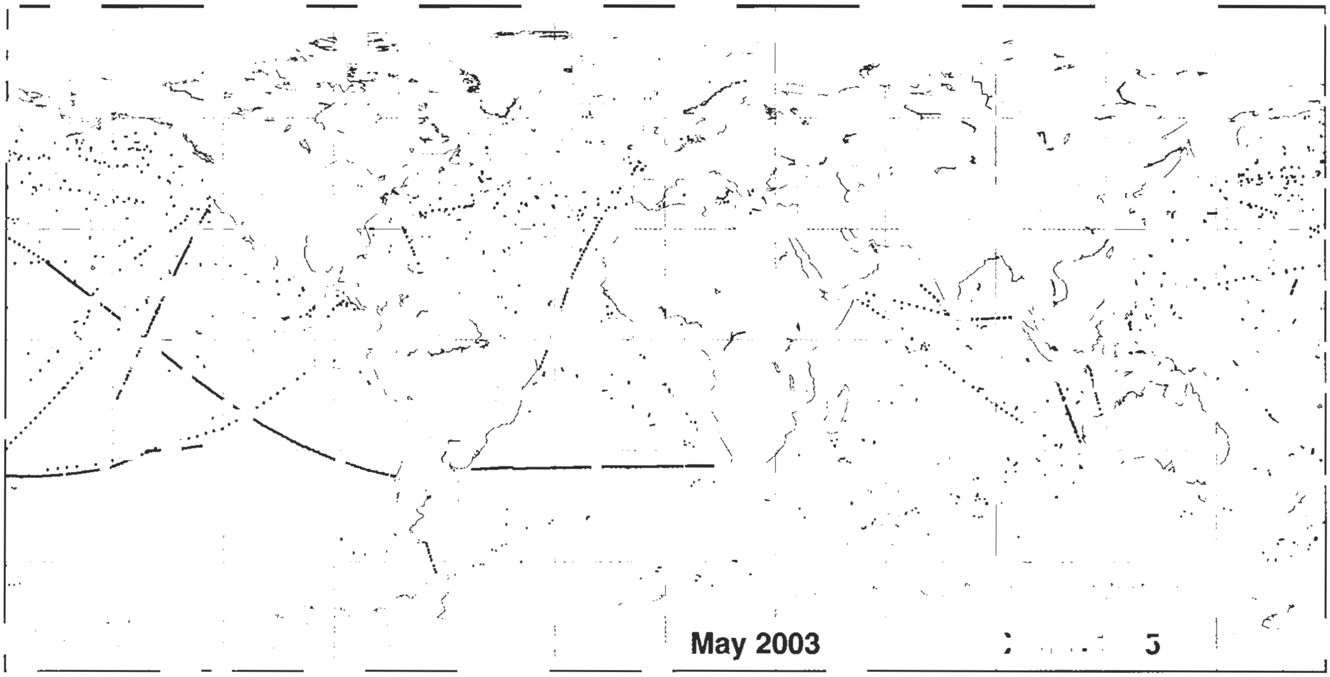
The Future of Climate Observations in the Global Ocean

International Commitments for Collection of High-Quality Observations are in Process and Will Yield Many Benefits



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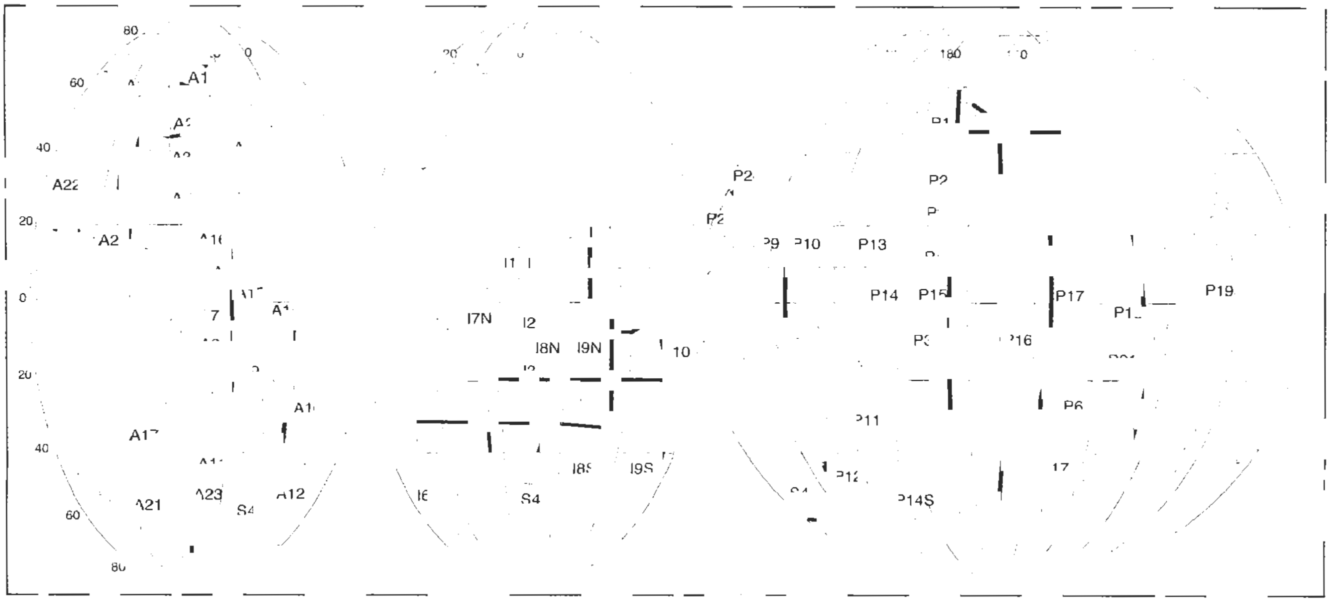
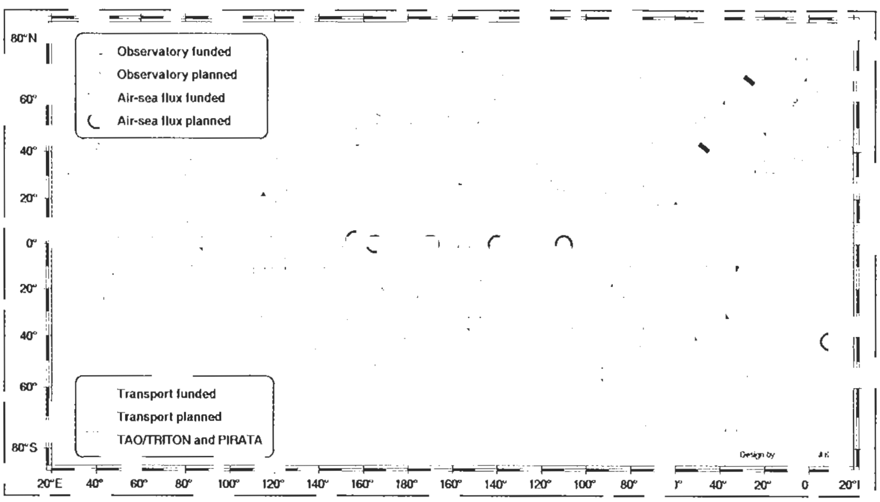
Global ocean observations for climate research are a major part of the legacy of the World Climate Research Program's (WCRP) Tropical Ocean Global Atmosphere (TOGA) and World Ocean Circulation Experiment (WOCE). They remain as a major element of the WCRP's ongoing Climate Variability and Predictability (CLIVAR) project. TOGA demonstrated that an integrated observing system spanning the tropical Pacific would lead to a better understanding of El Niño/Southern Oscillation (ENSO) variability and to successful El Niño predictions. WOCE showed, with a one-time global survey, that the oceans make an important contribution to the total heat budget of the climate system through heat transport, as well as heat storage. To build on the legacies of WOCE and TOGA, CLIVAR will include two classes of *in-situ* ocean observations. Limited duration regional process studies will focus on phenomena that are poorly understood in order to improve their representation in ocean and coupled models. Sustained observations on basin-to-global scales, which are the topic of this article, should resolve the patterns of climate variability and the large-scale climate processes that the models aim to simulate.

The CLIVAR Ocean Observations Panel (COOP) and the Ocean Observing Panel for Climate (OOPC) jointly attempted to develop and summarize a community consensus on the ocean observing system through the OceanObs '99 Conference.[1]

Planners were required to consider the practicality and resource limitations for every element of the observing system, as well as technical feasibility. The planning process was broad in scope, including satellite measurements, *in-situ* observations and the data assimilation systems needed to synthesize them. Reviewed herein is the substantial progress made since





OceanObs '99 in several elements of the *in-situ* observing system, as well as to point out the major challenges that lie ahead for this endeavor.

Climate Observation Objectives

The primary elements of the physical climate system are the heat and hydrological cycles. These are complemented by the carbon cycle, which will not be addressed in this article. Climate observations and models should be capable of tracking heat and water (and carbon) through the ocean-atmosphere-cryosphere system, including how changes in the atmospheric inventory of radiationally active components modulate such transfers.

The specific objectives for sustained large-scale ocean observations are to:

- provide a basic description of the physical state of, the global ocean, including its variability on seasonal and longer time-scales
- reveal processes that influence climate on long time-scales
- provide the large-scale context for regional process studies of limited duration
- produce the required data sets for data assimilation and (seasonal and longer) forecast model initialization
- complement the satellite remote sensing systems with data needed for validation, calibration and interpretation.

Status of Implementation

The ENSO Observing System–TOGA's Legacy. The ENSO observing system was the prototype for basin-scale integrated observing systems. It initiated sustained observations in the tropics, including the TAO/TRITON tropical mooring network (12 westernmost U.S.-NOAA-built/operated Atlas buoys replaced with Japanese-built TRITON buoys with contributions by France), broad-scale XBT network, surface drifter network and sea-level network. These networks have been maintained since the 1980s, with the latter three elements extended to extra-tropical coverage. The ENSO observing system also pioneered real-time public data delivery in order to serve the needs of a broad user community with both research and operational objectives. The successes of the ENSO observing system are a better understanding of ENSO variability and successful seasonal prediction, and its continuity has paved the way for global observations to build on its capabilities.

The Argo Network. The Argo global profiling float project collects temperature/salinity profiles and mid-depth velocity measurements on broad spatial scales over all of the world's ice-free deep oceans. Argo will provide near real-time measurements of heat and freshwater storage, plus large-scale circulation and transport. As of July 2003, Argo had achieved over 25 percent of its target of 3,000 floats, and there were substantial float arrays in all of the oceans. There are international commitments for most of the floats needed to complete the Argo array, and it is planned that by 2006, Argo will collect about 100,000 temperature/salinity profiles and mid-depth velocity measurements annually. Argo floats are supplied and deployed by 15 nations (and the European Union), with coordination by the international Argo Science Team. Each float must work autonomously for its four-year life, cycling every 10 days over a pressure range of up to 200 atmospheres while retaining its sensor calibration. As float reliability has improved, deployments have increased rapidly. Argo data are publicly available in near real-time from two global data assembly centers, and scientific analyses and operational usage of Argo data have begun. The early results from the use of Argo data will be discussed at a workshop in Tokyo in November 2003.

Deep Ocean Hydrography. During the 1990s, WOCE obtained a global baseline survey of the oceans from top-to-bottom, sampling a wide range of naturally occurring and man-made tracers, including inventories of elements of the global carbon cycle. Later this year, the first of a set of four atlas volumes of the WOCE Hydrographic Program data will be published. There are now commitments to repeat many of these WOCE lines. Re-occupying these transects every five to 10 years will make it possible to investigate variability in water-mass inventories and renewal rates, physical and biogeochemical properties, and to reassess ocean carbon inventories.[2] The data will help to reveal the nature of deep ocean circulation variability, long time-scale fluctuations in the deep meridional overturning circulations, and the corresponding transports of heat and freshwater—all of vital importance to understanding the stability of our climate.

Time-Series Stations. Time-series observations at fixed points are an important complement to the broad-scale arrays such as Argo. This is because they may occupy special locations, sample at high frequencies, and include a wide variety of physical and biogeochemical parameters. Time-series stations include several types of platforms: the tropical moored networks (TAO/TRITON and PIRATA), transport measurements at special locations such as choke points and western boundary currents, mid-ocean full-depth observatories for water properties (e.g., the Bermuda and Hawaii stations) and air-sea flux reference stations. While considerable progress has been made in developing a community plan and building support for time-series stations, a considerable part of the plan remains uncommitted.

Other Observing System Elements. While the above list includes the largest elements of the *in-situ* ocean observing system, others are also important for balanced and comprehensive sampling. As noted above, the surface drifter network, broad-scale XBT network and sea-level network have all been extended beyond the tropics to coverage that is quasi-global. Some additional expansion is needed—for example the drifter network will increase from about 800 active drifters today to 1,100. XBT networks include high-resolution XBT/XCTD (HRX) sampling in all of the oceans, with a selected set of repeating transects to observe variability in upper-ocean circulation and transport on spatial scales ranging from boundary currents and eddies to basin width. Pacific HRX transects have been sampled on a quarterly basis for up to 17 years (www.hrx.ucsd.edu). Acoustic tomography and thermometry offer great potential for integral measurements over regional-to-basin scales, and a number of regional arrays are planned in the near term.

Major Challenges

The most obvious challenge is to bring to bear the necessary resources from many countries to implement and sustain the observing system long enough to demonstrate its capabilities and its value. However, there are several other substantial challenges to be faced for success in this endeavor.

Completeness of the System. In the OceanObs '99 process, boundary currents were singled out as a crucial part of the circulation for which a systematic plan was not yet available.[3] At present there is still no overall plan for measuring the oceans' boundary currents—the low-latitude, subtropical and subpolar western boundary currents, as well as the eastern boundary currents. Several different techniques are in use or planned for boundary-current measurements in a few specif-

ic locations—moored transport arrays, HRX transects, tomography and repeat deep-ocean hydrography.

These approaches are valuable but not sufficient, and will leave many unmeasured flows that contribute critically to ocean circulation and transport. New technologies of gliders and other autonomous vehicles offer the potential to measure the oceanic boundaries efficiently. Gliders are slow—about 20 centimeters per second—so this plan exploits the swift flows in the upper one to two kilometers of the boundary currents to advect the instrument downstream as it glides across. By making multiple crossings, and having several gliders simultaneously in different parts of the current, the evolving 4D structure of the flow is measured. Transects might coincide with Jason-1 altimetric tracks in some places. Implementation of such a plan would require substantial local logistical support for repeated deployment, recovery, servicing and shipment of instruments.

Biogeochemical Measurements. Deep-ocean hydrography and time-series stations have been the starting points for adding appropriate biogeochemistry to the physical observing system. Many new autonomous sensors are being developed for float, drifter and mooring applications, and a few have already demonstrated considerable promise. The challenge will be to select and implement those sensors that increase the value and completeness of the observing system and are compatible with the existing missions of autonomous instruments. Broadening the observing system to increase its multi-user aspect is a crucial selling point, but careful judgements are required for initiation of any new long-term observations.

Co-Evolution of the Observing System with Models. Researchers are counting heavily on models to be the tools that enable full integration of global satellite and *in-situ* observations. It is essential that the evolution of the observing system and of data assimilation systems and forecast models be harmonized.

The roles of observations must be to provide appropriate data and statistics for data assimilation and model initialization, provide independent information for testing model results and model processes, and discover new phenomena not anticipated in models, thereby stimulating model improvement. A clear need is for global subsurface data sets to complement the coverage of satellite measurements of the sea surface.

The Research/Operations Interface. Operational oceanography has objectives and characteristics that can be specified in advance, has an indefinite operating life and evolves cautiously, and its success is judged by contributions with public benefits.

By this definition, TAO/TRITON is operational. For implementation and maintenance of the complete observing system, a strong partnership between research institutions and operational agencies must be created. A continuing strong leadership and participatory role is required of research institutions to assure the high quality and technical evolution needed in ocean observations for climate. The observing system needs to have vertical integration (instrumentation development, network design, implementation, data management, scientific analysis, data assimilation) as well as horizontal integration across the observing system elements.

Data and Information Management. In order to serve the needs of multiple users, data management and delivery systems are becoming increasingly sophisticated and versatile. For example, the Argo Data System must provide both near real-time data for operational applications and a scientifically reviewed data set for research. Argo Global Data Assembly Centers merge the data from all national data centers and maintain "best copy" profile data—including quality-control flags and histories—plus trajectory data and metadata.

Conclusion

The collection of high-quality observations in order to study climate on a global scale is an enormous undertaking, too ambitious and too costly for any single country or for the research community to carry out alone. A partnership is growing internationally that includes research institutions and operational agencies in order to implement an ocean observing system with a wide range of benefits. The various elements of the *in-situ* observing system are interdependent and complement one another.

Since the OceanObs meeting in 1999, enormous strides have been made to implement the vision that the meeting put forward. If that progress is maintained through the continued commitment of researchers, operational agencies and funders, we have within our grasp the prospect of being able to monitor the state of the global ocean before the end of this decade. The products and predictions stemming from this monitoring will have an enormous range of applications.

Acknowledgement

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References

1. Koblinsky, C., and N. Smith, eds., *Observing the Oceans in the 21st Century,* Bureau of Meteorology, Melbourne, Australia, 2001.
2. Sabine, C.L., and M. Hood, "Ocean Carbon Scientists Organize to Achieve Better Coordination, Cooperation," *EOS Transactions,* American Geophysical Union, 84, 23, p. 218, June 10, 2003.
3. Imawaki, S., W. Zenk, S. Wijffels, D. Roemmich and M. Kawabe, "Oceanic Boundary Currents," *Observing the Oceans in the 21st Century,* C. Koblinsky and N. Smith, eds., Bureau of Meteorology, Melbourne, Australia, 2001.

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