Annex VIII


Building a Sustained Ocean Observing System for Climate
Altimeter and Scatterometer
3°x3° Argo Float Array
Volunteer Observing Ships
Ocean Reference Stations
Research Ships
5° x 5° Drifting Buoy Array
Moored Arrays
Tide Gauge Stations
Global Ocean Observing System for Climate and Marine Services
Initial Ocean Observing System Milestones
Phased Implementation Plan, including international contributions

Ten-year Implementation Plan

For

Building a Sustained Ocean Observing System for Climate

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NOAA Office of Global Programs

Executive Summary

NOAA is committed to the task of building and sustaining a global climate observing system to meet the long-term observational needs of the operational forecast centers, international research programmes, and major scientific assessments. This paper describes a 10-year implementation plan for building the ocean component of that system.

Central to this effort is the opportunity and necessity for international collaboration. A global observing system by definition crosses international boundaries and the potential exists for both benefits and burdens to be shared by many nations. The plan reflects that reality.

Of equal importance is the need to coordinate across agencies within the United States. It is recognized that an effective global ocean observing system can be achieved only through continuing interaction among all national (and international) partners. In this context, NOAA's effort will provide a long-term component of the composite observing system to complement the contributions of the other ocean agencies.

The strategic approach underlying this implementation plan is as follows:

- Build the long term ocean component of the observing system in the context of a comprehensive, multi-year, climate services initiative. Improved marine and coastal forecast services will be immediate byproducts.
- Set a 2000-2010 time line for phased implementation.
- Establish accountability for the ocean component of the observing system by defining specific objectives and performance measures.
- Define an "initial observing system" that will accomplish the objectives and performance measures. Identify annual milestones to complete the initial observing system over the ten-year time line. Emphasize that the initial system is our best guess at this time – it must be evolutionary.
- State the obvious – a global observing system can not be built with existing budgets. Estimate the annual funding needed to achieve the identified milestones. Estimate that NOAA will implement about 50% of the global system.
- Work pro-actively with national and international partners to achieve 100%.

Although NOAA's marine and coastal services and the mission services of the other agencies and nations will benefit from this plan, and are considered throughout, accomplishing NOAA's climate mission is the fundamental driver. The scientific foundations come from the Climate Variability and Predictability Program (CLIVAR), the Carbon Cycle Science Program, and the Global Water Cycle Program. It is not the intent of the plan to provide all of the observations needed by these programmes but to provide a baseline observing system, to be sustained over the long term, that can be built upon where needed to solve specific questions. This baseline system looks for efficiencies to be gained by utilizing common platforms/sites/data infrastructure for several objectives in parallel, and seeks to foster a system approach to effective international organization of complementary in situ, satellite, data, and modeling components of climate observation.

The initial system design objectives (performance measures) are established as:

- For the global ocean, deliver four times daily analyses of sea surface pressure, sea surface wind, and marine weather and sea state conditions.
- For the global tropics, deliver daily analyses of precipitation, sea surface temperature, and air-sea fluxes.
- For the global ocean, deliver weekly analyses of upper ocean temperature and salinity, sea surface temperature and currents, and sea level.
- For the global ocean, deliver an ocean carbon inventory once every 10 years, and seasonal (four times yearly) analyses of the variability of ocean-atmosphere carbon exchange.
- At fixed climate reference stations, document long term trends in sea level change, and ocean/atmosphere variability.

In order to meet these objectives, the plan draws upon the observational experience gained in building the ENSO observing system in tropical Pacific, and upon the international design of *The Ocean Observing System for Climate* (Saint-Raphael, France, 1999). Again, this plan does not seek to implement all aspect of the Saint-Raphael system, but only those base-line components needed to meet the design objectives, and those for which NOAA should expect to have primary mission responsibility in the United States. The initial system (emphasizing adjustable and evolutionary) is comprised of twelve complementary in situ, space based, data and assimilation subsystems:

1. Global Tide Gauge Network
2. Global Surface Drifting Buoy Array
3. Global Ships of Opportunity Network
4. Tropical Moored Buoy Array
5. Argo Profiling Float Array
6. Coastal Moored Buoy Arrays
7. Ocean Reference Stations
8. Ocean Carbon Monitoring Network

9. Satellite Altimeter
10. Satellite derived Surface Vector Winds (Scatterometer)
11. Research Ship Operations
12. Data and Assimilation Systems (the Global Ocean Data Assimilation Experiment – GODAE)

A phased plan for systematically extending these networks to provide the needed global coverage is laid out with the following milestones targeted:

- Implement Argo, increasing the global array from the present 620 floats to the designed 3000 float array (by 2004).
- Expand the global SST/velocity drifter array from 800 to 1250 buoys (by 2004), and add pressure, wind, and precipitation measurement capabilities to all oceans.
- Install permanent GPS receivers at 86 select tide gauge stations -- the present network contains 45 GPS stations (by 2006).
- Implement a global network of ocean reference station moorings, expanding from the present two pilot flux stations to a permanent network of 16 (by 2006).
- Rejuvenate the U.S. coastal mooring network and assist South American countries in establishing their coastal moorings bringing the international array to 114 stations from the present 85 (by 2006).
- Expand the tropical moored buoy network from 77 to 106 stations spanning all three oceans (by 2007).
- Expand ships-of-opportunity high-resolution ocean and atmospheric sampling from the present 17 lines to 22 lines, and collapse the present broadcast XBT network into 19 frequently repeated lines (by 2007).
- Add autonomous carbon dioxide sampling to the moored arrays and the VOS fleet, and implement an ongoing ocean carbon inventory that will survey the entire globe once every 10 years (by 2007).
- Utilize international GODAE to develop an operational capability for routine assimilation of ocean data into forecast and climate prediction models, and provide a free and open global data management system for all ocean climate information (by 2007).
- Transition the U.S. partnership in altimeter operations from NASA to NOAA (by 2008).
- Systemize routine climate observations aboard the U.S. and international research fleets (by 2009).
- Transition the U.S. partnership in scatterometer operations from NASA to NOAA by 2010).

These subsystems in their present state comprise about 25% of what will be needed to complete the initial global observing system. As noted above, it is not expected that this system can be completed with existing resources. A significant National investment will be required by the United States, as well as a significant commitment to growth by our international partners. It is estimated that in the year 2000, at the outset of this effort, the international community was spending about $108 million annually, to which NOAA was contributing $26 million. By the year 2010 when the initial system will be fully in place, NOAA must plan to contribute $142 million annually to an international effort of $265 million.

Introduction

NOAA context: In FY 2000, NOAA embarked on a multi-year Climate Services Initiative with the goal of building a national capability to routinely deliver climate forecasts and assessments of economic value. The initiative is designed as a phased plan to build a complete suite of climate services over ten years. Central to this effort is the task of implementing a sustained global climate observing system. This paper describes one element of that task - a 10-year plan for phased implementation of the ocean component of the observing system. The objective is to meet NOAA's climate mission requirements - to provide the sustained ocean observing system needed to support climate forecasting, assessments, and directed research.

Interagency context: At the same time the observing system must be advanced in support of climate services, it must also be advanced in response to a national demand for the ocean agencies to coordinate implementation of the U.S. contribution to the global ocean observing system. It is recognized that an effective global ocean observing system can be achieved only through continuing interaction among all national (and international) partners. In this context, NOAA's climate contribution will provide a long-term component of the composite observing system that complements the contributions of the other ocean agencies. Implementation will be coordinated with the National Oceanographic Partnership Program agencies, just as all of NOAA's climate observation and research activities have been coordinated through the U.S. Global Change Research Program for the past decade.

International context: The observational component of climate services has by far the greatest opportunity and necessity for international collaboration. A global observing system by definition crosses international boundaries and the potential exists for both benefits and burdens to be shared by many nations. The climate system described below is based upon the international design of, and is an U.S. contribution to, *The Ocean Observing System for Climate* (Saint-Raphael, France, 1999). The observing system projects that make up the climate component have been developed, and will continued to be evolved, organized and managed, in cooperation with the international implementation panels of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology.

Ocean Observing System for Climate

This plan for implementation of a sustained ocean component of the observing system includes: 1) deployment and maintenance of observational platforms and sensors, both remote and in situ; 2) data delivery and management; and 3) routine delivery of ocean analyses. This end-to-end ocean system will provide the critical "up-front" information needed for climate forecasting, research, and assessments – continuous, long term, climate quality, global data sets and a suite of routinely delivered ocean analyses. At the same time, the system will provide real-time data to serve the needs of NOAA's marine and coastal forecast missions and the needs of the other agencies in accomplishing their missions.

The initial design objectives are:

- For the global ocean, deliver four-times-daily analyses of sea surface pressure, sea surface wind, and marine weather and sea state conditions.
- For the global tropics, deliver daily analyses of precipitation, sea surface temperature, and air-sea fluxes.
- For the global ocean, deliver weekly analyses of upper ocean temperature and salinity, sea surface temperature and currents, and sea level.
- For the global ocean, deliver an ocean carbon inventory once every ten years, and deliver seasonal (four-times-yearly) analyses of the variability of ocean-atmosphere carbon exchange.
- At fixed climate reference stations, documented long term trends in sea level change and ocean/atmosphere variability.

A strong scientific basis must underpin the implementation and continued improvement of the ocean observing system for climate. The system must be long-term and stable, but not static. The future will bring better understanding of climate and other ocean requirements, and new awareness of better sampling techniques, methods, and trade-offs between data and numerical models. Consequently, the ongoing, central involvement of the research community is essential to maintaining an ocean system that is dynamic and responsive, even as it is continuing. An institutional commitment to this blend of research and operations is central to NOAA's programme.

The scientific drivers for this plan derive from three global research programmes – the Climate Variability and Predictability Program (CLIVAR), the Carbon Cycle Science Program, and the Global Water Cycle Program. These programmes have developed comprehensive science plans that specify observational requirements. Each programme is coordinated in the U.S. by an interagency working group that in turn coordinates internationally. The elements of this NOAA 10-year plan are not intended to satisfy all of the observation requirements of these programmes, rather they are intended to provide a backbone infrastructure to be sustained over the long term for climate service applications, a backbone that can built upon where research requires. Additionally, the elements of this plan are those that can promote efficiencies through the use of common platforms/sites/data infrastructure for several objectives in parallel.

The three general classes of activities within the ocean observing system for climate - operation of in situ and space networks, data and information management, and ocean analysis - must be complemented by the technology development needed to improve the entire system. Although, these activities are typically listed independently, it is critical to recognize that an integrated observing system is proposed -- integrated in the sense that sensors and networks are multi-purpose, remote and in situ data are combined, data management is multi-dimensional in data access and product generation, assimilation into the models uses multiple data types, and the over arching goal of the observing system is to effectively serve multiple research, forecast, and assessment objectives.

Specifically, past research and operational advances clearly demonstrate that a multi-platform/sensor system is crucial for accurate forecasts, increased understanding of the climate system and accurate detection, attribution and assessment results. Each network brings its own strengths and weaknesses to the system. None can do the job alone. Although satellites provide global coverage with spatial resolution typically not available from in situ networks, data from the latter networks are needed to calibrate, validate and interpret data from the former. Furthermore, experiments with climate models show that initializing the ocean components of the forecast models with combined remote and in situ data vastly improves the initialization process.

NOAA's climate contribution to the global ocean observing system will focus on those networks that can deliver data in real time and of the highest possible accuracy so that the observations are suitable for forecasting and analysis at all time scales from immediate marine weather conditions to seasonal climate variability to long term climate change. Implementation of the in situ networks will be through distributed centers of expertise at the NOAA laboratories, the National Data Buoy Center, and the university laboratories that have developed the instruments and techniques. The space components will be centered in the National Environmental Satellite Data and Information Service. The focal point for developing global ocean data assimilation capabilities will be the Geophysical Fluid Dynamics Laboratory in partnership with university-based applied research centers. Specific components and aspects of this end-to-end observing system are described below. The composite system is illustrated in Figure 1.

Figure 2 is a graphic representation of the phased, 10-year implementation strategy. Achievement of the annual milestones and the network goals described below will depend upon the success of the multi-year budget initiative process in producing the necessary resources. Cost estimates for the NOAA, interagency, and international contributions to this climate component of the ocean observing system are summarized in Figure 3 and are detailed in Table 1. The numbers listed are intended to indicate the magnitude of the work to be done and are based on the best estimates presently available. It should be emphasized, however, that the observing system must be evolutionary, and that the design objectives will change over the 10-year term of this initiative as research, forecasting, and assessment experience advances.

Tide Gauge Network: Tide gauges are necessary for accurately measuring long-term trends in sea level change and for calibration and validation of the measurements from satellite altimeters which are assimilated in to global climate models for predicting climate variability. Many tide stations need to be upgraded with modern technology.

Additionally, permanent GPS receivers will be installed at a selected subset of stations, leading to a climate network expansion from the present 45 GPS sites to 86 sites globally by 2006.

Drifting Buoy Array: Data sparse regions of the global ocean are a major source of uncertainty in the seasonal forecasts and are also a major uncertainty in the detection of long term trends in global sea surface temperature, which in turn is an indicator of global change. Data gaps must be filled by surface drifting buoys to reduce these sources of error to acceptable limits. NOAA, together with international partners, will extend the global SST/velocity drifting buoy array to data sparse regions, increasing from 800 to 1250 buoys by 2004, while adding wind, pressure, and precipitation measurement capabilities to serve short term forecasting as well as climate research, seasonal forecasting, and assessment of long term trends.

Tropical Moored Buoy Network: The advanced understanding of the role of the tropics in forcing mid-latitude weather and climate was learned primarily through the observations of the tropical moored buoy array (TAO/TRITON) in the Pacific. A similar pilot array in the Atlantic basin (PIRATA) now offers the potential of even better understanding, improved forecasts, and improved ability to discern the causes of longer term changes in the Oceans. The global tropical moored buoy network will be expanded from 77 to 106 stations by 2007 and will ultimately span all three oceans - Pacific, Atlantic, and Indian Ocean.

Volunteer Observing Ships: The global atmospheric and oceanic data from ships of opportunity have been the foundation for understanding long-term changes in marine climate and are essential input to climate and weather forecast models. Improved instrument accuracy, automated reporting, and improved information about how the observations were taken will greatly enhance the quality of these data, reducing both systematic and random errors. NOAA will improve meteorological measurement capabilities on the global VOS fleet for improved marine weather and climate forecasting in general, and will concentrate on a specific subset of high accuracy VOS lines to be frequently repeated and sampled at high resolution for systematic upper ocean and atmospheric measurement. This climate-specific subset will build from 23 lines presently occupied to a designed global network of 42 lines by 2007 and will provide measurements of the upper ocean thermal structure, sea surface temperature and chemistry, and surface meteorology of high accuracy for documentation of ocean-atmosphere exchanges of heat, water, and carbon dioxide.

Argo array of profiling floats: The heat content of the upper 2000 meters of the worlds oceans, and the transfer of that heat to and from the atmosphere, are variables central to the climate system. The ocean provides the “memory” that influences the differences that are seen in seasonal weather patterns from year to year. The Argo array of profiling floats is designed to provide essential broad-scale, basin-wide monitoring of the upper ocean heat content. Three thousand floats will be deployed worldwide by 2004. The U.S. contribution is approximately one-third of this international project.

Ocean Reference Stations: NOAA, together with international partners, will implement a global network of ocean reference station moorings, expanding from the present two pilot stations to a permanent network of 16 by 2006. Many of these new ocean moorings will be located at the historical sites of the former Ocean Weather Ship stations. The records from these abandoned sites have been invaluable is studying ocean atmosphere exchange and long term trends in ocean climate. Re-establishing the sites with modern technology (autonomous moorings instead of manned ships) will allow the historical records to be extended into the future and will also add calibration/validation points to the global in-situ and remote networks for improved climate and marine forecasting.

Coastal Moorings: Improved near shore measurements from moored buoys are critical to coastal forecasting as well as to linking the deep ocean to regional impacts of climate variability. Furthermore, the coastal regions are critical to the study of the role of the ocean in the intensification of storms which are key to the global transport of heat, momentum and moisture, and are a significant impact of climate on society. Coastal arrays are maintained by many nations making this a “global” network of “coastal” stations. NOAA’s existing network will be improved by augmenting and upgrading the instrument suite to provide measurements of the upper ocean as well as the sea surface and surface meteorology.

Ocean Carbon: Understanding the global carbon cycle and the accurate measurement of the regional sources and sinks of carbon are of critical importance to international policy decision making as well as to forecasting long term trends in climate. Projections of long term global climate change are closely linked to assumptions about feedback effects between the atmosphere, the land, and the ocean. To understand how carbon is cycled through the global climate system, ocean measurements are critical. NOAA will add autonomous carbon dioxide sampling to the moored arrays and the VOS fleet to analyze the seasonal variability in carbon exchange between the ocean and atmosphere, and will implement a programme of systematic global ocean surveys that will provide a complete carbon inventory once every ten years.

Platform Support: Ship time within the UNOLS research fleet for deployment of the moored and drifting arrays, and for deep ocean surveys is an essential component of this initiative. The deep ocean can not be reached by VOS and Argo; yet quantification of the carbon and heat content of the entire ocean column is needed to solve the climate equations. In addition to providing the survey and deployment platforms for the autonomous arrays, the research fleet will maintain sensor suites on a small core of these vessels as the highest quality calibration points for validation of the other system measurements.

Altimeter: The value of spaced-based altimeter measurements of sea level height has now been clearly demonstrated by the TOPEX/ Poseidon and Jason missions. Changes in sea level during major El Nino events can now be discerned at high resolution affording more realistic model initializations for seasonal climate forecasting. NOAA must now take on the role of ensuring that these altimeter data become part of the routine long-term set of climate observations by beginning the transition of the U.S. partnership in altimeter operations from NASA to NOAA, to be completed by 2008.

Scatterometer: An aggressive satellite ocean winds observation programme, coupled with the greater number of *in situ* wind observations planned for the ocean system, is necessary for improved understanding of climate process as well as improved forecasting of both climate and marine weather events. As a first step NOAA will establish a science team to serve as a focal point for cooperative research on ocean winds with the immediate goal of developing ocean wind data assimilation techniques for numerical weather and ocean prediction models to serve both short-term marine forecasting needs and climate predictions. The long-term goal will be to transition proven ocean wind sensing capability (e.g. scatterometry) to an operational satellite system by 2010.

Data Management: A robust and scalable data management infrastructure is essential to the vision of a sustained ocean observing system. The value of the observations does not end with their initial use in detecting and forecasting climate variability. The data must be retained and made available for retrospective analyses to understand long term climate change, and for designing observing system operations and improvements. NOAA's long history and unique expertise in environmental data management will be applied to the ocean observing system. NOAA also will include the vast holdings of historical ocean observations within the context of the integrated environmental data access and archive system. Support will also be provided for a World Ocean Database to incorporate modern data into an integrated profile system.

Ocean Analyses: For climate and marine forecasting, the combined fields from many different networks are used as initial conditions to begin the forecast. These combined fields, or analyses, are used to document what the ocean and atmosphere are doing at present and what they did in the past (if sufficient historical data are available). By routinely comparing models and data, shortcomings in the observing system can be identified and both the models and forecasts can be improved. To utilize effectively the ocean observations, NOAA will expand the current ocean analyses (presently focused on the tropical Pacific) to the global domain and will develop and implement improved assimilation systems that can more effectively use the new data types that are being collected. The principal vehicle for doing this, involving both national and international communities and producing a variety of marine products in addition to the use of these observations in forecast systems, will be the Global Ocean Data Assimilation Experiment (GODAE).

Observing System Targeted Research: The ten-year implementation plan and activities outlined here represent a best estimate of an initial ocean observing system for climate. But this initial system must evolve as understanding of the climate system advances, technology improves, and numerical models improve. In addition to supporting the research, forecasting, and assessment requirements of climate services, the observations resulting from these global arrays will be used for applied studies to make the observing system and its products more effective. Sampling strategies will be evaluated to ensure the most efficient and effective combination of remote and in site measurements. Through data syntheses and assimilation processes, the targeted research will constantly evaluate the observing system products that result from the combination of the data streams in order to ensure that the best ocean analyses are produced. The research will ensure that the most effective quality control is done, that new technology is implemented once it is ready, and that duplicative or out dated activities are minimized.

Interagency/International Strategy

This plan includes elements that fall principally under NOAA's mission responsibilities for implementation within the United States. As noted throughout, however, the plan depends critically on interagency and international collaboration. Figures 1, 2, and 3, and Table 1 reflect the composite interagency/international system. The general strategy of this plan assumes that NOAA will implement approximately 50% of the system over the next 10 years. This means that NOAA will "buy out" NASA's share of the operational satellite missions (these missions are international partnerships). This buy-out represents the largest decrease in interagency funding illustrated in Figure 3. Continued partnership with NSF and the Navy is required in supporting in situ ship operations, carbon monitoring, and deployment of the drifting arrays; this is the interagency contribution that continues across the entire ten years in Figure 3. All of the in situ networks require international partnerships and success in implementing the ocean observing system for climate will depend on the entire international community ramping up over the next decade.

Benefits

The data and analyses deliverables noted above (the initial design objectives) are of limited value in-and-of themselves -- the data and analyses must be converted to information that is of economic value to the Nation by the forecast, assessment, and research components of NOAA's climate me. At the same time, the forecast, assessment, and research components can not do their jobs without receiving accurate data and analyses from the observing system. The benefits outlined below are achieved only through a complete climate service of all four elements: observation, research, forecasting, and assessment.

Seasonal variability: The last several years have graphically demonstrated the vulnerabilities of social and economic systems to natural climate variability. During the 1997/98 El Nino, impacts were felt in agriculture, the energy sector, transportation, retail, ecosystem disruptions, public health, property damage, extreme weather events, to name a few. Estimates suggest that the impacts were of the order of billions of dollars in several of these sectors just in the U.S. The seasonal forecasts are now being used by managers in most of these sectors. Mitigation efforts, based on the NOAA forecast, by FEMA and local emergency management agencies in California alone are estimated to have reduced losses by perhaps $1 billion. Forecasts were also used internationally to help mitigate the global impacts of that powerful El Nino event. The U.S. economy (and indeed the global economy) is vulnerable to climate variability. The energy and retail sectors were the first to quantitatively use climate forecast information (which depends directly on a global observing system). The weather derivatives market is now estimated to be several billion dollars and can be expected to grow. It has been estimated that roughly 20% of the $9 trillion U.S. economy is sensitive to weather and climate variability. This suggests that with improved forecasts, understanding, and action partnerships with end users, the advantage to the U.S. economy can be enhanced of order 10's of $ billions.

Long term climate variability and change: Changes in oceanic heat transport from the tropics to the poles, regime shifts in ocean productivity, and changes in atmospheric circulation related to long-term changes in the ocean have affected and will affect societies in general. Improved documentation and analysis of long term variability in ocean properties and fluxes will provide the information needed for society to anticipate and adapt to the general changes in the earth's climate system that will result. Improved estimates of the oceanic burden of CO_2 will assist decision-makers in establishing national policy for adapting to climate change. Accurate documentation and forecasting of sea level change are crucial to engineering and land use decisions as the U.S. population continues to migrate to the nation's coastal regions.