# AN INTEGRATED, SUSTAINED OCEAN OBSERVING SYSTEM

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## 1 - INTRODUCTION

The purpose of this paper is to convince those involved in the design and implementation of a sustained ocean observing system that a systematic, coordinated, and integrated approach is in the best interest of everyone—be they a provider of data, a processor of data, or a user of the resulting products or information. Observing system measurements must have certain common characteristics that have been agreed on. But, the observing system must be much more than gathering information over a variety of time scales—it also must focus on providing the infrastructure and techniques to ensure that this information is utilized efficiently. To those ends, the observing system must be based on a strategy with elements that ensure that all the parts work together to provide for the needs of all.

Scientific and practical rationale for sustained ocean observations and the climate information and products derived therefrom have been enunciated in various documents, including notably the Ocean Observing System Development Panel Report (OOSDP, 1995; Nowlin et al., 1996), the CLIVAR Implementation Plan (WCRP, 1998), and the Action Plan for Existing Bodies and Mechanisms (IOC/WMO, 1999). The requirements are set by the Global Ocean Observing System and the Climate Variability and Predictability (CLIVAR) program; they include needs for research, operations, and policy making. These rationale have been reviewed and details of consequent observing system elements that are required have been discussed in detail during this First International Conference on Ocean Observing Systems for Climate.

A strategic plan is essential if we are to have truly long-term (sustained) observations, not just observations that benefit, and last during the course of, an individual's or group's research project. Sustained observations are needed by scientists studying long-period phenomena as well as other users of practical information and products derived from sustained observations. Moreover, sustained observations provide the background against which shorter period phenomena and processes can be viewed, described, and understood.

Key elements in this strategy are:

- The need for the observations to be sustained and
- The need for integration between elements of the observing system.

Section 2 gives an overview of the recommended approach to an integrated, sustained ocean observing system. The meanings of system, sustained, and integrated are given; the generally agreed characteristics of observing system elements are reviewed; and the suite of elements suggested by Nowlin (1999) as comprising an observing system strategy are repeated. Finally, some needed new mechanisms are suggested, including a Joint Technical Commission for Oceanography and Marine Meteorology, integrated infrastructure for production of products and for handling data and products of the system, and procedure for migrating ocean observing techniques into the sustained observing system.

The remaining sections elaborate on selected concepts, strategic elements, and mechanisms. Sections 3 and 4 discuss more fully the meaning of sustained and integrated, respectively. Section 5 elaborates on the orderly transition of observing techniques from development into elements of an integrated system. The absolute need for free and timely data release is the subject of Section 6. Section 7 points to the need to implement common infrastructure, including that needed for the production of products and information from the data, and for the improved management of data and information. Thus, it closes the paper with a reminder that the system is not comprised solely of observations, but rather is an end-to-end system from observations to the results needed by users for research, operations, and policy making.

## 2 - AN ORDERLY, STRATEGIC APPROACH

### 2.1 - The meanings of system, sustained, and integrated

We speak of an integrated, sustained observing system. It is well that we review the meaning of those concepts and keep them firmly in mind as we embark on the exercise of implementing such a system.

By "system" we mean "a complex unity comprised of often many diverse parts subject to a common plan or serving a common purpose" (Webster's Third International Dictionary, 1981). A second definition is "an assemblage of objects [observing system elements] joined in regular interaction or interdependence". Clear in the definition of system are the notions of diverse elements interacting to complete objectives of a common strategic plan.

Webster's Third International Dictionary (1981) defines "sustain" as "to cause to continue; to keep up, especially without interruption, diminution, or flagging". This is clearly our intention of an observing system that will continue measurements with continuity into the foreseeable future.

Needed is more than just coordination among the elements of an ocean observing system (strategic element number 3 in the list in Section 2.3). The elements must be truly integrated ("composed of separate parts united together to form a more complete, harmonious, or coordinated entity" or "operating as a single coordinated physically interconnected unit or system" (Webster's Third International Dictionary, 1981).

Thus, it is clear that we wish for an integrated, sustained ocean observing system.

### 2.2 - Characteristics of observing system elements

As enunciated in the final report of the Ocean Observing System Development Panel (OOSDP, 1995), it is generally agreed that sustained observations must have certain characteristics. They must be:

- Long-term. Once begun, measurements should continue into the foreseeable future. Continuity is sought in the observed quantity, not in the measurement method.
- Systematic and relevant to the observing system. Measurements should be made in a rational fashion, with spatial and temporal sampling, precision, accuracy, and care in calibration tuned to address the products needed by users.
- Subject to continuing examination. Trade-offs must be subjected to scientific evaluation on a continuing basis to take advantage of new knowledge and technology.

Because of the global scope and intended longevity of the observing system for climate, it is realized that there are further practical constraints on the measurements. They should be :

- Cost effective. To maximize returns using available resources (financial and manpower), economical and efficient methods should be used.
- Timely. All data must be delivered to deadlines. In some cases this means in real time, while in others substantial quality control will require lapsed time between measurement and data delivery.
- Routine. The observation tasks should be carried out by dedicated staff, responsible for acquisition and quality control of data and the dissemination of products. Thus for some variables, the collection of observations and related work may be integrated into agencies capable of making a long-term commitment; for other variables, the desired quality of routine observations may be best achieved by providing long-term support to research organizations capable of ensuring the quality and continuity of the measurements. This may vary from nation to nation.

## 2.3 - Elements of the strategy

It is essential that a strategy be adopted for implementing and integrating ocean observing system elements to be maintained for the foreseeable future. A suite of elements comprising such a strategy were discussed by Nowlin (1999) and are repeated here:

1. Implement operational observing systems for different environments.
2. Determine user needs and design sustained observing systems to meet requirements.
3. Coordinate observing systems via an integrated global observing strategy.
4. Develop mechanisms to involve researchers in the planning and oversight of observing system components.
5. Establish formal relationships between the ocean and atmosphere communities for purposes of data collection, communication, and analyses.
6. Ensure timely release of data for intended uses.
7. Implement data and information management systems, supplementary to existing systems, that are attuned to the multiple sources of data and their multiple uses.
8. Develop and implement enhanced capabilities for the production of products—syntheses of different data types; gridded, interpolated fields; nowcasts; forecasts; and assessments and warnings, among others.
9. Establish the coordination and agreements between agencies within nations necessary to integrate observing system activities.
10. Devise arrangements to provide stable, long-term support for required observing system elements.
11. Develop and use new technologies.

A number of those elements were agreed to prior to this conference and have been confirmed here. These include the need to “*implement operational observing systems for climate*” and “*determine user needs that underpin the general design of a climate observing system*”. Many other needed elements of a strategy for implementing and integrating ocean observing system elements for climate are not so well articulated, agreed upon, or institutionalized. This paper discusses some of those key elements.

## 2.4 - New mechanisms

Mechanisms are being put into place to ensure other needed elements of observing system strategy. The Integrated Global Observing Strategy (IGOS) is an attempt “*to coordinate the various observing systems being developed for distinct purposes and environments*”, including GOOS, the Global Climate Observing System (GCOS), the Global Terrestrial Observing System, and the World Weather Watch. Activities of IGOS include, among others, (1) the initiation of a data inventory center jointly between the systems and (2) the assembly, coordination, and joint presentation to the space agencies of space-based measurements required by the combined observing systems. In this latter regard, the sponsors of the observing systems and the space agencies are preparing very long-term requirements for space-based observations related to a series of specific themes; oceans is a lead theme under consideration.

The new Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) agreed to by the World Meteorological Organization and the Intergovernmental Cceanographic Commission is an unprecedented effort to "*establish formal relationships between the ocean and atmosphere communities for purposes of data collection, communication, and analyses*". The number of ocean observations used by the meteorological community—for research, weather forecasting, extended weather prediction, and climate forecasts—is growing, as is the value to the ocean community of many marine meteorological observations. Moreover, many of these data sets are collected or transmitted via the same platforms and systems. It is logical that common systems be used where feasible for data collection, communication, and analyses, and that joint mechanisms be established to obtain commitments from nations for the financial resources necessary for these actions. The JCOMM is a combination of the WMO Commission for Marine Meteorology and the IOC/WMO Integrated Global Ocean Services System (IGOSS) with its Ship-of-Opportunity Programme Implementation Panel. Affiliated with this Commission are the Global Temperature and Salinity Profile Program of IGOSS, the IOC Global Sea-level Observing System, the TAO Implementation Panel, and the WMO/IOC Data Buoy Coordination Panel; strong relationships will be established with the International Oceanographic Data and Information Exchange. JCOMM will coordinate the definition, development, and operation of the global marine meteorological and oceanographic observing systems and supporting communications facilities to meet the needs of IOC and WMO programs, particularly those of the World Weather Watch, GCOS, and GOOS. Clearly climate requirements form a large part of these needs.

The observing system must be sustained, but it must not be static. User needs will evolve, and new and improved observing technologies will be developed. There is the requirement for orderly adaptation of the system to meet evolving needs (including recommendations for development of new technologies to make sustained ocean observations more complete, more effective, and more affordable) and to incorporate new technologies without loss of continuity of the variable sought. The recommendations for change should address actions that will enable immediate improvements to the existing observations and associated data management, ensure continuity of critical observations, lead to integration for maximal shared use of platforms and data, and foster coordinated planning and implementation. It is recognized that the overall observing enterprise must engage the scientific, business, public, and government communities from initial conception through to societal benefits. Priorities must be set among interested and committed partners to decide what elements comprise the system and what elements are required to augment the system. The generic sequence of activities by which new observing technologies are migrated into the observing system is discussed in Section 5.

## 3 - SUSTAINED OBSERVATIONS

The ocean observing system for climate is intended as a sustained observing system—just as the World Weather Watch is a sustained system designed for weather analysis and forecasting. Because the variability of the atmosphere and ocean occurs over a very large range of time scales, observations are needed for very long times if we are to separate natural from anthropogenic variability and begin to make predictions of phenomena affecting the ocean and its users. Continuity is key to a successful sustained observing system.

The observing system envisioned must be both integrating and sustaining while also fostering innovation. Not only must required ongoing observations be continued, but additional or improved observations that are needed as part of the system must transition from the research and pilot phases to sustained, long-term status. Perhaps no single sector of the government-industry-academic partnership is capable of achieving this goal. A combination of interests are needed to ensure that observing systems adapt to new technologies while maintaining continuity in time series of the quantities needed for general use.

Sustained observations are often required by both research and operational users (and a range of uses between). The global climate observing system is being designed on the basis of this range of users. On the one hand, the CLIVAR goals require sustained observations to research long-term variability of the ocean and its predictability; on the other, there is urgent, growing public demand for continuing and improved operational forecasts of ENSO phenomena (La Niñas and El Niños) and their environmental impacts. Data obtained for these goals, as well as others, are needed for estimating the states of the ocean, particularly on periods of decades and longer. Included in such state estimation are estimates of heat, freshwater, and carbon budgets and their rates of change, as well as global to regional sea level changes. These state estimations provide much of the information on which assessments of the Intergovernmental Panel on Climate Change are based, and thus there is the need for sustained observations for policy as well as for operations and research.

A sustained observing system is a new concept for the ocean research community and there is continuing debate about just what constitutes a sustained observing contribution and what does not. There are many techniques which have been developed with specific hypotheses and/or process studies in mind; some have been successful, some less so. It does not follow that every such successful technique is ready for broader research application since such applications often demand robustness and effectiveness beyond that needed for focused, local studies. In turn, one should not assume that every successful technique used for research will necessarily migrate over to sustained operation—more will be said later about the process of migration of observing techniques into the sustained observing system.

Satellite-borne instruments make measurements that are required to complement in situ observing systems, and whose accuracy depends on adequate high quality in situ calibration data, and we must strive to ensure long-term continuity of key observations from both. Satellite measurements of particular importance to the oceans are sea surface temperature (SST), sea ice, sea surface height, surface vector winds, and ocean color. Satellite missions needed for sustained estimation of SST and sea ice are accepted as operational requirements of various agencies. On the other hand, satellite missions to obtain sea surface height, surface vector winds, and ocean color are still considered and funded as research missions, even though it has become clear that for a variety of reasons such measurements must continue on a sustained basis. This emphasizes the vital need for a plans to ensure orderly transition of needed, sustained ocean measurements from support as research-and-development activities to long-term operational activities. Given that space-borne data sets meet research, operational, and policy needs, there is the strong need for procedures to ensure the transition of required measurements in an orderly manner so as not to interrupt their continuity.

## 4 - INTEGRATE THE OCEAN OBSERVING SYSTEM ELEMENTS

The infrastructure that provides financial support and implementation of our present ocean observing systems is largely designed to accommodate components for a single use and a specific time period. Multiple, in-situ systems are often deployed independently in the same ocean regions, each justified for its own specific uses. We must broaden our concepts and change our structures to obtain an integrated system that is responsive to a broad spectrum of user needs through the combined use of in situ and remote measurements of multidisciplinary environmental variables from shared use platforms. We should realize that secondary data users can produce unforeseen added value. The goal is a locally relevant, fully coordinated, cost effective ocean observing system for multiple uses.

Many ocean observing system elements can meet the needs of multiple users, provided they have access. Oceanography often draws on data collected for meteorology; climate change assessments draw on data collected for meteorology for ENSO predictions and other sources; seasonal-to-interannual forecasting draws on data collected throughout the system. Many sustained observations have multiple uses. Examples with many users are sea surface temperature and surface wind stress. An example with a growing number of users is sea surface height from satellite altimetry—such observations support monitoring of regional sea level changes, monitoring and predicting El Niño/Southern Oscillation variability, monitoring ocean currents, and basic research into energetic variability. Moreover, the need for an observation in support of a single use may not provide compelling justification for the support of a sustained measurement program. Even in those cases for which support is justified, costs will invariably be even better justified when multiple uses are made of the observations.

The importance of designing an integrating ocean observing system is documented in many national and international planning reports. In particular, integration will bring together diverse communities by (1) forcing connections between in situ and space-based data, (2) bringing together operational and long-term research programs, (3) encouraging partnerships between the federal, private, and academic sectors, and (4) connecting disciplines and spheres (e.g., ocean, atmosphere, cryosphere, biosphere (IOC, 1998)). This bringing together of cultures will greatly enhance the value of individual efforts to the users. Integration will promote cost-effectiveness, elimination of duplication, sustained observations, and responsiveness to user needs.

An integrated system will allow much infrastructure to be used commonly for production of information/products needed for diverse reasons. Common infrastructure needed includes selected positioning systems, measurement systems, communications systems, data quality assessment and control systems, product generation, data archives, modeling and data assimilation capabilities, and technology developments. The commonalty of infrastructure is envisioned as a primary mechanism for developing a truly integrated observing system.

In summary, there are multiple needs for sustained ocean observations, and it is critical that we have observing system components that harmoniously combine measurements of multiple variables for multiple uses. This points to the need for some fundamental changes in the way business is done within the ocean science communities of many nations (particularly nations in which ocean observations mainly are by individuals rather than by institutions). In the broadest terms, we need evolution of our infrastructure to ensure common use of multiple-data systems by multiple users, so as to capitalize on potential synergy between components and to help justify the collection of sustained observations. To do this, we must entrain into the observing systems those operational users (private and governmental) who require sustained observations for specific single uses while ensuring that the resulting common-use systems meet the multiple needs of the global observing systems and the research communities for sustained observations.

The ocean observing system also has a critical role to play in the development and long-term sustainability of other environmental observing systems and related activities. The Report on the Adequacy of the Global Observing Systems (GCOS, 1998) highlighted the importance of an integrated, cohesive observing system for monitoring and understanding climate change. There is a mutual dependency and mutual benefits to be gained from a system that works well together, over and above the benefits that might be gained from any of the individual component systems. A similar synergy applies to the Global Ocean Observing System. For example, a well designed sea level network serves many different aspects of GOOS, not just climate. The remote sensing network will, in general, be serving all components (modules) of the GOOS.

## 5 - MIGRATION OF OBSERVING TECHNIQUES INTO THE SUSTAINED OBSERVING SYSTEM

In developing a sustained ocean observing system, the critical initial task is to identify the sustained (on-going, long-term) needs of users for information. This is not a precise exercise since it requires some measure of matching the ability of the user community to effectively use information (utility, capability) to the availability of information from potential elements. It is found that many elements of the required ocean observing system already exist. It is also found that the utility of some existing elements may have diminished to the point where sustained support may no longer be obvious. The next task then is to identify and integrate those elements into an efficient and effective system and to develop and implement effective data management activities.

At the same time, augmentations to the system must be considered, because we know that many needs can not be met with existing elements. Deciding what elements to add to the system, and when, requires a detailed scientific knowledge of the requirements and a detailed scientific and technical appreciation of the potential input from candidate elements. It also requires a willingness to make choices and set priorities.

Candidate systems will normally pass through several different phases on the path from idea and concept to a mature, robust technique (Ocean Observations Task Team, 1999). It is rare for this research and development process to occupy less than a decade. It is useful to focus on four broad stages, or phases, and to illustrate them with some examples. These stages are:

1. Development of an observational/analysis technique within the oceanographic community.
2. Community acceptance of the methodology gained through experience within pilot projects whose principal objective is to demonstrate. (A pilot project is taken to mean an organized, planned set of activities with focused objectives, a defined schedule, and outcomes which contribute in a significant way to the global climate observing system. A process study would be analogous for research.)
3. Pre-sustained use of the methods and data by researchers, application groups, and other end users, to ensure proper integration within the global system and to ensure the intended augmentation (and perhaps phased withdrawal of an old technique) does not have any negative impact on the integrity of the GOOS data set and its dependent products.
4. Incorporation of the methods and data into a continuing framework with sustained support and for sustained use in support of societal objectives.

To illustrate the stages of progression through this sequence, we may name: (1) the ENSO observing system as an element that recently reached the operational stage, (2) PIRATA as an ongoing pilot project, (3) Argo as a sampling methodology fully vetted by the research community and now recommended as a pilot project, (4) GODAE as a methodology used extensively by the atmospheric science community for research, analysis, and forecasting and now ready to be tested as an ocean observing system pilot project, and (5) Acoustic Thermometry of Ocean Climate as an example of sampling methodologies still being explored by the research community but with potential as a future sustained observing system element. There are many such nascent observing system elements.

## 6 - TIMELY DATA RELEASE FOR INTENDED PURPOSES

The observations from a sustained observing system must be transmitted and released as required by the users. For sustained observations for a multiplicity of needs this means release on a time scale compatible with the needs of the user with the shortest time scale. For use in nowcast and forecast systems, and in many other cases, the communication of data must be rapid and automated—essentially in real time. Rapid transmission often equates to some compromise in quality or loss of detail, but the majority of users for nowcast and forecast purposes will accept this as justified. In other cases, post-collection processing of samples must be done and data communication must proceed as rapidly as possible consistent with a quality controlled product. In all cases, sustained observing systems with multiple users are incompatible with the concept of data being proprietary to any entity. It should be clear that data sharing does not preclude data use by researchers in parallel with its real-time use in other products.

There are numerous examples of how allowing broad use of data sets and products has resulted not only in manifold use of the information, but in major improvements of the data quality and products because of feedback from the users. These examples include the surface fluxes from Florida State University, observations and products from TAO (the Tropical Atmosphere Ocean array of buoys), and sea level observations from the TOGA/WOCE real time sea level center. It seems clear that the system elements that have advanced most rapidly in the production of quality products have been those with multiple users (and thus both critics and helpers).

The design and uses of the observing system must be scientifically sound. So, scientists likely will be involved in the planning, implementation, and oversight of system components. A new paradigm is therefore needed to replace the current mind set and rules attributing "ownership" to data sets collected in whole or in part by scientists. Almost all data are being collected with public funding. Needed are new agreements to ensure that data collected as part of the observing systems are released in a timely manner for multiple purposes. This likely will require formulation and enforcement of new guidelines by agencies supporting observing system components. At present, such guidelines are missing, dated, or loosely enforced.

## 7 - IMPLEMENT COMMON INFRASTRUCTURE, INCLUDING IMPROVED DATA AND INFORMATION MANAGEMENT SYSTEMS

The common infrastructure for the sustained, integrated ocean observing system are those elements providing platform location, data communication, protocols and standards for data collection and quality control, data storage, and data redistribution. More effective methodologies for interpolating, extrapolating, and drawing inferences from measurements should reduce reliance on any one particular observation, and so build confidence in results. Ultimately much of the analysis will be performed by assimilating the observations into numerical ocean models. Major objectives of the infrastructure are:

1. To improve and expand effectiveness of shared use platforms and sensors.
2. To improve and expand the data management and communication facilities necessary for routine monitoring, analysis, and prediction of the ocean on required time scales.
3. To improve and expand facilities for processing assembled data sets and providing timely analyses, model interpretations, and model forecasts.
4. To enhance and develop application centers to assist with the interpretation and application of observations and products to users, as examples: improved climatologies (means and variances) of key ocean variables (e.g., temperature, salinity, velocity, and carbon) and the temporal evolution of these variables.

Data management systems already exist for most types of ocean data that will be required for the climate observing system. However, not all of these systems are well tuned to the needs of the user communities and few of the systems are readily able to exchange data with each other. In the past, most data systems were designed primarily for one type of data and one group of users; multiple use was not often expected. Essentially these systems were independent, each having its own formats and input standards. Today, many, if not most, users often need to acquire data from many different data management systems and thus now must deal with varying formats and access requirements.

For the future, the fundamental requirements for data management are: (1) an integration of existing data management systems, (2) more attention to the needs of end users (including especially timeliness), (3) responsive and sufficient quality control, (4) provision of adequate metadata, (5) continued auditing of the data streams to reduce loss, duplication, or other mislabeling of data and metadata and to ensure that metadata give error estimates, and (6) free, open, and rapid access. The use of model output is rapidly increasing in ocean science and that trend will accelerate. Thus, provision also must be made for the management of model-derived fields, including error estimates.

Needed is a quiet revolution in ocean data and information management systems. Access and order are the keys—leading to the ability to obtain efficiently all data needed. The concepts underlying GODAE, including the idea of a common server through which a complex array of both in situ and remotely-sensed data can be assessed in a timely manner for assimilation into numerical models of ocean systems, seem to embody the rationale for this revolution.

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