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Climate Change, Sustainable Development and Coastal Ocean Information Needs

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Abstract

Local expressions of climate change are threatening the capacity of coastal ecosystems to support goods and services valued by society on a global scale. As articulated in many international and national ocean policies, conventions and agreements, there is widespread agreement that adaptive, ecosystem-based approaches are needed to manage climate risks and to adapt to the impacts of climate change on our environment. Design and implementation of such approaches requires routine and continuous provision of data and information that enable regular assessments of the states of marine and estuarine ecosystems, changes in states and likely future states in terms of their capacity to support goods and services. The provision of these data and information is a major goal of the climate and coastal modules of the Global Ocean Observing System (GOOS), the oceans and coastal component of the Global Earth Observing System, which is coming into being through an international effort led by the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) to integrate, improve and build on existing monitoring and modelling capabilities.

The objective is to establish sustained, integrated and interoperable approaches that efficiently link observations and models through data management and communications on national, regional and global scales. Initial requirements for the climate module have been completed and global implementation has begun. However, implementation of coastal GOOS has been slow and uneven geographically, especially in the coastal zones of developing countries and emerging economies. Challenges that must be addressed to move this process along more rapidly and effectively include (a) capacity building; (b) reaching international agreements that enable timely exchanges of data on the states and changing states of coastal ecosystems regionally and globally; (c) achieving international consensus on priorities for phased implementation of coastal GOOS strategic plans; (d) establishing mechanisms to transition advances in science and technology into operational modes as needed; (e) effecting regional and global coordination and collaboration among coastal nations and existing regional bodies with related goals and data requirements; and (f) coordinating the development of the climate and coastal modules of GOOS. Issues associated with these challenges are discussed and the current effort of the GOOS Scientific Steering Committee to document observing system requirements for the coastal ocean is described.

Keywords: Marine ecosystems; Global Ocean Observing System; capacity building; GOOS regional alliances; global coordination.

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1. Introduction

Coastal nations worldwide are experiencing changes in their marine and estuarine ecosystems that jeopardize the safety, health, security and economic wellbeing of 40–50 per cent of the human population [1][2][3][4][5]. Concerns over these changes have led to many national ocean policies and international agreements for sustainable development (Table 1). A common theme of these agreements is the need for adaptive, ecosystem-based approaches to sustainable development (www.un.org/esa/dsd/agenda21; www.worldsummit2002.org; www. ebmtools.org) that will maintain the capacity of ecosystems to support goods and services valued by society [6][7][8][9]. However, design and implementation of ecosystem-based approaches remains an elusive goal, in part because of the lack of sustained monitoring, modelling and assessments of the health of marine ecosystems on local to global scales.

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Table 1. A small 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, Intergovernmental and International
Ramsar Convention, Convention on Biodiversity, Convention on International Trade in Endangered Species
Convention on the Law of the Sea and the 2009 United Nations Session on Oceans and Law of the Sea
Convention on the Conservation of Migratory Species
Agreement on the Conservation and Management of Straddling and Highly Migratory Fish Stocks
Conference on the Human Environment
United Nations Framework Convention on Climate Change
United Nations Conference on Environment and Development, Agenda 21: Programme of Action for Sustainable Development
Plan of Implementation of the World Summit on Sustainable Development
International Convention for the Prevention of Pollution from Ships
Global Programme of Action for the Protection of the Marine Environment from Land Based Sources
Code of Conduct for Responsible Fisheries
Reykjavik Declaration on Responsible Fisheries in the Marine Ecosystem
Regional, 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 Cooperative Management)
Regional, Europe
The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention)
The Helsinki Commission (HELCOM) Baltic Sea Action Plan
European Union Sustainable Development Strategy, Maritime Policy, Habitats Directive, Urban Waste Water Treatment Directive and Nitrates Directive, Common Fisheries Policy
Portuguese National Ocean Strategy
United Kingdom Marine and Coastal Access Act, Safeguarding Our Seas (DEFRA)
National, United States
Changing Oceans, Changing World: Ocean Priorities for the Obama Administration and Congress
An Ocean Blueprint for the 21st Century
Clean Water Act, Fishery Conservation and Management Act, Coastal Zone Management Act, Endangered Species Act, Oceans and Human Health Act

www.un.org/geninfo/bp/enviro.html; www.johannesburgsummit.org; www.earthobservationsummit.gov

On seasonal to decadal time scales, the primary anthropogenic drivers of change in marine and estuarine ecosystems are human population growth and global climate change. Both drivers of change are increasing the vulnerability of people, coastal infrastructure and coastal ecosystems to natural hazards (tropical cyclones, storm surges, tsunami, etc.). Climate-driven sea-level rise drowns low-lying lands (for example, tidal wetlands, sand dunes, river deltas), and there is growing evidence that climate-driven ocean warming will increase the intensity and/or frequency of tropical cyclones ([10]; http://wind.mit.edu; www.wmo.ch/). The socio-economic, ecological and political risks associated with the combined effects of sea-level rise and natural hazards will increase accordingly.

While acknowledging the synergy between impacts of population growth and climate change (such as coastal development and sea-level rise), this white paper is primarily concerned with the provision of data and information needed to assess and anticipate impacts of climate change on marine ecosystem goods and services (Table 2). Developing this capability is essential for effective climate risk management where risk is a function of vulnerability, hazard intensity and hazard frequency. Impacts of sea-level rise and coastal inundation are emphasized because they pose clear and significant threats to our socio-economic, ecological and political systems. In a companion paper, Bindoff and others [11], address the climate driver and changes in the global ocean-climate system.

1.1 Adapting to changing ecosystem states

Ecosystems are complex systems characterized by many variable properties and processes that cannot be monitored in all places at all times. Thus, it is important to identify key ecological indicators that enable assessments needed to guide the evolution of ocean policies and adaptive responses to and anticipation of the impacts of climate change on marine ecosystem goods and services (climate risk management). An important role of the Global Ocean Observing System is to provide data and information required to compute indicators routinely and continuously (Figure 1).

Proactive, ecosystem-based approaches to climate adaptation and risk management depend on timely delivery of frequently updated indicators and indicator-based assessments of changes in ecosystem states that affect the goods and services they provide. Thus, parties to the 2002 World Summit on Sustainable Development emphasized the importance of repeated environmental assessments 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" (www.worldsummit2002.org/). In 2005, the United Nations General Assembly endorsed the need for the regular process and established an ad hoc Group of Experts to oversee the preparation of an "Assessment of Assessments" (AoA). The AoA [12] 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. This information will be used to

Table 2. Examples of changes in coastal estuarine and marine ecosystems states and the goods and services they provide caused, directly or indirectly, by increases in human population size, global climate change or a combination of both

Ecosystem State Changes	*Impacted Ecosystem Goods and Services*
Sea-level rise and changes in shoreline position	Resiliency to coastal inundation and erosion, surface and groundwater quality, primary production, sustainability and extraction of living marine resources (LMRs), essential fish habitat, biodiversity
Ocean warming	Human health risks, surface water quality, natural regulation of water, nutrient and green house gasses; primary production, sustainability and extraction of LMRs; essential fish habitat, biodiversity
Ocean acidification	Natural regulation of greenhouse gasses, primary production, essential fish habitat (coral reef networks), biodiversity (calcareous species of coral, foraminifera, etc.)
Habitat loss and changes in near shore bathymetry	Resiliency to coastal inundation and erosions, primary production, sustainability and extraction of LMRs, essential fish habitat, biodiversity, aesthetic value
Chemical contamination of the environment and organisms	Human health risks, sustainability and extraction of LMRs, biodiversity
Distribution, abundance and virulence of waterborne pathogens	Human health risk, surface water quality, sustainability and extraction of LMRs, biodiversity, recreation
Loss of biodiversity	Human health risks (drugs from the sea), resiliency to coastal inundation and erosion, sustainability and extraction of LMRs, aesthetic value
Eutrophication and dead (hypoxic) zones	Habitat loss, natural regulation of nutrient cycles, primary production, sustainability and extraction of LMRs, essential fish habitat, biodiversity, aesthetic value
Harmful algal events	Human health risks, recreation, sustainability and extraction of LMRs, biodiversity
Distribution and abundance of non-native species	Habitat loss, sustainability of LMRs, biodiversity
Disease and mass mortalities of marine organisms	Human health risks, biodiversity, sustainability and extraction of LMRs, aesthetic value
Distribution and abundance of LMRs	Biodiversity, sustainability and extraction of LMRs
Aquaculture production	Surface water quality, sustainability and extraction of LMRs, biodiversity

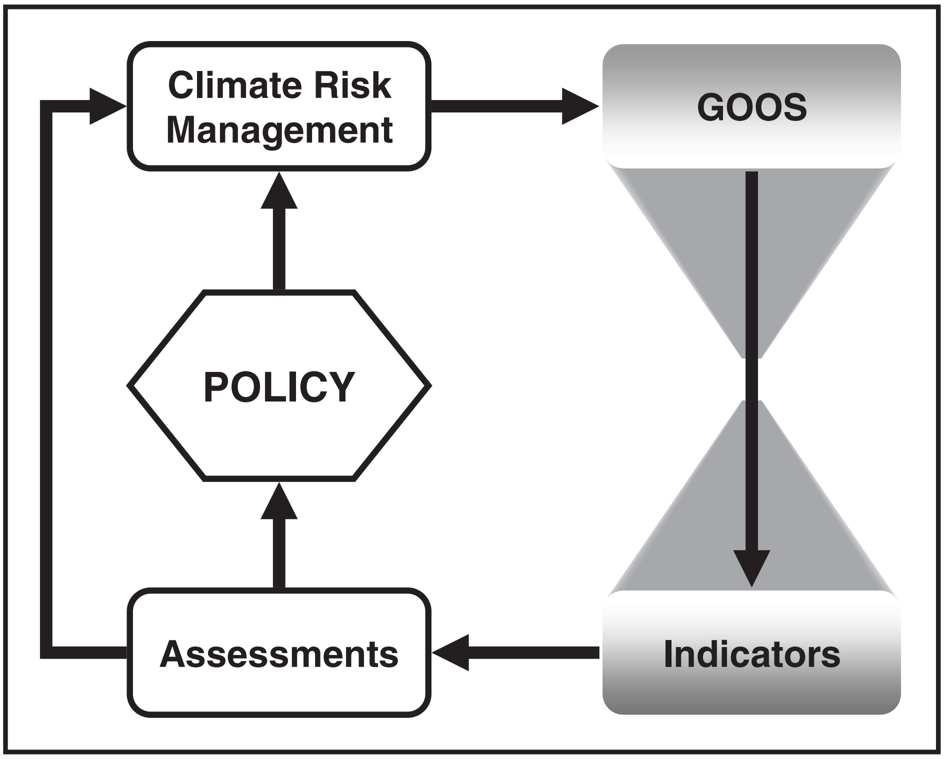


Figure 1. Effective climate risk management depends on regular assessments of the states of marine ecosystems that are informed by quantitative indicators, the computation of which is made possible by the sustained provision of data from ocean observing systems such as GOOS.

recommend principles and design factors that are relevant to the implementation and future conduct of a regular process for global reporting of assessments.

Implementing the regular process will not be easy. Marine and estuarine ecosystems are characterized by a broad spectrum of variability and change spanning physiological, ecological and evolutionary timescales from minutes to millennia. This reflects scale-dependent interactions between internal ecosystem dynamics and external pressures from both natural and anthropogenic drivers of change and variability [13][14][15][16][17][18][19]. Major climate-driven pressures on marine ecosystems include (a) rising sea level, (b) increasing heat content of the upper ocean, (c) increases in sea surface temperature, (d) melting of glaciers and polar ice caps, (e) increases in the intensity of tropical cyclones, (f) geospatial changes in the hydrological cycle and (g) ocean acidification [20]. Ice melt and, therefore, sea-level rise, have the potential for rapid and abrupt change (www.climatescience.gov/Library/sap/sap3-4/final-report/; www.ncdc.noaa.gov/paleo/abrupt/index.html). Thus, the provision of indicators that enable assessments required for sustainable development presents many challenges, not the least of which is the continuous and sustained monitoring of marine ecological properties and processes needed to inform timely ecosystem assessments of the impacts of climate change in general and sea-level rise and tropical cyclones in particular. Addressing this challenge is a major goal of the Global Ocean Observing System, a building block of the Global Earth Observing System of Systems (www.earthobservations.org/geoss.shtml).

Sustained observations and modelling of ecosystem dynamics are needed to provide the data and information necessary to track and analyse indicators routinely at rates most useful to policymakers and decision-makers responsible for implementing ecosystem-based approaches. These policy and decision-makers include government agencies responsible for coastal zone management, resource management, environmental protection, land-use practices, flood plain management and public health. To be most effective, indicators must enable (a) public understanding of climate risks, (b) risk-wise behaviour and (c) timely assessments of current ecosystem states, likely future states and the efficacy of ocean policies and management decisions (www.nehrp.gov/pdf/grandchallenges.pdf). The Driver-Pressure-State-Impact-Response (DPSIR) model provides a framework for identifying and linking the required indicators (Figure 2).

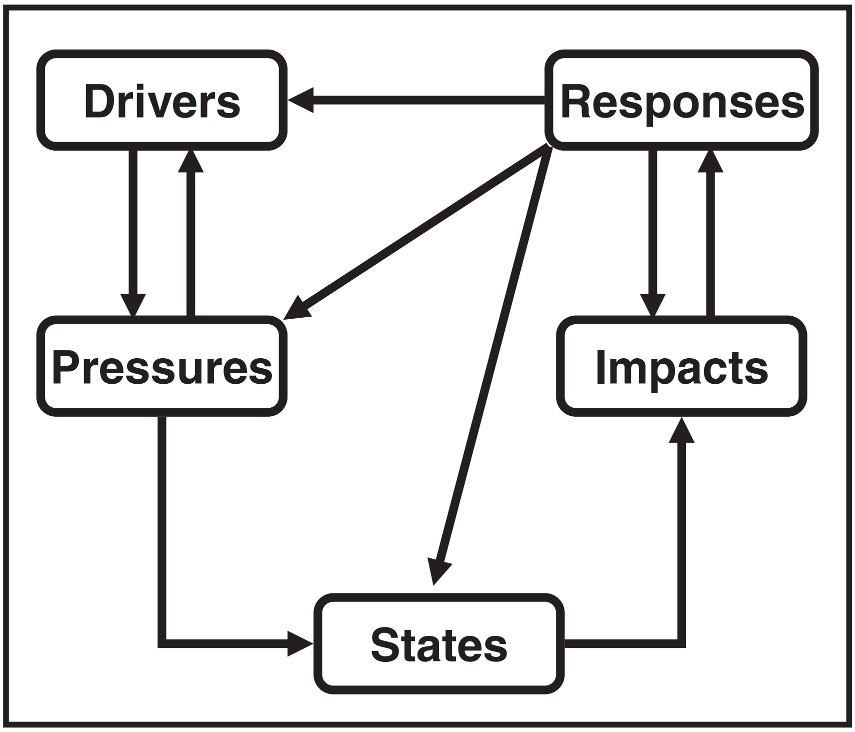


Figure 2. The Driver-Pressure-State-Impact-Response (DPSIR) model (Source: Bowen and Riley [21])

The DPSIR model provides a guide for indentifying a set of indicators that, as a group, can be used to inform ecosystem assessments [22]. Sustained monitoring of driver and pressure indicators enable early warnings of impacts; sustained monitoring of state and impact indicators enable assessments of how ecosystem goods and services are changing and their socio-economic consequences; sustained monitoring of response indicators track the evolution of ocean policies and related actions; and sustained monitoring of all the above enable adaptive improvement of said policies and actions (Table 3).

Table 3. Measures of the state of marine ecosystems; drivers of change and associated pressures; impacts that reduce the capacity of marine ecosystems to support goods and services valued by society; and societal (political and social) responses to current and anticipated future changes

DPSIR	*Measures*
State of Marine Ecosystems	Physical: Temperature, salinity, wave, and current fields; heat content
	Chemical: pH, pCO_2, dissolved O_2 and dissolved inorganic nutrient fields
	Biological: Habitat extent and condition (coral reefs, seagrass beds, kelp beds, tidal wetlands), biodiversity, primary productivity, trophic structure, abundance of living marine resources
	Public health: Distribution, abundance and virulence of waterborne pathogens; distribution and concentration of marine biotoxins and chemical contaminants
Drivers	Global climate change
	Human population growth
Climate Pressures	Sea-level rise
	Increasing heat content of the upper ocean
	Rising sea-surface temperature
	Ocean acidification
	Melting glaciers and ice sheets
	Geospatial changes in the hydrological cycle
	Increase in the intensity of tropical storms
Population Pressures	Combustion of fossil fuels
	Land-use practices
	Extraction of living marine resources
	Extraction of oil and gas
Impacts	Vulnerability to coastal inundation
	Increase public health risks
	Habitat loss
	Increase in number and spatial extent of dead zones
	Increase in spatial extent of biological deserts
	Decrease in abundance of living marine resources
Responses	Adapting to and mitigating impacts
	Managing anthropogenic drivers and pressures

1.2 The global ocean observing system

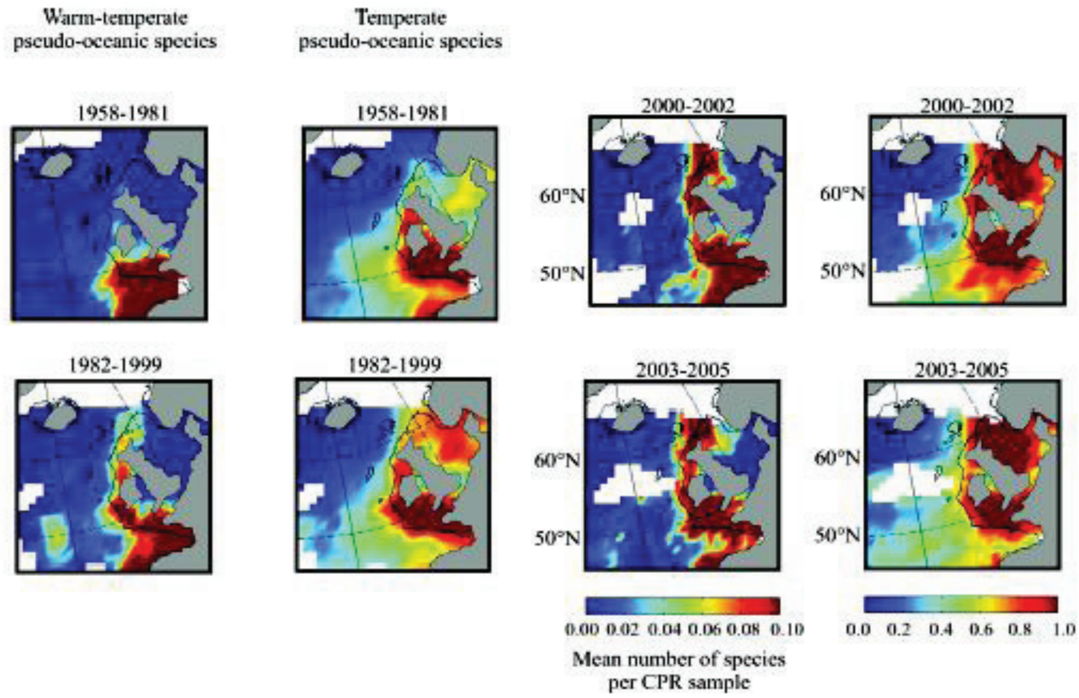
The Global Ocean Observing System is developing as a global system of systems (SoS) [23] that systematically acquires and disseminates data and information based on requirements specified by those who use, depend on, manage and study marine and estuarine systems. As such, GOOS performs functions that cannot be performed by any of the component systems individually (the value-added result of integration). It consists of component systems with their own unique purpose, and each component system can be managed separately for its purpose, can perform independently of the other components and no component interferes with the operation of other components. (See Box 1.) Furthermore, GOOS continually evolves as needs change and new technologies and knowledge become available through scientific research and technical development. The Global Ocean Observing System is being implemented by nations (developed countries for the most part) and GOOS Regional Alliances (www.ioc-goos.org/content/view/159/89/). This is a global effort to improve our ability to observe and predict changes in ocean states by building on, enhancing and expanding existing programs and capabilities.

GOOS consists of two interdependent modules (Table 4) that efficiently link ocean observations to modelling via an integrated data management and communications system. The basin-scale climate module is primarily concerned with the climate change driver and related pressures, that is, the continuous provision of data and information needed to improve predictions of climate change and associated pressures (Table 3). The ecosystem scale (5–200,000 km^2) (for example, Sherman et al. [25]; Spalding et al.[26]; www.wri.org/marine-protected-areas-world), coastal module of GOOS is primarily concerned with detecting and forecasting the resulting changes in ecosystems states and their impacts on ecosystem goods and services, that is, the continuous provision of data and information needed to assess and predict impacts of climate change, natural hazards and human activities on public health, ecosystem health and living marine resources. The coastal module is conceived as a global coastal network (GCN) and regional observing systems that enhance the GCN to meet the data and information needs of users in their respective regions [27][28]. Together, the climate and coastal modules provide data needed to inform ecosystem-based approaches to managing human uses and adapting to and mitigating the impacts of climate change [28][29][30][31]. Thus, the provision of data and information needed to inform regular assessments of the state of the marine environment is a central objective of the Global Ocean Observing System (GOOS).

In June 2009, the parties to the twenty-fifth Assembly of the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO) re-affirmed their commitment to sustain the climate module of GOOS and to implement the coastal module. Sustained and coordinated implementation of both modules depends on a well conceived, orderly, phased and iterative process that is driven by user needs, advances in science and technology and performance evaluations.

Box 1. Integrating ecology into GOOS: an example

The continuous plankton recorder (CPR) of the Sir Alister Hardy Foundation for Ocean Science is an example of a sustained, end-to-end system that has been managed separately, performs independently of GOOS and is in the process of becoming an integral part of GOOS. The CPR survey has provided the only multi-decadal, basin and ecosystem scale in situ data on ecological indicators that document effects of ocean warming and basin-scale oscillations on pelagic marine ecosystems and their capacity to support living marine resources. For example, the figure below shows the poleward movement of warm-temperate and temperate zooplankton species between 1958–1981 and 2003–2005, a clear indicator of a warming ocean [24].



The next steps are to incorporate CPR data streams into models of ecosystem dynamics via GOOS data management and communications and globalize the program to help achieve the goals of both the CPR program and GOOS. This will not be easy and the process underscores some of the many challenges of establishing operational marine ecology as an integral component of GOOS.

Data management and communications (DMAC), the link between observations and modelling, is of central importance to the development of an interoperable, integrated SoS. Thus, priority must be given to establishing a DMAC system that serves the needs of decision-makers by providing rapid access to diverse data from many sources. Reducing the time required to acquire, process and analyse data of known quality is a major operational objective that requires the development of an integrated data management and communications system. Access to data in both real time and delayed mode is occurring through a hierarchical distributed system of national, regional and global organizations (including national ocean data centres and world data centres) that function through the use of common standards, reference materials and protocols for quality control, rapid access to and the exchange of data (metadata standards, for example), and long-term data archival. The system is developing incrementally by linking and integrating existing national and international data centres and management programmes.

Interoperability is of critical importance because of the many contributors to data collection, processing and distribution. Since it is only through the use of standard practices that the required level of interoperability can be attained, the adoption of standard procedures in all areas of data management is a high priority. The IOC committee for the International Oceanographic Data and Information Exchange (IODE, www.iode.org/), the Joint Technical Commission for Oceanography and Marine Meteorology Data Management Coordination Group (http://ioc.unesco.org/jcomm/), and WMO are working in collaboration to oversee the establishment of the DMAC system for GOOS (for example, the WMO Information System and the End-to-End Data Management Prototype Pilot Project)[32].

In this context, an important first step toward the routine use of biological data required for ecosystem-based management (Table 4) is to ensure that the Ocean Biogeographic Information System (OBIS) is maintained and continues to develop. The system was developed for the Census of Marine Life (CoML, www.coml.org/), and the International Oceanographic Commission has adopted a resolution accepting OBIS into its International Oceanographic Data and Information Exchange (IODE) program. Under the terms of the resolution, OBIS activity will continue under IODE and the OBIS Secretariat (Rutgers University, New Jersey, United States) will host an IOC programme office. A multi-source fund has been established by the IOC to ensure continued operation of the OBIS enterprise (www.coml.org/node/302). This is an important step toward creating an ocean observing and prediction system for marine and estuarine ecosystems.

Table 4. GOOS modules, societal benefits and associated phenomena (state changes) of interest

Module	*Societal Benefit Areas*	*Phenomena of Interest*
Climate & Coastal	Marine Weather and Climate	• Variations in water temperature and heat content; • Surface fluxes of momentum, heat and fresh water; • Sources and sinks of heat and carbon; • Melting glaciers and ice sheets
Climate & Coastal	Maritime Operations	• Variations in water level, bathymetry, surface winds, currents and waves; • Sea ice mass and distribution; • Susceptibility to natural hazards
Climate & Coastal	Natural Hazards	• Coastal flooding and storm surge; • Susceptibility to natural hazards and coastal erosion; • Public safety and property loss
Coastal	Public Health	• Risk of exposure to waterborne pathogens (viruses, bacterial), chemical contaminants, and marine biotoxins (contact with water, exposure to aerosols, seafood consumption)
Coastal	Ecosystem Health	• Loss of biodiversity; • Habitat loss and modification; • Ocean acidification; • Excess nutrient enrichment from anthropogenic sources, accumulations of organic matter, and oxygen depletion (cultural eutrophication); • Harmful algal events and invasions of non-native species; • Chemical contamination of sediments; • Diseases in and mass mortalities of marine organisms
Coastal	Living Marine Resources	• Fluctuations in spawning stock size, recruitment and natural mortality; • Changes in areal extent and condition of essential habitat; • Food availability for harvestable stocks; • Aquaculture production and water quality

Source: UNESCO, 2003, 2009 [27][31]

Note that coastal GOOS includes ecosystem health and living marine resources for the oceans as a whole (coastal and open ocean) and that physical oceanographic and meteorological data and information are needed for both modules and for all six societal benefit areas.

2. Needs assessment

Implementing the regular assessment process requires routine, sustained and interdisciplinary observations and modelling that provide data and information needed to inform repeated assessments and adaptive, ecosystem-based approaches to climate risk management (Figure 1). We do not have this capability today. It is an unfortunate reality that, in the current environment, it takes far too long to complete regional- and global-scale ecosystem assessments (3–5 years); they are completed too infrequently; and there are major gaps in the data needed to calculate the required indicators (for example, www.ioc-goos.org/content/view/191/121/; www.heinzctr.org/ ecosystems/index.shtml; www.millenniumassessment.org/en/index.aspx). The inherent dynamics of marine ecosystems, the potential for abrupt climate change, the time required to produce ecosystem assessments and the gaps in them underscore the shortcomings of current ecological information systems and the importance of sustained and integrated ocean observation and prediction systems and of implementing, maintaining and improving GOOS as a contribution to the Global Framework for Climate Services (GFCS).

In addition to the need for sustained observations and modelling, the effectiveness of the regular assessment process (and, therefore, our ability to adapt to and mitigate the effects of climate change) depends on a sustained collaboration among data providers and decision-makers to ensure the provision of useful indicators at rates and in forms needed to inform timely decisions. To this end, it is important that countries that contribute to and benefit from GOOS establish mechanisms that enable positive feedbacks between providers and users, that improve the usefulness of data and information provided by GOOS over time and that increase public and political support for sustained development of GOOS in perpetuity (user pull). The insurance and reinsurance industry can play a critical role in this process (Box 2).

2.1 Implementation status of GOOS

Substantial progress has been made in the design and implementation of the climate module of GOOS since the United Nations Conference on Environment and Development in 1992 and some elements of GOOS are now operational or rapidly becoming operational, for example, nowcasts and forecasts of sea-surface temperature, waves and currents; and nowcasts of sea-surface chlorophyll [31][33][34]. An intergovernmental body has been established to coordinate, regulate and manage the climate module (the Joint WMO-IOC Technical Commission on Oceanography and Marine Meteorology [JCOMM], http://ioc.unesco.org/jcomm/). For in situ observations, nearly 60 per cent of the initial specification for the global module has been implemented. Satellite-based remote sensing of sea-surface temperature, sea ice, sea-surface height, surface waves and currents and ocean colour has been sustained. At this time, the primary challenges for remote sensing are to sustain in perpetuity the temporal continuity of observations,

Box 2. The insurance industry and climate change
Kyoto Statement, The Geneva Association's Thirty-sixth General Assembly, 29 May 2009

The prospect of extreme climate change and its potentially devastating economic and social consequences are of great concern to the insurance industry…We, the leaders of the world's largest insurance and reinsurance companies as assembled in The Geneva Association, want to make known our view through the following key messages.

Customers
- We are committed to enhancing our research capabilities to provide better evaluation and management of climate risks.
- We promote incentives for offsetting or reducing greenhouse gas emissions and for mitigating and adapting to climate change.
- We are willing to design insurance products that support low-carbon energy development projects and help attract investments in such products.

Policy-makers
- We are prepared to help counter climate risks through active cooperation in implementing building codes or similar means which encourage the use of sustainable practices.
- We offer to work closely with policy-makers on communicating to our customers their climate risk levels, possible strategies of mitigation and adaptation, and in quantifying the financial benefits of those strategies.
- We recognize the significant benefit of pooling climate risks and urge policy-makers to collect robust data and make it freely available to allow risk assessment and to facilitate efficient solutions where premiums are risk-based.

United Nation's Climate Change Conference (COP15)
- The insurance industry is uniquely positioned to provide specialized services for countries and businesses facing climate risks worldwide.
- Insurers have the expertise to develop a broad range of affordable private insurance solutions for climate risks.
- Insurance mechanisms are an effective tool to promote climate-related risk management and reduction.
- Recognizing that no stakeholder can succeed alone in solving the challenges of climate change, the insurance industry can and should be a strong complementary mechanism in a broader framework of adaptation.

Insurance industry
- We encourage political processes to work towards a better understanding of the potential costs of climate change and the advantages of market-based solutions.
- We continue to work towards further reducing the relatively moderate carbon footprint of the insurance industry.
- We are willing to play a major and concerted role in the global efforts to counter climate risks.

The Geneva Association acts as a hub for expert networking and strives to create opportunities for the insurance industry to join forces in dealing with climate risks where relevant and appropriate.
(See: http://www.genevaassociation.org/Home/Climate_Change.aspx.)

increase their resolution in time and space, and, for ocean colour, to increase spectral resolution and improve algorithms for computing pigment concentrations in coastal waters.

While the transition of the climate module of GOOS from planning and research to the first stages of an integrated, operational system has begun (for example, the Global Ocean Data Assimilation Experiment, [GODAE, www.godae.org/]), long-term commitments by developed countries to sustained ocean observations remain uncertain. Much of the justification for investing in the climate module is based on the provision of data and information needed to improve assessments (rapid detection and timely predictions) of when and how changes in the ocean–climate system will impact the coastal zone where people and ecosystem goods and services are most concentrated, that is, when and how large-scale changes in the ocean–climate system will be expressed in coastal ecosystems where the potential demand for data and information on the oceans is greatest (Box 3). Thus, coordinated development of the ocean–climate and coastal modules is needed to justify long-term commitments to maintain and improve GOOS as a whole over time. This, in fact, may be the greatest requirement that has yet to be addressed effectively.

2.2 Implementing coastal GOOS

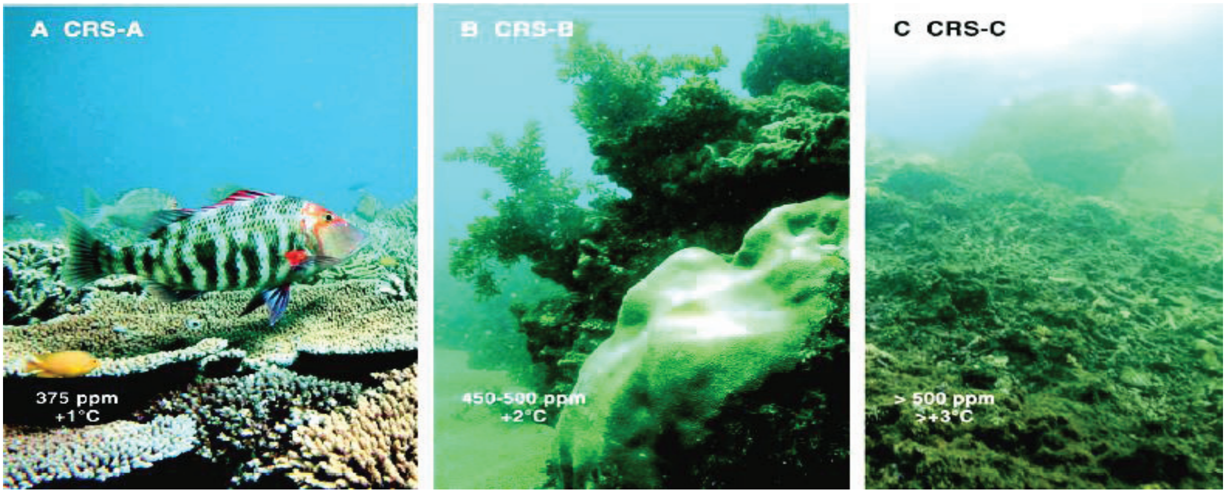
The Integrated Design Plan for the Coastal Module calls for establishing Regional Coastal Ocean Observing Systems (RCOOSs) worldwide and, through this process, the development of a Global Coastal Network (GCN) [27]. The former has begun, and coordinated development of regional observing systems is now needed to create a GCN that measures, manages and analyses common variables needed by all or most coastal nations and regions; establishes sentinel and reference stations; and implements internationally accepted standards and protocols for measurements, data telemetry, data management and modelling. As recently updated by the Panel for Integrated Coastal Observations (www.ioc-goos.org/content/category/15/52/92/), the provisional common variables include geophysical variables (temperature, salinity, currents, waves, sea level, shoreline position, bathymetry), chemical variables (dissolved inorganic nutrients, dissolved oxygen, pCO_2, pH), biological variables (faecal indicators, phytoplankton biomass, benthic biomass), and biophysical variables (bio-optical properties).

Box 3. Loss of coral reef habitats:
an example of ecosystem-scale impacts of global climate change

Coral reef ecosystems are among the most biologically diverse, economically important ecosystems on earth. They support ~25 per cent of marine species and provide ecosystem goods and services valued by society including fisheries, coastal protection, building materials, biochemical compounds and tourism [35][36].

Yet coral reefs are deteriorating at an alarming rate. Nearly 20 per cent of the world's coral reefs have been lost over the last two decades; 15 per cent are seriously threatened with loss within the next 10–20 years; and 20 per cent are under threat of loss in 20–40 years [37]. The primary causes of these changes in the spatial extent and health of coral reefs are local, anthropogenic pressures (fishing and increases in sediment and nutrient loading from land-based sources) and global pressures of climate change (warming of the upper ocean, sea-level rise, and ocean acidification) [38].

To illustrate the effects of global climate change,* Hoegh-Guldberg et al. [38] simulated the ecological implications of a 20.6 per cent reduction in coral growth rate, the measured rate of decline for the Great Barrier Reef *Porites*. Trajectories for three possible scenarios were run. (1) If $[CO_2]_{atm}$ stabilizes at the current level of 380 ppm, coral reefs will continue to change but will remain dominated by carbonate accreting corals. Local pressures become the primary determinants the health of coral reefs. (2) Given the current rate at which $[CO_2]_{atm}$ is increasing, reef erosion will exceed calcification when $[CO_2]_{atm}$ reaches 450–500 ppm. Under this scenario, the growth and biodiversity of coral reefs decline, leading to reductions in the extent and diversity of coral reef ecosystems and associated declines in animal populations (fish and invertebrates). (3) Should $[CO_2]_{atm}$ increase > 500 ppm, coral reefs will become rapidly eroding rubble banks resulting in the loss of coral-dependent fauna (50 per cent or more), dominance of macroalgae and frequent phytoplankton blooms.



* Small, prolonged increases in sea temperature cause corals to expel their endosymbiotic, food-producing algae resulting in bleaching, the effects of which on coral growth are exacerbated by lower light levels caused by sea-level rise. Ocean acidification is compromising the accretion of carbonate and, consequently, the health and growth of stony corals and coralline algae.

Although it is a high priority of the international community and some progress has been made, implementation of coastal GOOS has been slow and uneven geographically. Challenges that must be addressed to take implementation of the coastal module to the next level include the following:

(a) Operational marine ecology (from observations and data management to modelling) is in formative stages of development at best. Establish mechanisms to transition new technologies and models developed through research and development into an operational mode when they are ready and needed.

(b) The capacity to implement coastal GOOS varies substantially among coastal nations and regions. Enable developing countries (which account for most of the Earth's coastlines) to contribute to and benefit from GOOS through pilot projects that build capacity.

(c) Social, political and technical barriers inhibit the global development of coastal GOOS. Overcome these barriers to reach international agreements on policies and procedures for timely data exchange among countries on the states of their respective coastal ecosystems.

(d) The coastal module has a broad and complex mandate with interdisciplinary (meteorological, physical, geological, chemical and biological) requirements for data and modelling that differ substantially from place to place depending on the relative importance of a diversity of phenomena (Table 4). Reach international consensus on priorities for phased implementation on regional and global scales.

(e) Establishing a global system of systems that is interoperable and meets national needs requires global coordination and collaboration among a large number of coastal nations (wealthy, developing and economies in transition) and regional bodies with related goals (WMO Regions, GRAs, IOC Regional Offices, Regional Seas Conventions, Regional Fishery Bodies, and Large Marine Ecosystem [LME] programmes).

(f) The climate science community must attract funding for all of the above and develop sufficient demand for GOOS data and information by user groups to justify sustained funding.

The *Implementation Strategy for the Coastal Module of GOOS* recognizes these challenges and presents over 50 recommendations to address them as a step toward formulating specifications for the observing system [28]. Cross cutting recommendations address needs for sustained development of GRAs, capacity-building and global coordination.

2.2.1 GOOS regional alliances

Sustained development of GRAs is critical to the establishment of coastal GOOS, especially in the developing world where most of the Earth's coastal waters lie. Although many sectors are expected to participate (governments, intergovernmental organizations, academia, industry and non-governmental organizations), national contributions to the development and management of the coastal module are critical. Thus, IOC Member States have been asked to establish National GOOS Coordinating Committees (or entities within those states) and to coordinate or manage some aspects of their GOOS activities through GOOS Regional Alliances. Thus, the twenty-second IOC Assembly (June 2003) endorsed a Regional GOOS Policy and the creation of GRAs as a mechanism for promoting and implementing GOOS regionally. Today there are 12 GRAs in various stages of development (Figure 3).

The GOOS Regional Alliances (GRAs) are, in effect, Communities of Practice (http://home.att.net/~discon/KM/CoPCharacteristics.htm). These are community-based efforts to (a) work with user groups that use, depend on, manage or study marine systems to establish national and regional priorities for data and data-products; (b) guide and manage the establishment of regional ocean observing systems based on these priorities; (c) contribute to building an interoperable global coastal network (GCN) of observations, data management and modelling that meets both regional and global needs; (d) promote the implementation of pilot projects that will improve operational capabilities of the observing system; and (e) engage user groups in performance evaluations of the usefulness and efficacy of data and information provided by the observing system. The success of this effort depends on effective collaboration and coordination with existing regional bodies that have common or related goals and needs. These include IOC Regional Offices (www.ioc-goos. org/content/view/25/37/), Regional Seas Conventions (www.unep.org/regionalseas/), Regional Fishery Bodies (www.fao.org/fishery/rfb/search/en), and Large Marine Ecosystem programmes (www.lme.noaa.gov/).

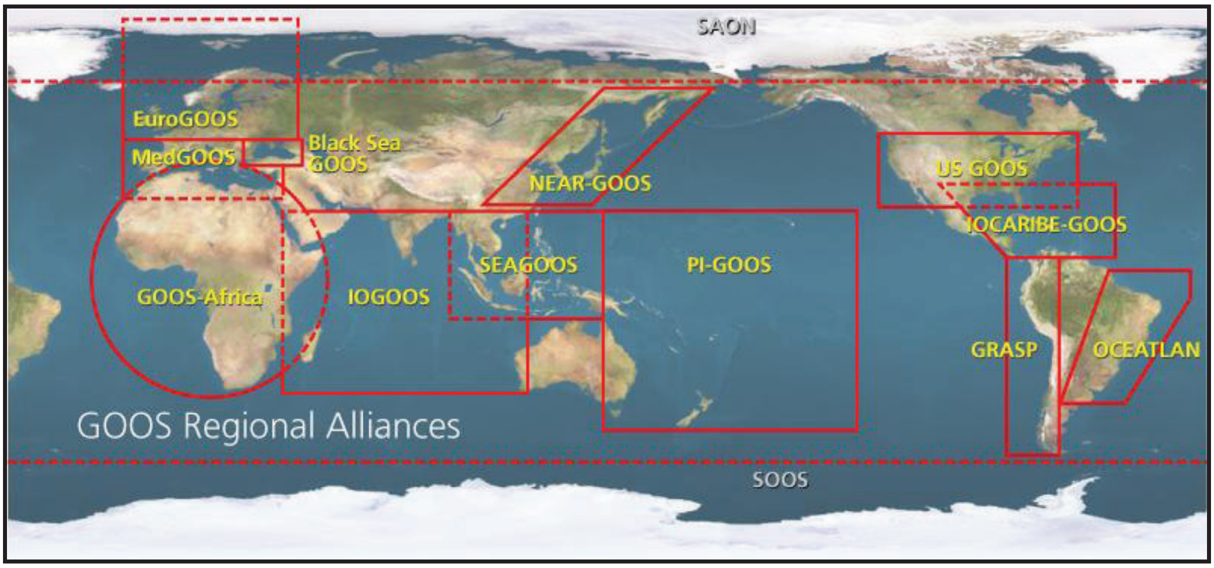


Figure 3. GOOS Regional Alliances

GOOS Regional Alliances have been established to design and implement Regional Coastal Ocean Observing Systems and to build a Global Coastal Network (GCN) of observations, data management and modelling. GRAs in yellow have been recognized by the IOC. Those in grey (SAON and SOOS) are in development.

2.2.2 Developing and improving capacity

A fully integrated GOOS that addresses all six societal goals (Table 4) can be achieved only by improving coastal observing system capabilities globally. Capacity-building [39] is needed on two related fronts: (a) enabling countries and GRAs in different stages of economic development to establish coastal ocean observing systems and to benefit from data and information provided by GOOS as a whole, and (b) developing new technologies and models through research that can be used to improve the operational capabilities of regional coastal ocean observing systems and the GCN. Both can be achieved most effectively by initiating cooperative pilot projects (www.ioc-goos.org/component/option,com_weblinks/catid,50/Itemid,87/) with GRAs and training programs that have focused, attainable objectives and will leave a legacy of self-sufficiency. Focusing on processes that will enable developing countries and economies in transition to contribute to and benefit from GOOS data and information, the Coastal Ocean Observations Panel recommended the following actions [27][28]:

(a) Create and sustain centres of excellence for ocean observations and modelling at established oceanographic institutions that will provide training and education to students and young professionals from developing countries and technical advisors to developing countries who will facilitate the deployment, use and maintenance of new and existing infrastructure (Box 4);

(b) Fund partnerships between developing and developed countries to implement pilot projects that will enable the provision of goods and services identified as high priorities by participating countries and GRAs in the developing world (Box 5);

(c) Encourage partnerships between GRAs, LME programmes, and other regional efforts to transition successful pilot projects to operational status as needed and endorsed by countries within each region (Box 6).

Box 4. Capacity-building initiatives of the
Partnership for Observation of the Global Ocean (POGO)

A lack of trained personnel is a major obstacle to development of a global ocean observing system. To help address this problem, POGO has initiated capacity-building and training activities that target scientists from developing countries and those with economies in transition.

In partnership with the Scientific Committee on Oceanic Research (SCOR), POGO initiated a Visiting Fellowship programme on Oceanographic Observations in 2001. The fellowships enable young professionals from developing countries to receive advanced education and training at a major oceanographic institution. The programme benefits about 12 students and scientists each year, and promotes collaboration among institutions in developed and developing countries. Applications for the programme exceed the number that can be accommodated each year by a factor of eight, a clear indication of the need for such programmes.

In collaboration with the Nippon Foundation, POGO established a Visiting Professor Programme under which marine scientists of international standing teach at marine institutions in developing countries for periods of up to three months. This exposed young scientists to the knowledge and experience of world-class oceanographers and facilitated interactions among scientists from developed and developing countries. This 3-year programme has transitioned into a new collaboration with the Nippon Foundation hosted by the Bermuda Institute for Ocean Science, namely the Centre of Excellence in Ocean Observations. The Centre provides 10 months of intensive training for 10 Ph.D. students per year.

Taken together, these programmes are important examples of the kinds of training initiatives needed to increase the capacity of developing countries to contribute to and benefit from ocean observing and prediction systems.

Box 5. End-to-end pilot projects: the chlorogin example

Pilot projects are an important mechanism for capacity-building, especially in those regions that do not have the resources to contribute to GOOS. An example of a pilot project that is important for developing the coastal module is the Chlorophyll Global Integrated Network project (ChloroGIN) sponsored by GOOS, GEO, the International Ocean Colour Coordinating Group (IOCCG), the Plymouth Marine Laboratory (PML) and POGO (www.chlorogin.org/). The project's goal is to promote the combined use of in situ chlorophyll-a measurements and estimates of surface chlorophyll-a concentrations from space-based measurements of ocean colour to improve hindcasts and nowcasts of surface fields of phytoplankton biomass and the frequency with which such fields are estimated (daily, weekly or bi-weekly, depending upon each region's needs and conditions).

Ocean colour provides regular (sometimes daily), low-cost estimates of phytoplankton biomass fields. These substantially increase our ability to detect and forecast harmful algal blooms and other public health risks such as exposure to Vibrio cholerae and other human pathogens [40] and aid fishing operations, fisheries management, and coastal zone management, among others. The time series generated by years of such observations have already led to explanations of haddock and shrimp recruitment fluctuations in the north-west Atlantic. Thus, the primary objectives of ChloroGIN are to (a) deliver maps of ocean chlorophyll and sea-surface temperature, as the basis for developing ecosystem indicators needed for stewardship of the oceans [41]; and (b) provide in situ time series of chlorophyll, temperature and water clarity [42]. These variables are needed to develop regional satellite algorithms for phytoplankton biomass and to calculate phytoplankton primary production. They are three of the core variables recommended for the Global Coastal Network.

Combining satellite data with in situ measurements allows applications to be extended to domains inaccessible by either method alone. To this end, a global network of in situ measurements is being established by coastal laboratories using existing technologies and well established methods. This enables routine and sustained measurements, regional enhancements to meet regional and national priorities, and access to data and data products by both developing and developed countries. As a first step, the global network is developing in regions where expertise is already available. The initial ChloroGIN regional nodes are in Canada, India, Latin America and South Africa.

Box 6. Rationale for GRAs and LME programmes to collaborate

Most of the world's coastal oceans are divided into 50 regional Large Marine Ecosystems (LMEs), most of which are located in at least one GOOS region. The LME programmes are funded by the Global Environmental Facility to develop and implement procedures for assessing and managing the effects of human activities on living marine resources in an ecosystem context, that is, for linking science-based assessments of changing states of coastal marine and estuarine ecosystems to the socio-economic benefits of sustaining ecosystem goods and services [43]. Thus, GOOS and LMEs have many common goals and observing system requirements. Consider, for example, observations required for both coastal GOOS and the Benguela Current LME.

Coastal GOOS	*Benguela Current LME*
Current fields	Coastal currents and upwelling
Phytoplankton biomass and diversity	Phytoplankton biomass
Dissolved inorganic nutrients (N, P, Si), dissolved oxygen, pH, pCO_2,	Dissolved inorganic nutrients
Chemical contaminants in water and biota	Chemical contaminants in water, sediment, biota
Zooplankton species and biomass	Zooplankton species and biomass
Commercial fish species abundance and distribution	Commercial fish species abundance and distribution
Non-exploited fish species abundance and distribution	Non-exploited fish species abundance and distribution
Top predator (marine mammals, birds) abundance and distribution	Top predator (marine mammals, birds) abundance and distribution
Extent and condition of biologically structured habitats (coral reefs, seagrass beds, kelp beds, tidal wetlands)	Regional assessment of vulnerable habitats

Given limited resources and these commonalities, GOOS Africa and the Benguela Current LME are in the early stages of a collaboration that can be considered a model for other GRAs and LMEs to follow.

2.2.3 Global coordination

With the establishment of national GOOS programmes and the formation of GRAs, there is a need for a mechanism to coordinate development of regional observing systems and ensure inter-operability on a global scale. As of this writing, four GOOS Regional Forums have been held (2002–2008) to facilitate coordinated implementation and interoperability; a GOOS Regional Council has been formed to oversee this process and represent GRAs on the Intergovernmental Committee for GOOS (I-GOOS); and regional observing systems for detecting and predicting state changes in the physical environment of the upper ocean are in various stages of development (www.gosic.org/goos/GOOS-observational-programs.htm; www.ioc-goos.org/content/view/159/89).

2.2.4 *The strategic action plan for implementing the coastal module of GOOS*

A realistic, phased action plan for implementing coastal GOOS based on observing system requirements and current and projected future capabilities is needed. To facilitate timely and cost-effective establishment of a global coastal ocean observing system, the next steps are to update the *Implementation Strategy for the Coastal Module* based on recent advances in scientific understanding (for example, Adger et al. [20]; Hall-Spencer et al., [2]; Diaz and Rosenberg [3]; Halpern et al. [4]) and technology (for example, www.act-us.info/); formulate observing system specifications; develop an international consensus on priorities for phased implementation regionally and globally; and prepare an action plan that can be used to guide the establishment of the GCN based on these specifications and priorities.

The Panel for Integrated Coastal Observations (www.ioc-goos.org/content/view/17/31/) was formed in 2008 and tasked with preparing a scientifically sound, realistic, prioritized and phased action plan that can be used by national GOOS programmes, GRAs and JCOMM to help guide their contributions to coastal GOOS. The plan will include:

(a) Observing system specifications and an action plan for a prioritized, phased build-out of an operational, global system of systems in 5-year increments out to 20 years (with time lines, milestones and cost estimates);

(b) An assessment of the current status of implementation with a gap analysis;

(c) Priorities for research and regionally organized pilot projects for improving and expanding operational capabilities (proof of concept, demonstration of operational capabilities that address one or more of the societal benefits);

(d) Performance metrics for the build-out and for improving operational capabilities.

The plan will unfold in three stages. Stage 1 will recommend end-to-end solutions (pilot projects such as ChoroGIN that include observations, data telemetry, data management communications, data analysis and modelling) for the provision of indicators to decision-makers (end-users). Because of their global impacts on ecosystem goods and services, PICO has identified six subjects (from four benefit areas, Table 4) for which indicator-driven, regionally specific pilot projects will be recommended:

(a) Managing and mitigating the impacts of sea-level rise and coastal inundation on marine ecosystems and coastal communities (natural hazards, ecosystem health benefit and living marine resources areas);

(b) Preventing human exposure to waterborne pathogens and biotoxins (public health benefit area);

(c) Monitoring ocean acidification and its effects (ecosystem health benefit area);

(d) Monitoring habitat modification and loss (natural hazards, ecosystem health and living marine resource benefit areas);

(e) Forecasting coastal eutrophication and hypoxic events (ecosystem health and living marine resources benefit areas);

(f) Predicting changes in the abundance of exploitable living marine resources (ecosystem health and living marine resources benefits areas).

Once end-to-end pilot projects are completed for each indicator or set of indicators, Stage 2 will present a cross-cut analysis to identify common requirements for modelling, observations and data management. This information will be used to specify a value-added, integrated system of systems that should be implemented on a global scale. Stage 3 will include a prioritized, step-by-step build-out plan with a timetable, milestones and cost estimates. The process of completing this three-stage process will reveal operational deficiencies and associated priorities that will be used to recommend priorities for pilot and research projects.

Phased implementation of the GCN requires prioritization of the proposed pilot projects. Four criteria were used to determine the highest priority project:

(a) Data integration must lead to more accurate and timely assessments of ecosystem states and predictions of changes in state that have major socio-economic consequences on a global scale;

(b) Such assessments and predictions must inform decision-makers working in two or more of the societal benefit areas (Table 4);

(c) Data integration resulting in new and improved products and services must occur sooner rather than later (2 years);

(d) Data streams produced by existing monitoring assets must be sustainable, reliable and quality controlled.

Improving the reliability of model-based predictions of climate-driven sea-level rise and hazard-driven (tropical cyclones, tsunami) coastal inundation, and the impacts of sea-level rise and coastal inundation on coastal marine ecosystems and public health meet these criteria and should be a high priority for the initial phases of coastal GOOS implementation (Box 7). Given the emphasis of the ocean–climate module of GOOS on the former, our focus here is on detecting and predicting the impacts of sea-level rise and coastal inundation.

2.3 Observing system requirements for managing vulnerability to sea-level rise and coastal inundation

Rising sea levels will have significant impacts on coastal populations and ecosystems worldwide. Climate-driven sea-level rise will exacerbate the impacts of tropical cyclones, extra-tropical storms (baroclinic, mid-latitude, winter storms), nor'easters and tsunami. 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 will receive less light, exacerbating the effects of ocean warming and acidification (Box 3); salinity will increase in estuaries; and aquifers will be contaminated with salt. 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 [48].

Since the human disaster of the December 2004 Indian Ocean tsunami, improving forecasts of the timing, location and magnitude (time–space extent) of coastal inundation events (hazard intensity and probability) has become an international priority ([49]; www.jcomm.info/index.php?option=com_oe&task=viewDoclistRecord&doclistID=84). Unfortunately, our ability to provide reliable, long-term, quantitative predictions of changes in ecosystem states on spatial scales needed for ecosystem-based coastal planning and public health management is limited at best. 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. With this in consideration and building on the important effort to improve forecasts of inundation events, the recommended end-to-end solution for coastal inundation focuses on data and information requirements for managing vulnerability.

Box 7. The insurance industry and coastal inundation
From: The Geneva Reports, 2009, No. 2.
http://www.genevaassociation.org/PDF/Geneva_Reports/Geneva_report%5B2%5D.pdf

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 [44]. Increases in storm surge will increase these numbers substantially. The Organization for Economic Co-operation 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 trillion to US$ 35 trillion [45]. As a proportion of GDP, economic losses from flooding are much higher for developing countries than for developed countries [46]. Financial losses from weather events are currently doubling every 12 years at an annual rate of 6 per cent [47].

One option for at-risk regions in adapting to greater storm surges is to invest in hard defences 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 (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 where 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 that 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.

Managing and mitigating the impacts of coastal inundation require high-resolution, digital, geospatial nowcasts and 5–10 year forecasts of vulnerability to coastal inundation that are updated at 1–10 year intervals depending on coastal geomorphology anthropogenic modifications of coastal habitats [48]. Such maps must be grounded in observations and capture the effects of changes in shoreline position, near-shore bathymetry and topography (for example, 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 habitat buffers (coral reefs, seagrass beds, intertidal wetlands, dunes), human population density and spatial extent of impermeable surfaces and hardened shoreline. An end-to-end solution for the provision of vulnerability maps as an integrated product is given in Table 5.

Maps of vulnerability will not only be important for land-use planning, habitat restoration and insurance purposes, they will also provide a framework for assessing changes in resiliency to and impacts of coastal inundation and sea-level rise on coastal ecosystem goods and services. Both of the latter require pre-planned, adaptive sampling scenarios that can be implemented immediately following inundation runoff events to document and assess ecological impacts, the ability of impacted socio-economic and ecological systems to recover and the time course of recovery or change. This includes impact assessments on coastal infrastructure, distributions of waterborne pathogens and chemical contaminants, coastal habitats and living marine resources.

Regions to be targeted are those vulnerable to sea level rise, that is, major river deltas, low lying estuarine and coastal land forms and small island development states (SIDS).

Table 5. An end-to-end solution for the provision of indicators to end-users responsible for coastal zone management and for managing and mitigating the impacts of coastal inundation

Indicator	Digital, high resolution, geospatial maps of susceptibility to flooding
End-Users	• Government: Policymakers and managers responsible for Flood Plain and Emergency Management; Land-Use, Coastal Zone and Resource Management; Environmental Protection; Public Health, Transportation and Public Works • Private Sector: Developers, Construction and Real Estate; Insurance and Re-insurance; Non-Governmental Organizations • The public
Data Providers	• Operational government agencies (for example, for the United States: NOAA, ACE, USGS), private consulting firms, and scientists
Required Observations (remote and in situ sensing)	• Geospatial boundaries of areas susceptible to flooding • Geospatial boundaries of historical flooding events • Within each area, continuous measurements of ➢ Sea level along the land–sea interface at representative locations ➢ River flows • Within each area, repeat at 5-year intervals and post flooding events: ➢ Digital, high resolution, geospatial mapping of bathymetry-topography across the land sea interface in these areas ➢ Spatial extent and condition of near shore habitats (coral reefs, seagrass beds, mangrove forests, tidal marshes, beaches and dunes, barrier islands) ➢ Near shore land uses (hardened shoreline, impervious surfaces, farm lands) and land cover (forests, grasslands)
Model Requirements	• High-resolution digital elevation models of topography, shoreline position, bathymetry • Algorithms to compute levels of susceptibility as a function of current or predicted seasonal and annual mean sea level using required observations • Geographic Information Systems to map levels of susceptibility
Operational Status	• Technology exists to make the required observations and maps (GPS linked tide and river flow gauges, satellite remote sensing [laser, radar altimetry, InSAR and gravity] and airborne LIDAR and photography) • Algorithms for computing levels of susceptibility are in development • Models for generating geospatial maps of levels of susceptibility are in development
Priority Research and Pilot Projects	• Achieve universal use of a standard vertical datum • Determine optimum locations for GPS equipped tide gauges for accurate estimates of sea level continuously along the shoreline • Develop algorithms and geospatial models to provide digital, high resolution maps of susceptibility to flooding • Validate maps • Build capacity in high risk, developing countries

Modified from Malone and Hemsley, 2006/2007 [50]

We emphasize that the efficacy of the recommendations given above depends on important assumptions including the following:

(a) There will be continuity in satellite radar altimetry missions (for example, Jason 3 will be launched on schedule in 2013);

(b) The Global Geodetic Observing System (GGOS) will be completed and sustained;

(c) The Global Sea-Level Observing System (GLOSS) will be expanded and improved (optimizing the distribution and number of gauges based on local, regional and global data requirements; equipping more gauges with GIS and real-time data telemetry as required to improve predictions of local mean sea level and absolute sea-level rise);

(d) Numerical model predictions of local mean sea level (relative to a land-based benchmark) will become operational (validated, routine and reliable with data assimilation) on event to seasonal timescales;

(e) Numerical predictions of absolute (eustatic) sea-level rise will become operational for predictions of annual to decadal trends.

3. Conclusions

The needs for climate adaptation and climate risk management are greatest in the coastal zone (marine and estuarine waters and adjacent lands) where people and ecosystem goods and services valued by society are most concentrated. Thus, it is in the best interests of all coastal nations to identify those goods and services that are at risk and how best to ensure the provision of data and information needed for sustainable development in a changing climate. To these ends, we strongly recommend the following:

(a) Continue to build a sustained and integrated global ocean observing and prediction system of systems (GOOS) as a major building block of a Global Framework for Climate Services (GFCS) that is both global in scope and locally relevant to all nations;

(b) Ensure the coordinated, interoperable development of the climate and coastal modules of GOOS as a part of this process;

(c) Support the continued development of GOOS Regional Alliances for engaging decision-makers and data providers in the sustained development of regional observing systems as building blocks of a global system of systems.

Given the cross-cutting socio-economic, ecological and political impacts of sea-level rise and coastal inundation, high priorities for developing the coastal module globally are the provision of data and information needed for (a) repeated assessments of the extent to which climate-driven changes in coastal ecosystems across the land–sea interface jeopardize sustainable development by increasing the vulnerability of coastal ecosystems, communities and infrastructure to sea-level rise and coastal inundation and (b) the provision of data and information required for climate risk management and effective adaptation to climate-driven changes in the coastal zone. With an emphasis on capacity-building in developing countries and economies in transition, five major challenges must be addressed:

a. Attract funding from developed countries for sustained capacity-building that leaves a legacy of self-determination and self-sufficiency in developing countries and economies in transition that have the greatest climate risks and needs for adaptation to climate change;

b. Establish an interoperable ocean and coastal information system that provides rapid, comprehensive access to multidisciplinary data on marine and estuarine ecosystems as part of the Climate Services Information System;

c. Effect international agreements that enable timely communication of data and information on the historical, current and likely future states of marine and estuarine ecosystems regionally and globally;

d. Strengthen research needed to implement continuous and sustained ecological observing and prediction capabilities on local to global scales;

e. Establish pilot projects in developing countries that:

  (1) Promote partnerships between developed and developing countries to address user-defined needs in developing countries;

  (2) Build capacity;

  (3) Efficiently link observations and models through reanalysis, data assimilation and validation;

  (4) Improve the skill of model predictions;

  (5) Facilitate interoperability among countries and the climate and coastal modules of GOOS;

  (6) Enable sustained development of GOOS Regional Alliances and partnerships with other regional programmes with overlapping objectives and data requirements (for example, WMO Regions, IOC Regional Offices, Regional Seas Conventions, Regional Fishery Bodies, and LME programmes).

The bodies needed to oversee coordinated implementation of the climate (JCOMM) and coastal (GRAs and the GOOS Regional Council) efforts are in place or in various stages of development, and the technologies required for operational marine ecology are emerging. High priority immediate needs are as follows:

(a) More effective collaboration between JCOMM and the GRA enterprise (via the GOOS Regional Council) to facilitate coordinated development of the climate and coastal modules of GOOS;

(b) International agreement on priorities for global implementation of coastal GOOS and collaboration to ensure effective use of limited resources (rather than competition for them);

(c) Commitments by rich nations to fund the development of coastal GOOS on a global scale through sustained capacity-building in the developing world;

(d) International agreements to ensure interoperability and rapid, timely and open access to monitoring data from national Exclusive Economic Zones globally.

Achieving these objectives will require clearer definition of the roles and responsibilities of intergovernmental bodies (IOC, I-GOOS, WMO, JCOMM, GOOS Scientific Steering Committee [GSSC]), and international bodies (for example, GRAs, Group on Earth Observations, Partnership for Observations of the Global Ocean) and stronger user pull from coastal nations worldwide to justify sustained funding of operational oceanography and marine ecology. The latter depends in part on coordinated development of the climate and coastal modules of GOOS and the establishment of GRAs that engage participating nations and user groups in designing, implementing and improving GOOS and the linkage between the climate and coastal GOOS modules.

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