and inquiries, preventing "reinvention of the wheel", and by spawning new ideas for products and services.

[291] A Service Level Agreement (SLA) is a formal written agreement made between the service provider and the service recipient. It is a core concept of Information Technologies Service Management, particularly Internet services. The SLA itself defines the basis of understanding between the two parties for delivery of the service itself. The document may underpins a formal contract. The contents will vary according to the nature of the service itself, but usually includes a number of core clauses that define a specified level of service (e.g., 99.99% availability), support options, incentive awards for service levels exceeded and/or penalty provisions for services not provided.

[292] Conceptual, statistical and/or numerical models may be used here.

[293] This may include some or all of the essential variables (Table 14), but is not limited to them.

[294] *These include Regional Sub-Commissions (IOCARIBE, IOCWESTPAC), Regional Committees (IOCEA, IOCINDIO, IOWIO, BSRC), Regional Programme Offices (GOOS Rio, IOC Perth, Suva-SOPAC/Perth), and Project Offices (HAB, IODE).*

[295] *http://www.earthobservations.org/geobon.shtml*

[296] *http://www.unep.org/regionalseas/*

[297] *MPAs are areas in the ocean where resources are protected by laws or regulations. Examples include marine sanctuaries, parks, wildlife refuges, and fishery management areas. Most MPAs are multiple use in that they allow activities in different zones such as commercial and recreational fishing, boating, and diving. MPAs are fundamental tools for EBAs in environmental protection and the management of marine resources.*

[298] *www.lme.noaa.gov/*

[299] *http://www.gobi.org*

[300] *www.earthobservations.org/documents/sbas/di/35_geo_coastal_zone_cop.pdf; www.czcp.org/workshops/*

[301] *The Black Sea, Wider Caribbean, East Asian Seas, Eastern Africa, South Asian Seas, ROPME Sea Area, Mediterranean, North-East Pacific, North-West Pacific, Red Sea and Gulf of Aden, South-East Pacific, Pacific, and Western Africa.*

[302] *www.Ramsar.org/*

[303] *http://cmsdata.iucn.org/downloads/durbanactionen.pdf*

[304] *See http://database.eohandbook.com/ and http://ceos-sysdb.com/CEOS/*

[305] *See http://www.coastcolour.org/, http://esa.gmes-marcoast.info/, http://coastwatch.noaa.gov/, http://coralreefwatch.noaa.gov/*

[306] *See http://goos.kishou.go.jp/ and http://sccoos.org/data/satellite/*

[307] *www.iode.org/*

[308] *http://www.fao.org/fi*

[309] *www.fao.org/gtos/gt-netRIV.html*

[310] *www.gloss-sealevel.org/*

[311] *www.chlorogin.org/world/*

[312] *Brainard, R. and others. 2010. "An International Network of Coral Reef Ecosystem Observing Systems (I-CREOS)" in Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.09*

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[315] *www.nagisa.coml.org/*

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[317] *UNESCO. 2011. IOC Committee on International Oceanographic Data and Information Exchange, Twenty-first Session, Palais des Congrès, Liège, Belgium, 23-26 March 2011.*

[318] *http://www.cwpnet.org/*

[319] *The Global Runoff Data Centre (GRDC), located in Germany, has compiled a global data base of stream flow data for the development and verification of atmospheric and hydrologic models. The data base, which is updated continually, contains daily and monthly discharge data information for over 2,900 hydrologic stations in river basins located in 143 countries. GRDC disseminates data and additional data products on request. A catalog with updated information and a standard set of tables, statistics and graphic displays can be provided to data users for selected stations (www.gewex.org/grdc.html).*

[320] *www.wmo.int/pages/prog/gcos/Publications/gcos-82_2AR.pdf*

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[325] *www.ioc-goos.org/index.php?option=com_content&view=article&id=159&Itemid=89&lang=en; http://gosic.org/goos/GRA.htm*

[326] *Capacity building for most developed countries means integrating existing assets and incorporating advances in science and technology. For most developing countries, capacity building means both training and building the initial system using existing operational assets.*

[327] *www.ocean-partners.org/*

[328] *Oceans United is an international forum of organizations interested in ocean observations founded by, and under the leadership of, the Partnership for Observation of the Global Oceans (POGO). It is intended to provide a common voice for participating entities on marine matters, especially those related to observing the ocean for societal benefit, and to be a clearinghouse for information of mutual interest. Members include the IOC, JCOMM, CoML, SCOR, SAHFOS, UNESCO and WMO (http://www.oceans-united.org/).*

[329] *www.ocean-partners.org/training-and-education/pogo-visiting-professorship/completed-nf-pogo-professorship*

[330] *www.bios.edu/education/cofe.html*

[331] *http://odinafrica.org/index.php?option=com_content&view=article&id=60&Itemid=27*

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[338] *http://imos.org.au/facilities.html*

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[340] *www.oceancouncil.org/*

[341] *UN Convention on the Law of the Sea, Article 145; http://works.bepress.com/cgi/viewcontent.cgi?article=1009&context=chad_mcguire*

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[347] *http://goos.kishou.go.jp/; http://gosic.org/goos/NEAR-GOOS-program-overview.htm*

[348] *http://imos.org.au/facilities.html*

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[353] *http://www.iode.org/index.php?option=com_content&task=view&id=35&Itemid=75*

[354] *http://gosic.org/goos/SEA-GOOS-program-overview.htm*

[355] *http://www.unepscs.org/; iwlearn.net/iw-projects/885*

[356] *www.wcpfc.int/west-pacific-east-asia-oceanic-fisheries-management-project*

[357] *http://atsea-program.org/*

[358] *www.ssme-fishproject.org/*

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