Quantitative Assessments of the Condition of Marine Ecosystems: The Need for the Coastal Module of the Global Ocean Observing System

Thomas C. Malone, Robin O'Malley, and Mary G. Altalo

Abstract— **Coastal nations worldwide are experiencing changes in their coastal marine and estuarine systems that jeopardize the capacity of marine ecosystems to support products and services valued by society. Developing the capacity for rapid detection and timely predictions of these changes requires that quantitative indices of ecosystem condition be reported routinely and periodically. This contribution discusses the importance of linking the development of the Global Ocean Observing System to the provision of quantitative indicators for policy makers and the public at rates and in forms needed for scientifically sound decision making.**

Index Terms—**marine ecosystem assessments, Global Ocean Observing System, indicators of ecosystem state, coastal monitoring**

I. Introduction

THE cumulative effects of natural hazards, human activities and climate change are, and will continue to be, most pronounced in the coastal zone where people and ecosystem goods and services are most concentrated, risks of natural hazards are greatest, and inputs of energy and matter from land, sea and air converge [1]-[3]. Consequently, coastal nations worldwide are experiencing changes in their coastal marine and estuarine systems that jeopardize sustainable development, human health and safety, and the capacity of marine ecosystems to support products and services valued by society. Because these changes and their causes frequently transcend national borders, concerns over their impacts have led to numerous international agreements that require sustained, timely, routine and reliable assessments of the condition of coastal marine and estuarine systems [4]. This contribution uses data and information requirements for calculating indices of the condition of marine and estuarine ecosystems to illustrate the need for implementing the coastal module of the Global Ocean Observing System (GOOS) as articulated in design and implementation plans for coastal GOOS [5]-[6].

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T. C. Malone is with the Ocean.US Office and the University of Maryland Center for Environmental Science, Cambridge, MD 21613 USA (phone: 703-588-0849; fax: 703-588-0872' e-mail: t.malone@ocean.us).

R. O'Malley is with the H. John Heinz Center for Science, Economics, & the Environment, Washington, D.C. 2006 (e-mail: omalley@heinzctr.org).

M. G. Altalo is with the Ocean.US Office, Arlington, VA 22201 (e-mail: m.altalo@ocean.us).

II. Assessing the Condition of Coastal Marine and Estuarine Ecosystems

Ecosystem-based management, which considers the effects of human activities in the context of natural variability and change, is emerging as a unifying approach to environmental protection, resource management, land-use planning and environmental engineering [7]-[8]. Coastal ecosystems are subject to multiple forcings from both natural and anthropogenic sources, and the effects of one are often exacerbated by the other, e.g., sea level rise associated with global warming increases the susceptibility of coastal populations to storm surge and flooding; over fishing leading to declines in water quality. However, current efforts to manage human uses and mitigate their impacts typically focus on specific human activities, habitats, or species without due consideration of the propagation of variability and change across multiple scales in time, space and ecological complexity [9]-[10]. As environmental research reveals the intricacies of ecosystem dynamics, it is becoming increasingly clear that managing human uses and mitigating their effects with the goals of sustaining and restoring healthy ecosystems and the goods and services they support can best be achieved through strategies that consider ecosystem state changes in the context of the next larger scale that must be observed to understand and predict the local scale of interest [11]. Implementing such strategies depends on knowledge of current and likely future states of marine ecosystems [12]-[13]. This requires the capacity to routinely and rapidly assess environmental conditions, detect changes, and provide timely predictions of likely future states. We do not have this capacity today.

This reality is clearly illustrated by recent attempts to assess the state or condition of ecosystems. Adaptive management of human activities to protect, sustain, and restore healthy ecosystems and the goods and services they provide depends on the capability to repeatedly and rapidly assess the state of

coastal ecosystems and living resources and to anticipate changes in them. Efforts to provide quantitative assessments on local to global scales increased dramatically in the 1990s [14]-[15]. The Millennium Ecosystem Assessment Synthesis Report released in 2005 [16] and the State of the Nation's Ecosystems [17] released in 2002 by the Heinz Center are prominent examples of recent attempts to assess the state of terrestrial, freshwater and marine ecosystems on global and national scales, respectively. Both reports used similar categories of indicators for coastal marine and estuarine ecosystems and took over 5 years to compile. However, the Heinz Center assessment reported results only when sufficient data were available to compute indicators quantitatively on a national scale while the Millennium Assessment often did not specify quantitative indicators or relied on regional examples.

Here we use the 2002 Heinz Center report to evaluate our current ability to provide quantitative indices of ecosystem state at rates that are tuned to the time scales on which management decisions should be made. A panel of experts from academia, government, industry and non-governmental environmental organizations identified indicators for system dimension, chemical and physical conditions, biological components and human uses (Table 1). The report, which is to be updated every 5 years, targets policy makers and the public, is non-partisan and is based on sound science. In addition to the goal of providing a comprehensive assessment of ecosystems on a national scale, the results are used to identify gaps in knowledge and deficiencies in current monitoring programs and data management systems.

A most noteworthy result of the 2002 assessment is that, despite the length of time devoted to compiling and analyzing the data (~5 years) and the relative simplicity of the indicators, only 2 of the report's 16 coastal marine indicators (sea surface temperature, annual fish landings) could be estimated quantitatively with some degree of confidence. The message is clear: If assessments of the status of coastal ecosystems and resources are to be quantitative and comprehensive, and if they are to be repeated periodically in a timely fashion for decision makers and the public, major improvements are needed in the kinds, quality and quantity of data collected and in the efficiency with which data are disseminated, managed, and analyzed. These are goals of the Global Ocean Observing System (GOOS).

III. The Coastal Module of the Global Ocean Observing System (GOOS)

GOOS, the ocean and coastal component of the Global Earth Observing System of Systems [18], is being established to provide data and information needed to achieve six related societal goals: (1) improve predictions of weather and climate change; (2) improve the safety and efficiency of marine operations; (3) mitigate the effects of natural hazards more effectively; (4) reduce public health risks; (5) protect and restore healthy ecosystems more effectively; and (6) sustain and restore living marine resources. GOOS consists of two interdependent modules, one for the global ocean and one for coastal marine and estuarine systems. The global module of GOOS is primarily concerned with monitoring and predicting maritime weather, global climate change, and natural hazards. Coastal GOOS is primarily concerned with the provision of data and information needed to assess and predict the effects of global climate change, natural hazards and human activities on human health risks, the state of marine and estuarine ecosystems, and the sustainability of living marine resources (Table 2). Improving the safety and efficiency of maritime operations are addressed by both modules.

Rapid detection and timely assessment and prediction of state changes relevant to the six societal goals depend on establishing a sustained observing system that efficiently links measurements and modeling via integrated data communication and management to provide data and information in forms and at rates required by decision makers. Linking user needs to measurements requires an efficient and managed flow of data and information among three essential "subsystems" (Figure 1). The system is being built by integrating and enhancing existing capabilities for each of these subsystems. Together, the subsystems constitute an "end-to-end" system that provides data and information for informed decisions on time scales required to achieve desired affects.

The GOOS Scientific Steering Committee (GSSC) [19] was established to provide guidance for building GOOS based on sound science and the development of operational capabilities as required by end users, e.g., decision makers who use, manage or depend on oceanic and coastal systems. As part of this process, the Coastal Ocean Observations Panel (COOP) [20] identified a set of common variables (Table 3) to be monitored globally by answering two questions:

(1) What is the minimum number of variables that must be monitored to address a maximum number of the phenomena of interest (Table 2), and
(2) Of these variables, which ones must be monitored globally?

The panel also specified observing system requirements for estimating their time-space distributions [6]. In so doing it was recognized that C-GOOS must include both a global network of coastal observations (the Global Coastal Network or GCN) to monitor the common variables and regional observing systems to customize coastal observations to the specific needs of users within their respective regions (i.e., increase the number of variables measured and the resolution at which the common variables are measured based on user requirements in each region). As discussed in the implementation strategy for C-GOOS, regional observing systems are currently being

developed by GOOS Regional Alliances [6]. Here we compare requirements for the GCN with the data requirements for assessing the state of coastal marine and estuarine ecosystems.

IV. DATA REQUIREMENTS FOR ECOSYSTEM ASSESSMENTS AS A DRIVER FOR GOOS DEVELOPMENT

To date, GOOS development has not considered the data requirements of ecosystem assessments explicitly, even though implementing the observing system has been justified in terms of the data and information requirements of numerous international environmental agreements and conventions which require repeated, periodic measures of many of the indicators given in Table 1. Monitoring the common variables will support the calculation of 5 of the 16 indicators; 2 of the indicators (living habitats and HABs) are partially addressed; and 9 are not addressed at all. These gaps reflect the fact that the specific variable(s) required for many of these indicators changes from region to region (e.g., the species of fish, harmful algae, native species at risk, chemical contaminants, etc. that are of interest are not the same worldwide; they change from region to region). This highlights the importance of regional observing systems [21] that not only contribute to the development of the GCN, but also enhance the GCN by measuring those specific variables that are very relevant within a given region or several regions but not so worldwide.

V. CONCLUSIONS

Recent attempts to provide rigorous, quantitative assessments are of limited value in terms of public understanding and political action. Limitations include (1) the lack of data (undersampling in time, space and ecological complexity); (2) the challenges of data discovery and access; (3) the length of time (often 5 years or more) and number of experts (often > 100) required to conduct the analysis; and (4) the need for nationally and internationally accepted numerical indicators of ecosystem condition that are useful to decision makers responsible for public health and well being and sustaining and restoring healthy marine ecosystems and the resources they support. A major goal of the Global Ocean Observing System is to provide data and information at rates and in forms required for annual, quantitative assessments of the condition of marine and estuarine ecosystems routinely.

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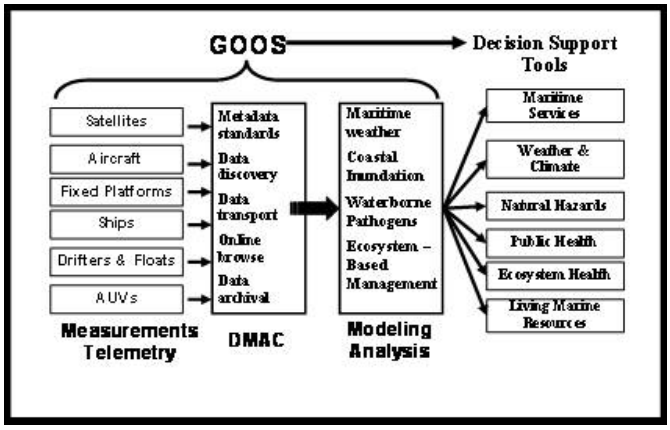

Figure 1. GOOS is an "end-to-end" system that efficiently and continuously links (1) observations and data telemetry to provide the required quality controlled data streams, (2) data management and communication for rapid access to diverse data from many sources, and (3) data analysis and modeling to provide data, products and services in forms and at rates specified by decision makers that use, depend on, manage or study marine and estuarine environments and resources.

Table 1. Summary of the results of the Heinz Center project to assess the condition of coastal marine and estuarine ecosystem on a national scale (no - data were unavailable to calculate the indicator; partial - some data available but insufficient to quantify the indicator on a national scale; yes - indicator quantified).

Category	Indicator	Data
System Dimension	**Living habitats**: area of tidal wetlands, seagrasses, coral reefs & shellfish beds	Partial
	Shoreline types: % shoreline that has been armored or consists of sandy beaches, rocky shores, cliffs, mudflats, salt marshes, & mangroves	Partial
Chemical & Physical Condition	**Dead zones**: % bottom area within 40 km of the coast line that is anoxic (0 ppm), hypoxic (< 2 ppm), low (2-4 ppm), and adequate (> 4 ppm)	No
	SST: deviation of seasonal mean maximum surface temperature from the long-term mean for surface waters within 40 km of the coast line	Yes
	Coastal erosion: % shoreline managed and natural & proportion of natural shoreline that is eroding, accreting, and stable	No
	Contamination: % benthic sediments that exceed federal sediment quality guidelines for concentration of pesticides, PCBs, PAHs, & metals	Partial
Biological Components	**Native species at risk**: % species identified as vulnerable to extinction, imperiled, or critically imperiled	No
	Invasive species: % estuarine area occupied or impacted by non-native species	No
	Condition of benthic communities: % bottom area for which the condition of benthic communities is classified as “undegraded”, “moderately degraded”, & “degraded”	Partial
	Mass mortalities: annual frequency of “unusual” strandings & mass mortalities of fish, mammals, turtles, & birds	Partial
	Plant biomass: seasonal mean maximum chlorophyll-a concentration in surface waters of the EEZ; % estuarine surface area with concentrations < 5 ug/liter, 5-20 ug/liter, and > 20 ug/liter	Partial
	Harmful algal blooms: annual frequency & duration of harmful algal events	No
Human Uses	**Commercial fish landings**: Annual harvest (weight) of fish & shellfish by region	Yes
	Status of commercial fish stocks: % commercially important fish stocks that are increasing, decreasing or stable	Partial
	Contamination: concentrations of PCBs, DDT & mercury in the edible tissue of fish & shellfish	No
	Recreational water quality: % beach-mile-days that have high, moderate and low concentrations of water borne pathogens as indicated by enteric bacteria o	No

Table 2. Examples of phenomena of interest for each societal goal that are the subject of GOOS.

SOCIETAL GOAL	PHENOMENA OF INTEREST
Climate & weather	• Variations in water temperature and heat content; surface fluxes of momentum, heat and fresh water; sources & sinks of heat & carbon; sea ice mass & distribution
Marine operations	• Variations in water level, bathymetry, surface winds, currents & waves; sea ice mass & distribution; susceptibility to natural hazards
Natural hazards	Coastal inundation & storm surge; coastal erosion; susceptibility to natural hazards; public safety & property loss
Public health	• Risk of exposure to human pathogens, chemical contaminants, and biotoxins (contact with water & aerosols, seafood consumption)
Healthy Ecosystems	• Habitat modification, loss of biodiversity, bottom water oxygen depletion, harmful algal events, invasive species, chemical contamination, diseases in & mass mortalities of marine organisms
Living marine resources	• Annual landings, fluctuations in spawning stock size, recruitment & natural mortality; changes in areal extent & condition of essential habitat; food availability; aquaculture production & water quality

Table 3. The provisional common variables recommended by COOP to be monitored as part of the Global Coastal Network (GCN).

Geophysical	Water level & bathymetry
	Shoreline position
	Temperature & salinity
	Currents and surface waves
	Sediment grain size
Chemical	Sediment organic content
	Dissolved inorganic nitrogen, phosphorus & silicon
	Dissolved oxygen & carbon dioxide
Biological	Phytoplankton biomass (Chlorophyll-a)
	Benthic biomass
	Fecal indicators
Biophysical	Inherent optical properties

Table 4. Heinz Center indicators of the condition of marine and estuarine ecosystems (from Table 1), GOOS phenomena of interest (Table 2), and common variables of the GCN (Table 3) that should be monitored for rapid detection of changes in the indicators.

Indicator	Phenomena of Interest	GCN Common Variables
Living habitats	Habitat modification & loss Changes in spatial extent & condition of essential fish habitat	Benthic biomass
Shoreline types	Habitat modification & loss Spatial extent & condition of essential fish habitats	
Dead zones	Bottom water oxygen depletion	Dissolved oxygen fields
SST	Sea surface temperature fields Upper water column heat content Air-sea heat flux	Sea surface temperature fields
Coastal erosion	Coastal inundation, storm surge & erosion Susceptibility to natural hazards	Shoreline position Near shore bathymetry
Contaminated sediments	Chemical contamination	
Native species at risk	Loss of biodiversity	
Invasive species	Invasive species	
Condition of benthic communities	Chemical contamination Benthic biomass	
Mass mortalities	Diseases & mass mortalities of marine organisms	
Plant biomass	Phytoplankton biomass Benthic plant biomass	Chlorophyll fields Benthic plant biomass Inherent optical property fields
Harmful algal blooms (HABs)	Harmful algal events	Chlorophyll fields Inherent optical property fields
Commercial fish landings	Annual landings of wild stocks Aquaculture production	
Status of commercial fish stocks	Spawning stock size, Recruitment Natural mortality, Food availability Spatial extent & condition of essential fish habitat	
Contaminated fish	Chemical contamination of seafood	
Recreational water quality	Risk of exposure to human pathogens, chemical contaminants & biotoxins	Fecal indicators